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Benefits of repeated alternations – Task-specific vs. task-general sequential adjustments of dual-task order control

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ABSTRACT

An important cognitive requirement in multitasking is the decision of how multiple tasks should be temporally scheduled (task order control). Specifically, task order switches (vs. repetitions) yield performance costs (i.e., task-order switch costs), suggesting that task order scheduling is a vital part of configuring a task set. Recently, it has been shown that this process takes specific task-related characteristics into account: task order switches were easier when switching to a preferred (vs. non-preferred) task order. Here, we ask whether another determinant of task order control, namely the phenomenon that a task order switch in a previous trial facilitates a task order switch in a current trial (i.e., a sequential modulation of task order switch effect) also takes task-specific characteristics into account. Based on three experiments involving task order switches between a preferred (dominant oculomotor task prior to non-dominant manual/pedal task) and a non-preferred (vice versa) order, we replicated the finding that task order switching (in Trial N) is facilitated after a previous switch (vs. repetition in Trial N - 1) in task order. There was no substantial evidence in favor of a significant difference when switching to the preferred vs. non-preferred order and in the analyses of the dominant oculomotor task and the non-dominant manual task. This indicates different mechanisms underlying the control of immediate task order configuration (indexed by task order switch costs) and the sequential modulation of these costs based on the task order transition type in the previous trial.

1. Introduction

When two tasks are to be executed in close temporal succession, performance decrements usually occur in one or both of the tasks. The most widely used experimental paradigm to study such dual-task performance costs is the "psychological refractory period" (PRP) paradigm (Telford, 1931). Various theoretical explanations have been advanced for how individual tasks are controlled in the PRP paradigm, and these issues have been studied extensively in the past (e.g., Pashler, 1994). However, considerably less attention has been paid to the fact that two temporally overlapping tasks, if they are to be performed correctly and efficiently, must be, first of all, scheduled appropriately in terms of their order (e.g., de Jong, 1995). The present study focuses on a particular aspect of task order control, namely on the impact of task dominance and preferred task orders on sequential effects of task order switches/repetitions, by re-analyzing previous data sets from a study by Huestegge et al. (2021) that are ideally suited to address this novel issue.

1.1. The PRP paradigm and dual-task order control

The PRP paradigm consists of the following elementary components. Two stimuli, typically denoted S1 and S2 and each associated with a speeded response (R1 and R2, respectively) are presented successively with a variable time interval, the so-called 'stimulus-onset asynchrony' (SOA) in between. Usually, in the PRP paradigm, the order of S1 and S2 is held constant, and participants are instructed to respond in the same order (i.e., execute R1 first and R2 second). The hallmark finding of this paradigm is an increase in reaction time to S2 (RT2) as the SOA decreases (i.e., as temporal overlap between Task 1 and Task 2 increases), the 'PRP effect' (Telford, 1931). The PRP effect has been explained in terms of the inability of the cognitive system to perform two response selection processes at the same time, thus requiring the delay of Task 2 response selection during ongoing Task 1 response selection. Such a structural response-selection bottleneck account was initially laid out by Welford (1952) in his single-channel hypothesis and was later

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formalized by Pashler (1994). Other theoretical accounts assume that the PRP effect is not a result of a structural limitation in response selection but rather of a strategic allocation of limited processing resource (s) (e.g., Meyer & Kieras, 1997; Navon & Miller, 2002; Tombu & Jolicœur, 2003).

Regardless of the specific explanatory account of the PRR effect, an important but often overlooked aspect of the PRP paradigm is that every 'PRP episode' (i.e., every trial) consists of a pair of two punctate tasks that need to be temporally scheduled (i.e., brought into a specific order) for adequate performance. The question of how task order is controlled has long been largely neglected because it was implicitly assumed that the order of task processing would be determined in a purely bottom-up manner by the order of stimulus presentation according to a first-come, first-served principle (e.g., Hendrich et al., 2012; Leonhard et al., 2011; Ruiz Fernández et al., 2011; Sigman & Dehaene, 2006; Strobach et al., 2018). However, the involvement of top-down processes in task-order control becomes evident when comparing situations with the explicit instruction to schedule responses in accord with the stimulus presentation order to situation with a free choice of response order. Response reversals (i.e., responses carried out in the opposite order as stimulus order would mandate) were less frequent with instructed order than with free-choice order, indicating strategic, top-down sources of influence on task prioritization (e.g., de Jong, 1995; Kübler et al., 2018). Furthermore, it has been demonstrated that the effector system eventually used to carry out the response constitutes a strong determinant of response order (e.g., oculomotor [vs. manual] responses were preferably executed first even when the stimulus triggering it came second), indicating effector-based task dominance (i.e., prioritization).[1] Finally, increased reaction times (RTs) in *both* component tasks were consistently observed when switching (vs. repeating) the task order from one 'PRP episode' to another (i.e., task-order switch costs; e.g., Hirsch et al., 2017; Luria & Meiran, 2003, 2006), indicating active reconfiguration of task-order representations.

1.2. Task-order control: sequential modulation and dominance-based asymmetries

Task-order switch costs were shown to be modulated by previous task-order control demands, specifically by the previous trials' task-order transition. Strobach et al. (2021) and Strobach and Wendt (2022) demonstrated reduced task-order switch costs in Trial N when Trial N - 1 itself required a task-order switch (i.e., when the task order in Trial N - 1 changed from the penultimate Trial N - 2) compared to when Trial N - 1 required a task-order repetition (i.e., when the task-order on Trial N - 1 was the same as in the penultimate Trial N - 2). This reduction of task-order switch costs was observed averaged across both tasks of the trial, affected RTs, error rates, and response reversal rates, and occurred not only in two-choice tasks but also in three-choice tasks, for relatively short and relatively long SOAs, as well as for relatively short and long inter-trial intervals. Taken together, the sequential modulation of order switch costs represents a rather stable and replicable phenomenon. However, the mechanisms underlying such an adaptive modulation of task-order control still lack specification. The present study, therefore, aimed at investigating the sequential modulation of task-order switch costs both in terms of its generality versus task specificity/task order specificity as well as in terms of the potential mechanisms underlying this phenomenon.

We aimed to do so by conducting a re-analysis of a set of experiments that is perfectly suited to address this issue (Huestegge et al., 2021). These authors demonstrated that the concrete implementation of task-order control (i.e., performing a task-order switch vs. task-order repetition) depended on the specific characteristics of the tasks to be (re) ordered. Huestegge et al. utilized combinations of tasks known to differ in *dominance* (i.e., prioritization), namely a dominant oculomotor task and a non-dominant manual (or pedal) task (e.g., Hoffmann et al., 2019; Huestegge & Koch, 2013), thereby creating task orders that have a 'natural' *preference* in comparison to non-preferred task orders (e.g., "oculomotor-manual" order preferred over "manual-oculomotor" order). Apart from demonstrating robust task-order switch costs overall, the main finding of that study was a clear asymmetry in task-order switch costs. Two (out of three) experiments consistently indicated that it was easier for participants to switch to the preferred task order (vs. to the non-preferred task order), as indicated by corresponding RT data. This effect therefore demonstrates that the task order control processes involved here take *specific* task characteristics (such as task-order preference) into account.

However, this study did not analyze the sequential reduction of task-order switch costs after *previous* task-order switches versus repetitions with regard to the characteristics of the specific tasks (i.e., task dominance) or task orders (i.e., task-order preference). On the other hand, studies concerned with this sequential modulation of task-order switch costs so far did not implement task combinations with one clearly preferred (and one non-preferred) task order, nor did they incorporate any task order specific analyses. A natural question arising based on the findings by Huestegge et al. (2021) is thus whether not only "first-level" task-order control (i.e., the actual task-order switch vs. repetition performed in Trial N), but also whether "second-level" modulation of task-order control (by a previous task-order switch vs. repetition in Trial N - 1) is dependent on specific task and task order characteristics, too.

According to such a *task/task order specific control modulation* hypothesis, different component tasks and their order would be expected to be differentially affected by the modulation of task-order switch costs; that is, the modulation of task-order switch costs should be different in size for the individual component tasks and their order. Alternatively, a *general control modulation hypothesis* assumes a general attention- (or other cognitive capacity-) related mechanism and would predict that participants react to an experienced task-order switch demand in a more general fashion by adjusting task-order control irrespective of the specific characteristics of the task and of the task order just switched to (or about to be switched to). This would imply that the impact of the "Order Transition" status (task order switch or task-order repetition) in the *previous* trial should be comparable regardless of whether the current trial requires a preferred vs. non-preferred task order and whether particular component task under analysis is dominant vs. non-dominant. The idea of allocating more general "mental capacity" to certain aspects of task-related processing in response to increased processing demands is a common notion in research on cognitive control (Kahneman, 1973) and still relevant in current theoretical dual-task frameworks (e.g., Tombu & Jolicoeur, 2005). For example, according to the classic model of action control by Norman and Shallice (1986), it is assumed that as long as "nothing unusual happens", behavior will be largely automatic and under the control of learned rules or schemata (e.g., responding according to the order of stimulus presentation when stimulus order repeats or is constant). Only when an extraordinary (and potentially performance-detrimental) event occurs, executive control (in form of the supervisory attentional system, SAS) is invoked to implement the appropriate rule (e.g., responding in accordance with the order of stimulus presentation when stimulus order switches). An overview of the experimental design and the hypotheses is provided in Table 1.

[1] The two terms *dominance* and *prioritization* do, in fact, imply two different potential concepts for capturing the preferential execution of one task compared with another. While dominance alludes to more automatic, learning-based mechanisms, prioritization may be interpreted to refer to more voluntary, strategic decisions to favor one task over another. Although such differences represent an interesting theoretical issue, we are here unable to decide between these two options based on the current data and, thus rather use the terms dominance and prioritization interchangeably throughout the manuscript.

Table 1
Overview of the task-order structure design and the hypotheses.

Specific task order in Trial N - 2	Specific task order in Trial N - 1	Specific task order in Trial N	Order transition in Trial N – 1 (i.e., Order Transition N – 1: Repetition vs. Switch)	Order transition in Trial N (i.e., Order Transition N: Repetition vs. Switch)	Task order in Trial N when investigating 2-way factor combination Order Transition N – 1 × Order Transition N	Prediction of task and task order specific control modulation hypothesis	Prediction of general control modulation hypothesis
Oculomotor ➔ manual/pedal	Oculomotor ➔ manual/pedal	Oculomotor ➔ manual/pedal	Repetition	Repetition	Preferred order	3-Way interaction of Task Order/Task × Order Transition N × Order Transition N - 1	No 3-way interaction of Task Order × Order Transition N × Order Transition N - 1
Manual/pedal ➔ oculomotor	Oculomotor ➔ manual/pedal	Oculomotor ➔ manual/pedal	Switch	Repetition			
Oculomotor ➔ manual/pedal	Manual/pedal ➔ oculomotor	Oculomotor ➔ manual/pedal	Switch	Switch			
Manual/pedal ➔ oculomotor	Manual/pedal ➔ oculomotor	Oculomotor ➔ manual/pedal	Repetition	Switch			
Manual/pedal ➔ oculomotor	Manual/pedal ➔ oculomotor	Manual/pedal ➔ oculomotor	Repetition	Repetition	Non-preferred order		
Oculomotor ➔ manual/pedal	Manual/pedal ➔ oculomotor	Manual/pedal ➔ oculomotor	Switch	Repetition			
Manual/pedal ➔ oculomotor	Oculomotor ➔ manual/pedal	Manual/pedal ➔ oculomotor	Switch	Switch			
Oculomotor ➔ manual/pedal	Oculomotor ➔ manual/pedal	Manual/pedal ➔ oculomotor	Repetition	Switch			

1.3. The present study

The dataset provided by Huestegge et al. (2021) was deemed optimally suited for answering our questions regarding the exact nature of the sequential modulation of task-order control processes by exhibiting three essential properties. First, all three experiments of their study demonstrated robust task-order switch costs that in turn can potentially be modulated by previous order sequences. Second, the dataset involves a sufficient number of trials with randomly mixed task orders for the analysis of higher order sequential effects. Third, task combinations were chosen that imply a clear dominance hierarchy of subtasks (e.g., oculomotor > manual) and thus a preference for particular task orders (e.g., oculomotor-manual > manual-oculomotor). The latter property was responsible for differential task-order switch costs based on task and task order characteristics in the original analysis and was thus regarded most conducive to finding a potentially differential modulation of these order switch costs based on task and task order characteristics.

Based on the previous literature and the considerations outlined above, the following predictions were made. Overall, task-order switch costs should be smaller after a previous task-order switch compared to a previous task-order repetition, thereby indicating a sequential modulation of task-order control (Strobach et al., 2021; Strobach & Wendt, 2022). Regarding the exact nature of this modulation, however, the following outcomes were deemed principally conceivable. (1) If the sequential modulation of task-order control depends on characteristics of the specific component task and/or task order (e.g., whether a particular task order is preferred or not) according to the task/task order specific control modulation hypothesis, we should observe a differential modulation (i.e., a differential reduction in switch costs after a previous task-order switch) depending on which task order is being switched to. This option can be further subdivided into (a) a stronger reduction in switch costs when switching to the preferred task order indicating a further efficiency gain of the overall "easier" switch, and (b) a stronger reduction in switch costs when switching to the non-preferred task order resulting from a greater potential for improvement for the overall "harder" switch. (2) If, however, the sequential modulation of task-order control does not depend on specific task and task order characteristics, but instead rather relies on a more abstract, general beneficial impact on cognitive task-order control (i.e., general control modulation hypothesis), there should be no differences in the reduction of switch-costs between different types of tasks and/or task orders.

Irrespective of whether the sequential modulation of task-order switch costs is specific for particular task-order switches or not, it is of further theoretical interest how exactly such a modulation comes about in the current situation. In other words, in which exact way were task-order switch costs reduced following a task-order switch (vs. a task-order repetition)? Again, different outcomes are conceivable. (a) The reduction in task-order switch costs following a task-order switch (vs. a repetition) could be caused by a truly generic increase of "general-purpose" capacity or alertness due to a greater recruitment of such cognitive resources after dealing with a principally demanding task order switch. This would be indicated by a performance gain for both task-order switches and repetitions following a previous task-order switch (vs. repetition), probably with a relatively greater gain for the task-order switch. (b) On the other hand, reduced task-order switch costs could also be caused in the context of a general increase in "cautiousness" following a task-order switch (vs. a task-order repetition) which would result in overall slower (more correct) responses with a relatively weaker (stronger) effect on task-order switch RTs (errors) compared to task-order repetition RTs (errors; Strobach & Wendt, 2022). (c) Finally, it is possible that (in the context of frequent task-order alternations) different task orders in a PRP episode are represented as independent task-order sets that are related to "first order" task-order control (Hirsch et al., 2017; Hirsch et al., 2018; Kübler et al., 2018). Any repetition of the task order could result in a performance benefit (explaining task order switch costs). Similarly, it is possible that different transition types (i.e., switch vs. repetition) are represented as higher-order task sets that are related to "second order" task-order control. Further, any repetition of task-order transition types could result in a performance benefit. This would imply that it is not only an advantage to perform a task-order switch (vs. repetition) after a *previous* task-order switch, but there is also an advantage to implement a task-order repetition after *previous* task-order repetition (vs. switch). Conversely, performing a task-order repetition (vs. switch) after a *previous* task-order switch and performing a task-order switch (vs. repetition) after a *previous* task-order repetition should be characterized by a performance decrement.

To differentiate between these options, we re-analyzed all three experiments from the study by Huestegge et al. (2021). Experiment 1 and 2 combined a spatial oculomotor task (Experiment 1: left vs. right saccades; Experiment 2: upward vs. downward saccades) with a spatial manual task (Experiment 1: upward vs. downward button presses; Experiment 2: left vs. right button presses). Experiment 3 combined the same spatial oculomotor task as in Experiment 2 (upward vs. downward saccades) with a spatial pedal task (left vs. right pedal presses). Task order was manipulated in all experiments by varying the stimulus presentation order randomly from trial to trial in mixed task-order blocks. Participants were explicitly instructed to respond in accord with the order of stimulus presentation (c.f., Hommel, 1998; Pashler & Johnston, 1989).

2. Experiment 1: combining a horizontal oculomotor and a vertical manual task

In this experiment, we combined an oculomotor task (left/right saccades to arrows pointing to the left/right) and a manual task (pressing upper/lower key to arrows pointing upward/downward) and had participants unpredictably switch between the order of the two tasks from trial to trial (in mixed task order blocks). The design is described in great detail in Huestegge et al. (2021); here, we only focus on the relevant methodological components.

2.1. Methods

2.1.1. Participants

Forty participants took part in the experiment. All gave their informed consent and reported normal or corrected-to normal vision. Data of participants with an accuracy below 67 % (>33 % errors regarding response direction and/or response order errors) were excluded and recollected to ensure full counterbalancing. In Experiment 1, three participants were excluded and recollected. The final sample contained 14 males and 26 females. Four participants were left-handed, and the mean age was 26.5 years (SD = 6.1, range: 20–55 years).

2.1.2. Apparatus

Participants were seated approximately 67 cm in front of a 21-inch cathode-ray tube (CRT) monitor with a spatial resolution of 1024 × 768 pixels and a temporal resolution of 100 Hz. Eye movements were recorded using an Eyelink 1000 eye-tracking system with a sampling rate of 1000 Hz (SR Research, Missisauga, Ontario, Canada). A chinrest with forehead support was used to minimize head movements. Manual responses were performed on a standard German QWERTZ keyboard with the thumb and index finger of the dominant hand (thumb: lower arrow key, index finger: upper arrow key).

2.1.3. Stimuli and procedure

Stimuli for both tasks were white arrows (↑↓→←), which were centrally presented for 80 ms. Horizontal arrows (pointing left or right) served as stimuli for the oculomotor task (looking to pre-specified targets on the corresponding left or right side), while vertical arrows (pointing up or down) served as stimuli for the manual task (pressing a spatially corresponding upper or lower key on a keyboard). Note that S-R translation demands were deliberately chosen to be low in order to focus more on task order processes than on any potentially difficult S-R translation processes. Both stimuli were visual in order to avoid any ambiguities related to stimulus order across different stimulus dimensions (e.g., auditory and visual). The two stimuli (one for each task) were presented one after another. The interval between the onset of both (i.e., the horizontal and the vertical) stimuli was relatively short (150 ms) to ensure that both are presented prior to the first response execution (note that oculomotor responses can be quite fast). Altogether, there were eight possible stimulus combinations (4 arrow combinations, each in two sequences).

To ensure that participants were able to follow task instructions and to learn the assignments of stimuli to responses, we decided to first present single-task blocks (which nevertheless involve both stimuli for the purpose of performance comparisons with dual-task blocks), followed by constant task order blocks (serving as a baseline) before participants work through the crucial mixed task order blocks. At the end of the experiment, participants again encountered constant task order blocks.

The sequence of stimulus combinations was randomized in mixed task order blocks and constant (with respect to the order of the horizontal and the vertical arrow) in fixed task order blocks. In single-task blocks, the task-relevant stimulus was always presented first. Each block consisted of 48 trials, that is, each stimulus combination was presented six times in the mixed order dual blocks, and 12 times in single and fixed order dual blocks (since in fixed stimulus sequence blocks there are only 4 possible combinations). To counterbalance sequence effects regarding the order of single task blocks and regarding the order of fixed order dual-task blocks, four block sequences were determined. These sequences were counterbalanced along the scheme outlined in Table 1 of Huestegge et al. (2021).

Participants were instructed to respond fast, accurately, and according to the stimulus sequence (in dual-task blocks). Each trial started with the onset of a central fixation cross (1200 ms) prior to the presentation of the first stimulus. Directly after the (second) response, the next trial started (fixation cross onset), unless a response reversal error was made. In the latter case, the second response was followed by the presentation of feedback ("wrong order!" printed in red) for 1000 ms followed by the fixation cross for 200 ms until the next stimulus was presented, thereby keeping the response-stimulus interval constant at 1200 ms (i.e., also for response reversal trials). Importantly, only the 8 blocks (48 trials each ➔ 384 trials in total) with mixed (i.e., randomly varying) task-order were considered for the present re-analysis. For the data of fixed-order dual-task blocks, see Huestegge et al. (2021).

2.1.4. Analyses/main predictions

Note that our central research hypothesis was addressed by analyzing performance in a way that differed from the analysis in Huestegge et al. (2021). Here, we addressed performance in the mixing blocks alone, and single-task blocks and dual-task blocks with fixed order were disregarded. We defined the following within-subject factors for two repeated-measures ANOVAs, one analysis each for the dependent variables RTs and directional errors: Task (dominant, i.e., oculomotor vs. non-dominant, i.e., manual), Task Order (preferred, i.e., oculomotor-manual vs. non-preferred, i.e., manual-oculomotor), Order Transition in Trial N - 1 (task-order repetition vs. task-order switch) and Order Transition in Trial N (task-order repetition vs. task-order switch). In addition, we defined the following within-subject repeated-measures ANOVA for reversal errors: Task Order (preferred, i.e., oculomotor-manual vs. non-preferred, i.e., manual-oculomotor), Order Transition in Trial N - 1 (task-order repetition vs. task-order switch) and Order Transition in Trial N (task-order repetition vs. task-order switch); note, that the factor Task is thus not available in this latter ANOVA. The analyses in Huestegge et al. exclusively included the factors Task Order, and Order Transition in Trial N (i.e., Order Transition in Trial N - 1 was not included factor in Huestegge et al.). Performance in the component tasks was analyzed in separate ANOVAs. This original analysis of the dataset revealed significant task-order switch costs (main effect Order Transition N) that were smaller for switches to the preferred (vs. non-preferred) task order, as indicated by an interaction of Order Transition N with Task Order. A sequential modulation of task-order control should be indicated by a significant interaction of Order Transition in trial N (task-order repetition vs. switch) and Order Transition in trial N – 1 (task-order repetition vs. switch). Crucially, if this sequential adjustment is task- or task order-specific, then this modulation should differ between switching to the preferred task order vs. switching to the non-preferred order as well as between the dominant oculomotor task and the non-dominant manual task, respectively. This should show up in significant three-way interactions between Order Transition N – 1 (repetition vs. switch), Order Transition N (repetition vs. switch), as well as Task (dominant vs. non-dominant) and/or Task Order (preferred order vs. non-preferred order). Bayesian follow-up analyses using the BayesFactor R package (Morey et al., 2022) with a Cauchy scale parameter of 1 were conducted to further quantify evidence for the absence of such interactions. Bayes factors (BF01) are thus reported in addition to the traditional ANOVA results only for the interaction effects critical to the specificity of sequential task order control adjustments.

For reversal error analyses, trials with directional errors in one or both component tasks were excluded while for the RT analyses, we excluded trials involving response reversals in addition to those trials with directional errors in one or both component tasks. Thus, response reversal errors were only analyzed in trials with directionally correct responses (i.e., correct responses executed in the wrong order). For directional error analyses, all trials were considered, including those with response reversals. Thus, participants could respond in the wrong order but still spatially correct in the individual component tasks. Furthermore, trials with RTs below 150 ms and exceeding 3000 ms were excluded from RT and reversal rate analyses. Saccades were considered as correct responses if they at least passed 1/3 of the distance toward the corresponding spatial target (otherwise they either counted as omissions or directional errors when crossing 1/3 of the distance into the opposite direction). In the present experiment, we excluded a total of 9.7 % of the trials from the overall analysis. On an individual participant level, the exclusion of the trials ranged between 2 % and 30 %. This resulted in analyzing between 267 and 377 trials for each participant (in the mean 346.7 trials per participant).

2.2. Results & discussion

2.2.1. Analyses of RTs

The repeated-measures ANOVA revealed main effects of Task, $F(1, 39) = 552.250$, $p < .001$, $\eta p^2 = 0.93$, Task Order, $F(1, 39) = 77.151$, $p < .001$, $\eta p^2 = 0.66$, and Order Transition N, $F(1, 39) = 115.627$, $p < .001$, $\eta p^2 = 0.75$. As illustrated in Fig. 1, responses were faster in the dominant oculomotor task ($M = 625$ ms) in comparison to the non-dominant manual task ($M = 900$ ms), faster in trials with the preferred task order ($M = 702$ ms) in comparison to trials with the non-preferred task order ($M = 824$ ms), and faster for task order repetitions ($M = 720$ ms) in comparison to order switches ($M = 805$ ms; thus indicating task-order switch costs). The latter finding replicates findings in previous studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the sequence in the previous trial, as indicated by the significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 53.853$, $p < .001$, $\eta p^2 = 0.58$. This interaction replicates findings of sequential adjustment of task-order control in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). To further specify this interaction, we conducted two sets of planned simple main effect analyses. The first set compared task-order repetitions and task-order switches in Trial N both after a task order switch in Trial N – 1, $F(1, 39) = 34.617$, $p < .001$, $\eta p^2 = 0.47$, as well as after a task-order repetition in Trial N – 1, $F(1, 39) = 144.983$, $p < .001$, $\eta p^2 = 0.78$. Although both significant, task-order switch costs in Trial N were substantially smaller after a task-order switch in Trial N – 1 ($M = 50$ ms) than after a task-order repetition in Trial N – 1 ($M = 121$ ms). The second set of simple main effect contrasts analyzed the specific nature of this reduction in task-order switch costs. Responses in task order repetitions in Trial N were significantly slower after a task order switch (vs. repetition), $F(1, 39) = 35.271$, $p < .001$, $\eta p^2 = 0.48$. At the same time, responses in task-order switches in Trial N were significantly faster after a task order switch (vs. a repetition) in Trial N – 1, $F(1, 39) = 15.201$, $p < .001$, $\eta p^2 = 0.28$. Most critically, we found no significant interactions of Order Transition N – 1 and Order Transition N with either Task, $F(1, 39) = 2.692$, $p = .109$, $\eta p^2 = 0.07$, BF01 = 5.130, Task Order, $F(1, 39) < 1$, BF01 = 5.788 or Task and Task Order, $F(1, 39) = 3.906$, $p = .055$, $\eta p^2 = 0.09$, BF01 = 4.486. Thus, there is no evidence that the sequential adjustment of task order control specifically affects certain tasks (dominant or non-dominant) or task orders (preferred or non-preferred). None of the other main effects or interactions were significant, $Fs(1, 39) < 2.795$, $ps > .103$, $\eta p^2 s < 0.07$.

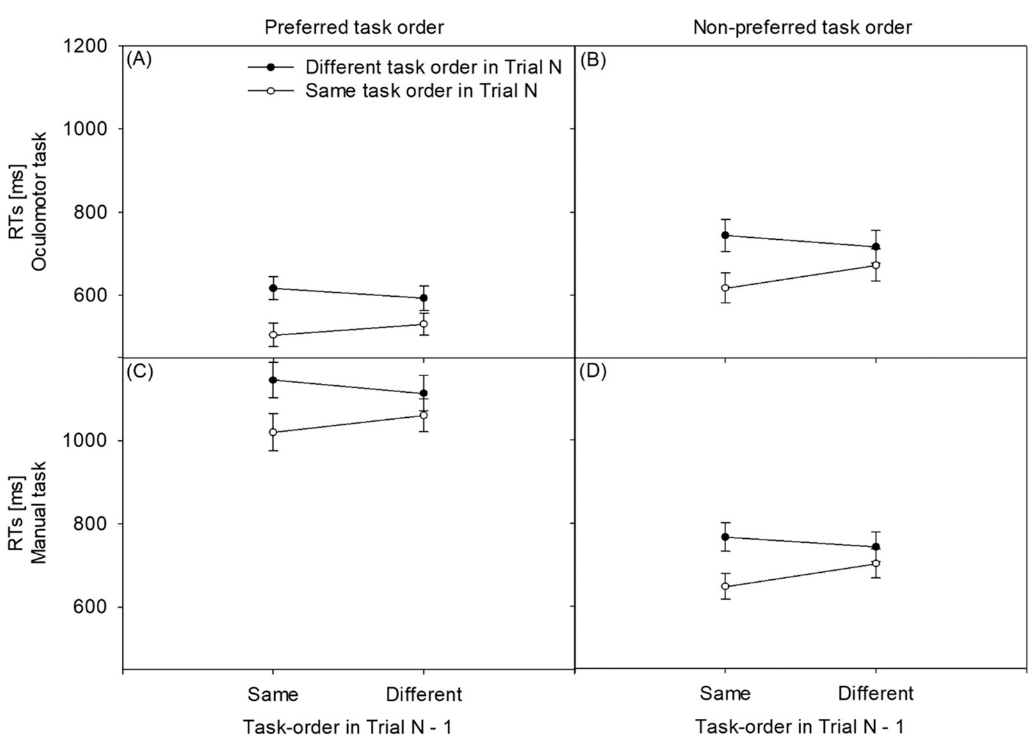

Fig. 1. Reaction times (RTs) of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 1. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-manual). Panel (B): Oculomotor task with "non-preferred task order" (i.e., manual-oculomotor). Panel (C): Manual task with "preferred task order" (i.e., oculomotor-manual). Panel (D): Manual task with "non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

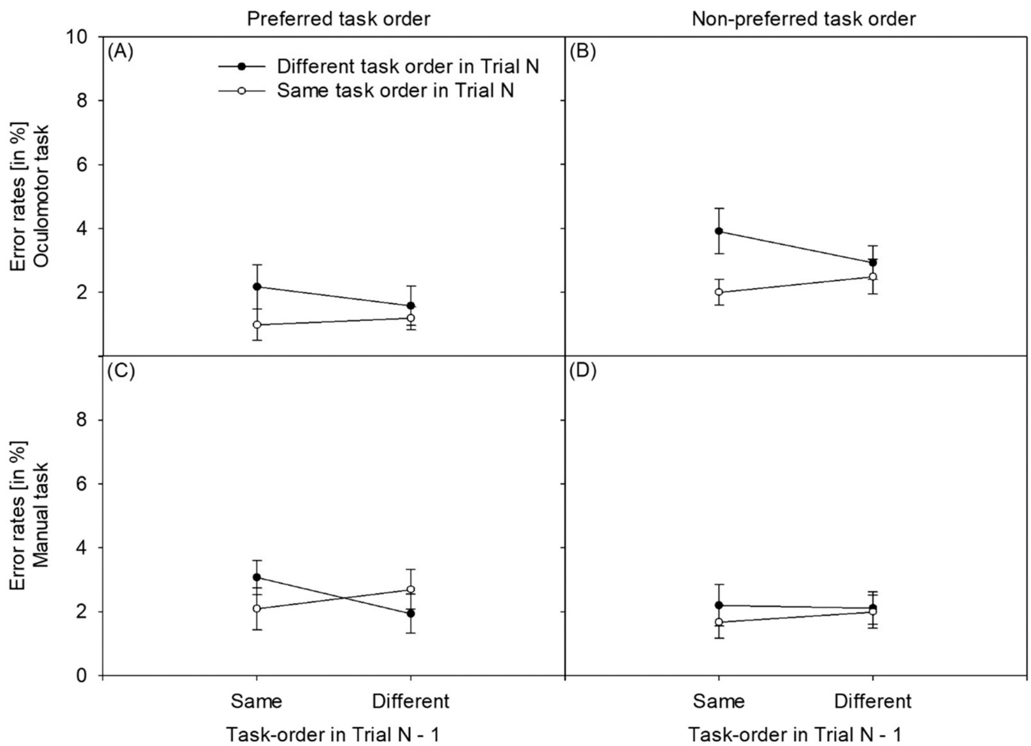

Fig. 2. Directional error rates of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 1. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-manual). Panel (B): Oculomotor task with "non-preferred task order" (i.e., manual-oculomotor). Panel (C): Manual task with "preferred task order" (i.e., oculomotor-manual). Panel (D): Manual task with "non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

2.2.2. Analyses of directional errors

The repeated-measures ANOVA revealed a main effect of Order Transition N, $F(1, 39) = 6.567$, $p = .014$, $\eta p^2 = 0.14$. As illustrated in Fig. 2, errors were lower for order repetitions ($M = 1.9$ %) in comparison to order switches ($M = 2.5$ %; thus, indicating task-order switch costs in error rates, too). This finding replicates findings in other studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the task-order transition in the previous trial; as indicated by the significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 7.881$, $p = .008$, $\eta p^2 = 0.17$. This interaction replicates findings of sequential adjustment of task-order control in other studies (Strobach et al., 2021; Strobach & Wendt, 2022). Again, we conducted two sets of simple main effects analyses to specify this interaction. The first set demonstrated that the task-order switch costs in Trial N were not significant after a task order switch in Trial N – 1, $F(1, 39) < 1$, but were significant after a task order repetition in Trial N – 1, $F(1, 39) = 13.772$, $p < .001$, $\eta p^2 = 0.26$. The second set of simple main effect contrasts revealed no error difference in task order repetitions in Trial N between a task order switch (vs. repetition) in Trial N – 1, $F(1, 39) = 2.642$, $p > .112$, while errors in task order switches in Trial N were less frequent following a task order switch (vs. repetition) in Trial N – 1, $F(1, 39) = 6.183$, $p = .017$, $\eta p^2 = 0.14$. Crucially, and in line with the RT data, there was no significant interaction of Order Transition N – 1 and Order Transition N with either Task, $F(1, 39) < 1$, BF01 = 6.845, Task Order, $F(1, 39) < 1$, BF01 = 7.814 or Task and Task Order, $F(1, 39) = 2.234$, $p = .143$, $\eta p^2 = 0.05$, BF01 = 3.281. Again, there is no evidence that the sequential adjustment of task order control is task-specific or task order-specific. The only other significant interaction of Task and Task Order, $F(1, 39) = 5.866$, $p = .020$, $\eta p^2 = 0.14$, demonstrated no differences in error rates in the manual task between the preferred and non-preferred task order, $F(1, 39) = 1.211$, $p = .278$, while there was such a difference in the oculomotor task, $F(1, 39) = 7.009$, $p = .012$, $\eta p^2 = 0.15$. Error rates in this task were lower in the preferred task order in comparison to the non-preferred task order. None of the other main effects or interactions were significant, $Fs(1, 39) < 3.381$, $ps > .074$ $\eta p^2 s < 0.08$.

2.2.3. Analyses of reversal errors

The repeated-measures ANOVA revealed main effects of Task Order, $F(1, 39) = 40.864$, $p < .001$, $\eta p^2 = 0.51$, and Order Transition N, $F(1, 39) = 42.692$, $p < .001$, $\eta p^2 = 0.52$. As illustrated in Fig. 3, reversal rates were higher in trials with the non-preferred task order ($M = 10.2$ %) in comparison to trials with the preferred task order ($M = 3.1$ %), and reversal rates were lower for order repetitions ($M = 4.7$ %) in comparison to order switches ($M = 8.6$ %), indicating task-order switch costs. The latter finding is consistent with the RTs and directional error rates and once more replicates findings of other studies on task order control (Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the sequence in the previous trial, as there was a significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 6.018$, $p = .019$, $\eta p^2 = 0.13$. This interaction replicates findings of sequential adjustments of task-order control in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). The first set of planned simple main effects demonstrated that the task-order switch costs in Trial N were significant, $F(1, 39) = 18.955$, $p < .001$, $\eta p^2 = 0.33$, but numerically smaller ($M = 2.8$ %) after a task order switch in Trial N – 1, in comparison to significant, $F(1, 39) = 35.646$, $p < .001$, $\eta p^2 = 0.48$, but numerically larger ($M = 5.0$ %) task-order switch costs after a task-order repetition in Trial N - 1. The second set of simple main effect contrasts revealed no reversal rate differences in task order repetitions in Trial N following a task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) < 1$. Reversal rates in task order switches in Trial N were significantly lower after a task-order switch (vs. repetition) in Trial N – 1, $F(1, 39) = 6.304$, $p = .016$, $\eta p^2 = 0.14$. Critically, the three-way interaction of Order Transition N – 1 and Order Transition N with Task Order was non-significant, $F(1, 39) < 1$, BF01 = 4.438. Thus, there was no evidence that the sequential adjustment of task order control differently affected switches to the preferred (vs. non-preferred) task order. The only other significant interaction of Order Transition N and Task Order, $F(1, 39) = 31.098$, $p < .001$, $\eta p^2 = 0.44$, demonstrated smaller task-order switch costs for the preferred task order, $F(1, 39) = 4.413$, $p = .025$, $\eta p^2 = 0.10$, in comparison to the non-preferred task order, $F(1, 39) = 46.762$, $p < .001$, $\eta p^2 = 0.54$. None of the other main effects or interactions were significant, $Fs(1, 39) < 3.303$, $ps > .077$,

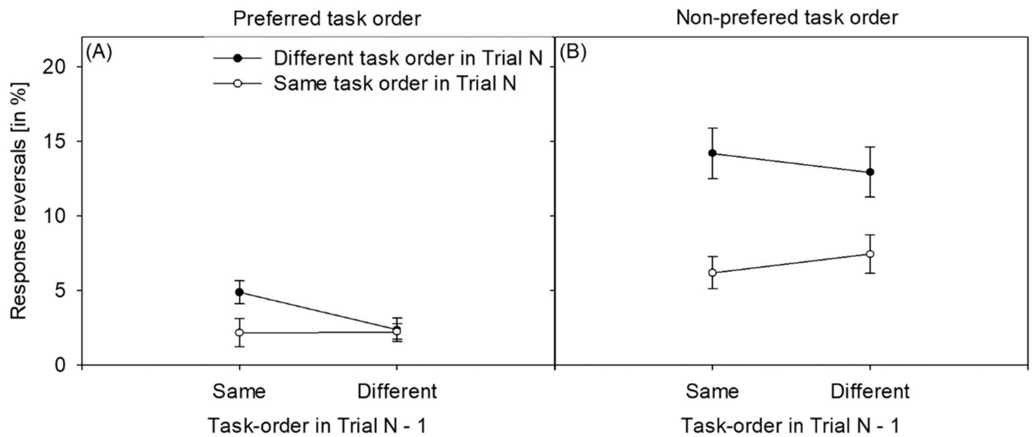

Fig. 3. Rates of response reversals of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 1. Panel (A): "Preferred task order" (i.e., oculomotor-manual). Panel (B): "Non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

ηp^2s < 0.08.

2.2.4. Discussion

In sum, the data generally show that switching to a different task order results in task-order switch costs. Further, we consistently demonstrated that these task-order switch costs were sequentially modulated: they were smaller after previous task-order switches in comparison to previous task-order repetitions. This reduction in order switch costs was caused by better performance in order switch trials (in RTs, directional errors and reversal errors) and lower performance in order repetition trials (in RTs) following an order switch (vs. an order repetition trial). Interestingly, we also observed a benefit for task order repetitions after a previous task order repetition, indicating a general advantage whenever a trial transition type is repeated (switch-switch or repetition-repetition).

Importantly, the specific task characteristics (e.g., the effector systems involved) that are usually known to be responsible for strong task-order preference effects (e.g., Hoffmann et al., 2019; Pieczykolan & Huestegge, 2014) had no effect whatsoever on the sequential modulation of task-order switch costs in this experiment. Thus, it appears that sequential adjustments of task-order control were neither stronger (nor weaker) for switches to the preferred (vs. non-preferred) task order. There is also no evidence that the sequential modulation of task-order switch costs differs between tasks of different dominance (i.e., the dominant oculomotor and the non-dominant manual tasks) in the RT and directional errors, generally supporting the general control modulation hypothesis. In contrast, Bayesian follow-up analyses even revealed substantial evidence against such a specific modulation across all dependent variables. This data pattern suggests that the sequential adjustment of task-order control does *not* take specific task and task order characteristics into account, and instead appears to depend on more general mechanisms.

Note, however, that in the original study by Huestegge et al. (2021), Experiment 1 also showed no indication of significant cost asymmetries between switching to the preferred and to the non-preferred task-orders, too. This absence of significant effects of specific task characteristics on "first-level" task-order control might of course preclude any effects of specific task characteristics on the "second level" sequential modulation of task-order control. We therefore performed the same re-analysis on the data of Experiment 2, where "first-level" task order control effects turned out to be task-order specific. Thus, Experiment 2 should be more informative regarding the question of whether "first-level" and "second-level" (sequential) task order control both rely on task/task order-specific mechanisms.

3. Experiment 2: combining a vertical oculomotor and a horizontal manual task

Experiment 2 of the original study by Huestegge et al. (2021) demonstrated lower costs for switching to the preferred (vs. to the non-preferred) task order. In this re-analysis we thus tested whether the absence of significant effects of such task-order characteristics on the sequential modulation of task-order control in Experiment 1 depended on the specific task arrangement used in that experiment. Experiment 2 was identical to Experiment 1 with regard to the involved effector systems (oculomotor and manual). However, there was a reversed spatial assignment of responses. Oculomotor responses were executed along the (usually less practiced) vertical dimension (top/bottom), while manual responses were executed corresponding to the horizontal dimension (left/right). Still, the oculomotor task was considered dominant in terms of prioritization. Thus, the oculomotor-manual task order was again preferred over the manual-oculomotor task order.

3.1. Method

3.1.1. Participants

Seven participants had to be excluded, and these data sets were recollected with new participants. The final sample consisted of 40 (83 % female, 93 % right-handed) participants with a mean age 24.8 years (SD = 6.5, range: 19–51 years).

3.1.2. Apparatus and procedure

The same basic procedure as in Experiment 1 was employed, except for the fact that the two saccade target objects were now located above and below the fixation cross (at the same eccentricity as in Experiment 1). For the manual task, the left and right arrow keys on the keyboard served as response keys, operated by two fingers (index and middle finger) of the dominant hand of the participant. Identical to the previous experiment, only the 8 blocks (48 trials each ➔ 384 trials in total) with mixed (i.e., randomly varying) task-order were considered for the present re-analysis. In Experiment 2, we excluded a total of 9.6 % of the trials from the overall analysis. On an individual participant level, the exclusion of the trials ranged between 1 % and 37 %. This resulted in analyzing between 240 and 382 trials for each participant (in the mean 343.7 trials per participant).

3.2. Results & discussion

3.2.1. Analyses of RTs

The repeated-measures ANOVA revealed main effects of Task, *F*(1,

39) = 269.602, $p < .001$, $\eta p^2 = 0.87$, Task Order, $F(1, 39) = 60.292$, $p < .001$, $\eta p^2 = 0.61$, and Order Transition N, $F(1, 39) = 117.322$, $p < .001$, $\eta p^2 = 0.75$. As illustrated in Fig. 4, responses were faster in the dominant oculomotor task (M = 597 ms) in comparison to the non-dominant manual task (M = 855 ms), faster in trials with the preferred task order (M = 676 ms) in comparison to trials with the non-preferred task order (M = 776 ms), and faster for order repetitions (M = 694 ms) in comparison to order switches (M = 757 ms; thus indicating task-order switch costs). The latter finding replicates findings in other studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were again modulated by the order transition in the previous trial; as there was a significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 108.815$, $p < .001$, $\eta p^2 = 0.74$. This interaction replicates findings of sequential adjustment of task-order control in Experiment 1 and in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). The first set of planned simple main effect contrasts demonstrated that the task-order switch costs in Trial N were significant both after task-order switches in Trial N – 1, $F(1, 39) = 27.043$, $p < .001$, $\eta p^2 = 0.41$, and after task-order repetitions in Trial N – 1, $F(1, 39) = 182.778$, $p < .001$, $\eta p^2 = 0.82$. They were, however, again numerically smaller after a previous task-order switch (M = 32 ms) compared with a previous task-order repetition (M = 94 ms). The second set of simple main effect contrasts revealed significantly slower responses in task-order repetitions in Trial N after a task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) = 46.057$, $p < .001$, $\eta p^2 = 0.54$. Responses in task-order switches in Trial N were, on the other hand, significantly faster after a task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) = 31.820$, $p < .001$, $\eta p^2 = 0.45$. Importantly, the interactions of Order Transition N – 1 and Order Transition N with either Task, $F(1, 39) < 1$, BF01 = 6.009, Task Order, $F(1, 39) = 3.019$, $p = .090$, $\eta p^2 = 0.07$, BF01 = 4.446, or Task and Task Order, $F(1, 39) < 1$, BF01 = 6.663, were non-significant. Thus, like in Experiment 1, there is no evidence that the sequential adjustment of task order control is task-specific or specific for particular task orders. The interaction of Order Transition N and Task Order, $F(1, 39) = 7.836$, $p = .008$, $\eta p^2 = 0.17$, demonstrated smaller task-order switch costs for the preferred task order, $F(1, 39) = 48.326$, $p < .001$, $\eta p^2 = 0.55$, in comparison to the non-preferred task order, $F(1, 39) = 117.532$, $p < .001$, $\eta p^2 = 0.75$. The interaction of Task and Task Order, $F(1, 39) = 181.198$, $p < .001$, $\eta p^2 = 0.82$, demonstrated that responses in the dominant (i.e., oculomotor) task were faster in the preferred task order (i.e., oculomotor-manual) compared with the non-preferred task order (i.e., manual-oculomotor), $F(1, 39) = 57.003$, $p < .001$, $\eta p^2 = 0.59$, while responses in the non-dominant (i.e., manual) task were faster in the non-preferred task order (i.e., manual-oculomotor) compared with the preferred task order (i.e., oculomotor-manual), $F(1, 39) = 220.608$, $p < .001$, $\eta p^2 = 0.85$. None of the other main effects or interactions were significant, Fs(1, 39) < 3.174, ps > .084, ηp^2s < 0.08.

3.2.2. Analyses of directional errors

The repeated-measures ANOVA revealed main effects of Task, $F(1, 39) = 21.165$, $p < .001$, $\eta p^2 = 0.35$, Task Order, $F(1, 39) = 5.419$, $p = .025$, $\eta p^2 = 0.12$, and Order Transition N, $F(1, 39) = 10.823$, $p = .002$, $\eta p^2 = 0.22$. As illustrated in Fig. 5, error rates were higher in the dominant oculomotor task (M = 4.6 %) in comparison to the non-dominant manual task (M = 0.9 %), higher in trials with non-preferred order (M = 3.0 %) in comparison to trials with the preferred order (M = 2.1 %), and errors were higher for order switches (M = 2.9 %) in comparison to order repetitions (M = 2.2 %; thus indicating task-order switch costs). This finding replicates findings of other studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were not modulated by the task-order transition in the previous trial, $F(1, 39) = 2.158$, $p = .150$, $\eta p^2 = 0.05$. Similarly, there was no significant modulation of the combination of Order Transition N – 1 and Order Transition N by the factors Task, $F(1, 39) = 1.011$, $p = .321$, $\eta p^2 = 0.03$, BF01 = 3.558, Task Order, $F(1, 39) = 1.281$, $p = .265$, $\eta p^2 = 0.03$, BF01 = 4.526 or Task and Task Order, $F(1, 39) = 1.663$, $p = .205$, $\eta p^2 = 0.04$, BF01 = 2.741. Thus, there is no evidence for a sequential adjustment of task order control, nor any evidence that this adjustment is task-specific or specific for a particular task order. The only significant interaction of Task and Task Order, $F(1, 39) = 13.929$, $p < .001$, $\eta p^2 = 0.26$, demonstrated lower error rates in the manual task in the preferred task order versus the non-preferred task

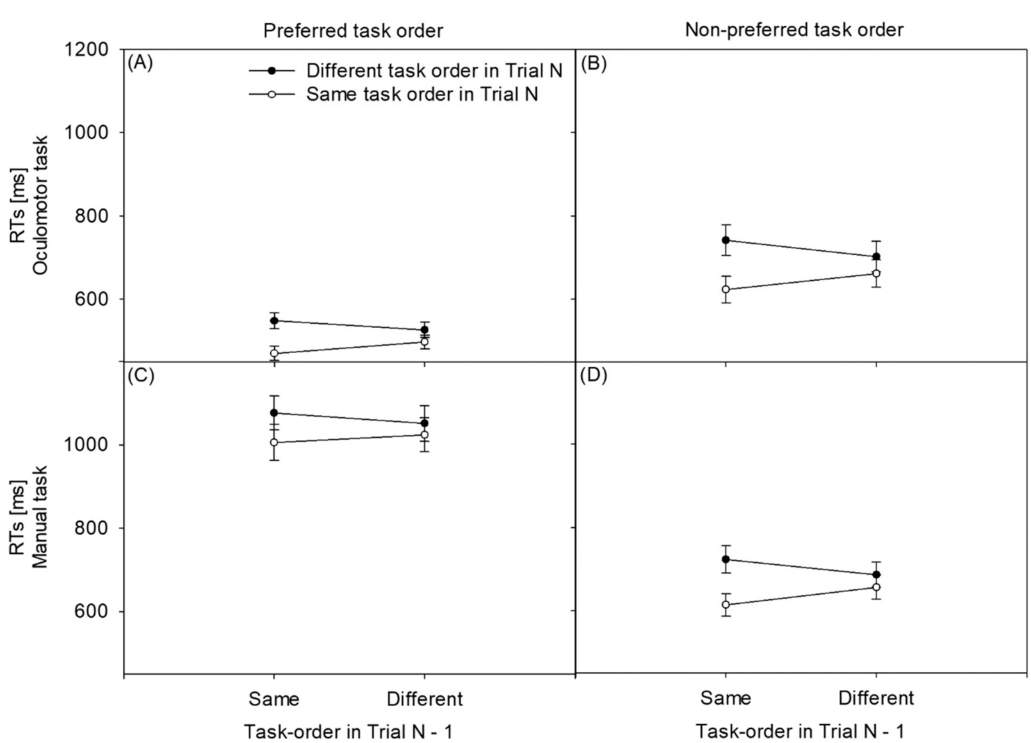

Fig. 4. Reaction times (RTs) of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 2. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-manual). Panel (B): Oculomotor task with "non-preferred task order" (i.e., manual-oculomotor). Panel (C): Manual task with "preferred task order" (i.e., oculomotor-manual). Panel (D): Manual task with "non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

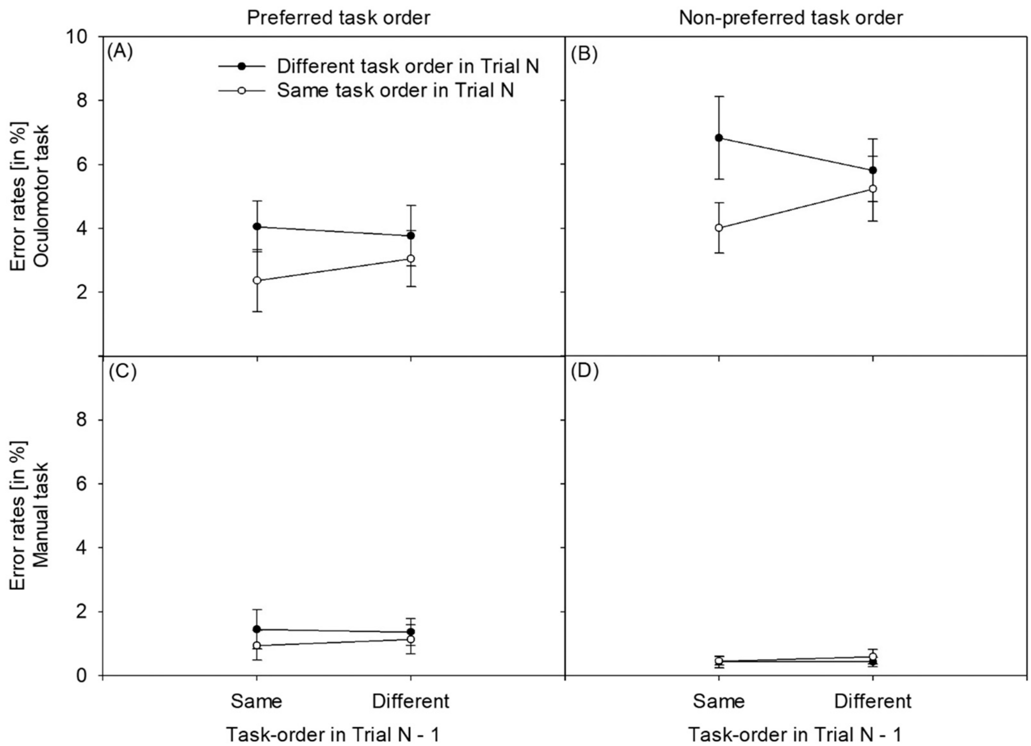

Fig. 5. Directional error rates of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 2. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-manual). Panel (B): Oculomotor task with "non-preferred task order" (i.e., manual-oculomotor). Panel (C): Manual task with "preferred task order" (i.e., oculomotor-manual). Panel (D): Manual task with "non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

order, $F(1, 39) = 7.206$, $p = .011$, $\eta p^2 = 0.16$, while the error rates in the oculomotor task were lower in the preferred task order in comparison to the non-preferred task order, $F(1, 39) = 10.856$, $p = .002$, $\eta p^2 = 0.22$. None of the other main effects or interactions were significant, $Fs(1, 39) < 2.983$, $ps > .092$, $\eta p^2 s < 0.07$.

3.2.3. Analyses of reversal errors

The repeated-measures ANOVA revealed main effects of Task Order, $F(1, 39) = 6.576$, $p = .014$, $\eta p^2 = 0.14$, Order Transition N – 1, $F(1, 39) = 6.946$, $p = .012$, $\eta p^2 = 0.15$, and Order Transition N, $F(1, 39) = 20.485$, $p < .001$, $\eta p^2 = 0.34$. As illustrated in Fig. 6, reversal rates were higher in trials with the non-preferred task-order ($M = 7.4$ %) in comparison to trials with the preferred task order ($M = 4.5$ %), reversal rates were higher for order repetitions in Trial N – 1 ($M = 6.7$ %) in comparison to order switches in Trial N – 1 ($M = 5.4$ %), and reversal rates were higher for order switches in Trial N ($M = 7.7$ %) in comparison to order repetitions in Trial N ($M = 4.4$ %) (indicating task-order switch costs). The latter finding is consistent with the RTs and directional error rates, and replicates findings of previous studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the sequence in the previous trial; so there was an interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 18.841$, $p < .001$, $\eta p^2 = 0.33$. This interaction replicates findings of sequential adjustment of task-order control of previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). The first set of planned simple main effect contrasts demonstrated that the task-order switch costs in Trial N were not significant after a task-order switch in Trial N - 1, $F(1, 39) = 2.322$, $p = .136$, but these costs were significant after a task-order repetition in Trial N - 1, $F(1, 39) = 22.299$, $p < .001$, $\eta p^2 = 0.36$. Consistent with the RT data, task-order switch costs were numerically smaller after a task-order switch ($M = 0.7$ %) compared with after a task-order repetition ($M = 5.9$ %). The second set of simple main effect contrasts revealed higher reversal rates in task-order repetitions in Trial N after a task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) = 4.428$, $p = .042$, $\eta p^2 = 0.10$, while there were significantly lower reversal rates in task-order switches in Trial N after task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) = 16.951$, $p < .001$, $\eta p^2 = 0.30$. However, we found no significant three-way interaction of Order Transition N – 1 and Order Transition N with Task Order, $F(1, 39) = 2.257$, $p = .141$, $\eta p^2 = 0.05$, BF01 = 2.802. Therefore, there is no evidence that the sequential adjustment of task order control is specific for particular task orders. The only other significant interaction of Order Transition N and Task Order, $F(1, 39) = 7.061$, $p = .011$, $\eta p^2 = 0.15$, demonstrated significant but smaller task-order switch costs for the preferred task order, $F(1, 39) = 4.829$, $p = .034$, $\eta p^2 = 0.11$, in comparison to the significant but larger task-order switch costs for the non-preferred task order, $F(1, 39) = 26.352$, $p < .001$, $\eta p^2 = 0.40$ (thus there are asymmetrical task-order switch costs depending on the task-order preference). None of the other interactions were significant, $Fs(1, 39) < 1.507$, $ps > .227$, $\eta p^2 s < 0.04$.

3.2.4. Discussion

Similar to Experiment 1, we can conclude that switching to a different task order results in task-order switch costs in the RT, directional error, and reversal error data. Further, we demonstrated that these task-order switch costs are sequentially modulated in a way that they are smaller after previous task-order switches in comparison to task-order repetitions; this was evident in RTs and response reversal rates and was caused by improved performance in task-order switches and deteriorated performance in task-order repetitions after a task-order switch (vs. a task-order repetition). Importantly, the specific task and task-order characteristics that are usually known to be responsible for strong task dominance and preference effects (e.g., Hoffmann et al., 2019; Pieczykolan & Huestegge, 2014) had no effect on the sequential modulation of task-order switch costs in this experiment. This was again supported by the results of Bayesian follow-up analyses. Thus, it appears that sequential adjustments of task-order control were neither stronger (nor weaker) for participants when switching to their preferred task order vs. their non-preferred task order (in the RT analysis) nor they differ between tasks of different dominance (i.e., the dominant oculomotor and the non-dominant manual tasks; in the RT and reversal rate analyses). This suggests that sequentially adjusting task order ("second-level" task order control) does not take specific task and task order

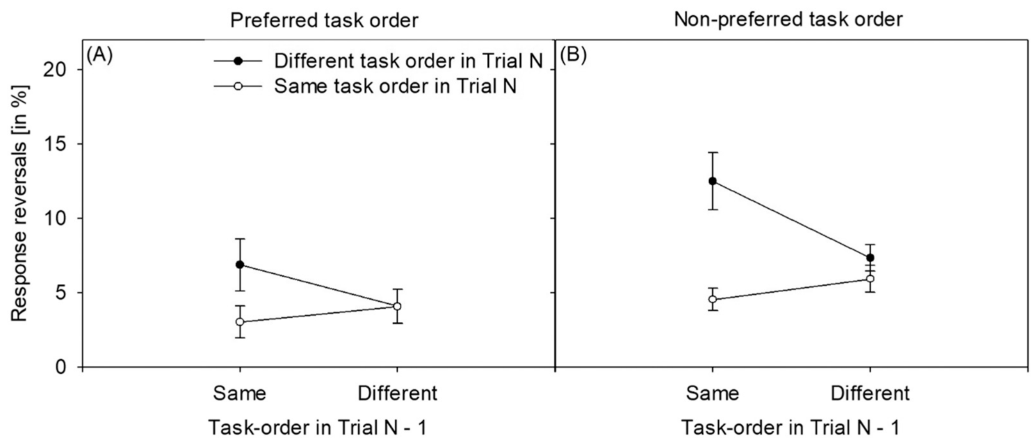

Fig. 6. Rates of response reversals of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 2. Panel (A): "Preferred task order" (i.e., oculomotor-manual). Panel (B): "Non-preferred task order" (i.e., manual-oculomotor). Error bars represent standard errors of the mean.

characteristics into account (supporting the general control modulation hypothesis), even though "first-level" task order switch costs were modulated by task order (and thus task-order specific). This may indicate two separate underlying mechanisms.

Interestingly, we again observed a benefit for task order repetitions after a previous task order repetition, indicating a general advantage whenever a trial transition type is repeated (switch-switch or repetition-repetition) in this experiment. However, unlike in Experiment 1, the error rates did not show sequential adjustments of task-order switch costs. One obvious difference between the experiments is that error rates were generally higher in the oculomotor task in comparison to the manual task in the present experiment, while this relation was reversed in Experiment 1. These differences might result from the orientation of the oculomotor and manual responses in the current experiment (vertically and horizontally, respectively), while this orientation was horizontal for the oculomotor task and vertical for the manual task in the previous experiment. Potentially, this difference might explain the lacking evidence for sequential modulation of task-order switch costs in the error rates.

4. Experiment 3: combining a vertical oculomotor and a horizontal pedal task

Experiment 2 demonstrated that the absence of any significant effects of specific task and task order characteristics on the sequential modulation of task-order control was not due to the specific spatial arrangement used in the oculomotor and manual task in Experiment 1. Although "first-level" task order control performance (i.e., immediate order configuration) depended on specific task and task order characteristics (unlike in Experiment 1), "second-level" sequential task order control modulations were evidently unaffected by such characteristics (similar to Experiment 1). Both Experiments 1 and 2 combined an oculomotor task with a manual task. The findings could thus be limited to this pairing of effector systems, which is special in that eye-hand coordination is highly practiced in everyday life. Hence, any conclusion that sequential modulations of dual-task order control are based on mechanisms that do not take task order preferences into account cannot easily be generalized. As a consequence, Experiment 3 served as a necessary generalization of the above findings by combining oculomotor responses with pedal (instead of manual) responses. This allowed us to test whether the sequential modulation of task-order control that was independent from task characteristics (as found in Experiment 1 and Experiment 2) would generalize to other, less common pairings of effector systems, while retaining a clear difference in component task dominance. Oculomotor responses have been shown to be dominant over pedal responses (similar to manual responses, see Hoffmann et al., 2019), again rendering one task order (oculomotor-pedal) preferred compared with the other (pedal-oculomotor). Any dependence of an order-switch cost modulation on the specific task and task order characteristics should once again reveal itself in a differential modulation when executing the dominant (vs. non-dominant) task and when switching to the preferred (vs. non-preferred) task order.

4.1. Method

4.1.1. Participants

Seven participants had to be excluded, and the corresponding data sets were re-collected by testing new participants. The final sample consisted of 40 (78 % female, 90 % right-handed) participants with a mean age of 25.1 years (SD = 5.9, range: 19–52 years).

4.1.2. Apparatus and procedure

The same basic procedure as in Experiment 2 was employed, except for the replacement of manual responses with foot responses. Pedal responses were recorded on a custom-made foot pedal device consisting of two (left/right) switches that registered as a USB computer mouse. Pedal responses were always executed with the same (right) foot. A designated area in the middle between the two switches was used as a resting position where the foot should be placed prior to (and after) responding. Identical with the previous experiments, only the 8 blocks (48 trials each ➔ 384 trials in total) with mixed (i.e., randomly varying) task-order were considered for the present re-analysis. In this experiment, we excluded a total of 13.3 % of the trials from the overall analysis. On an individual participant level, the exclusion of the trials ranged between 4 % and 33 %. This resulted in analyzing between 256 and 372 trials for each participant (in the mean 331.0 trials per participant).

4.2. Results & discussion

4.2.1. Analyses of RTs

The repeated-measures ANOVA revealed main effects of Task, $F(1, 39) = 305.144$, $p < .001$, $\eta p^2 = 0.89$, Order Transition N – 1, $F(1, 39) = 4.466$, $p = .041$, $\eta p^2 = 0.10$, and Order Transition N, $F(1, 39) = 163.733$, $p < .001$, $\eta p^2 = 0.81$. As illustrated in Fig. 7, responses were faster in the dominant oculomotor task (M = 662 ms) in comparison to the non-dominant pedal task (M = 906 ms), faster for order repetitions in Trial N – 1 (M = 779 ms) in comparison to order switches in Trial N – 1 (M = 789 ms), and faster for order repetitions in Trial N (M = 746 ms) in comparison to order switches in Trial N (M = 822 ms), thus indicating task-order switch costs. The latter finding replicates observations in the

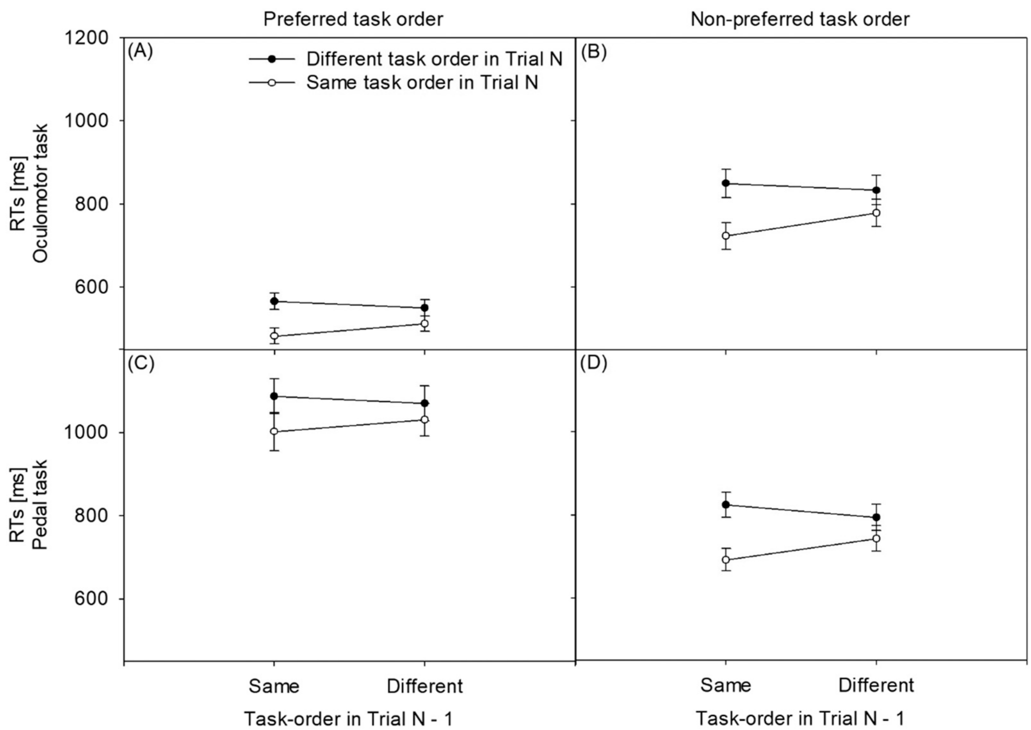

Fig. 7. Reaction times (RTs) of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 3. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-pedal). Panel (B): Oculomotor task with "non-preferred task order" (i.e., pedal-oculomotor). Panel (C): Pedal task with "preferred task order" (i.e., oculomotor-pedal). Panel (D): Pedal task with "non-preferred task order" (i.e., pedal-oculomotor). Error bars represent standard errors of the mean.

previous experiments and of other studies on task-order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the task-order transition in the previous trial, as indicated by the significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 27.203$, $p < .001$, $\eta p^2 = 0.41$. This interaction replicates findings of sequential adjustments of task-order control in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). The first set of planned simple main effect contrasts demonstrated that the task-order switch costs in Trial N were significant (but numerically smaller: $M = 46$ ms) after a task-order switch in Trial N – 1, $F(1, 39) = 39.979$, $p < .001$, $\eta p^2 = 0.51$, in comparison to the significant (larger: $M = 107$ ms) task-order switch costs in Trial N after a task-order repetition in Trial N – 1, $F(1, 39) = 129.709$, $p < .001$, $\eta p^2 = 0.77$. The second set of simple main effects revealed significantly slower responses in task-order repetitions in trial N after a task-order switch (vs. a task-order repetition) in trial N – 1, $F(1, 39) = 32.423$, $p < .001$, $\eta p^2 = 0.45$, while responses were significantly faster in task-order switches in Trial N after a task-order switch (vs. a task-order repetition) in Trial N – 1, $F(1, 39) = 5.963$, $p = .019$, $\eta p^2 = 0.13$. Crucially, however, the interactions of Order Transition N – 1 and Order Transition N with Task, $F(1, 39) < 1$, BF01 = 9.975, Task Order, $F(1, 39) = 2.858$, $p = .099$, $\eta p^2 = 0.07$, BF01 = 3.803, or Task and Task Order, $F(1, 39) < 1$, BF01 = 6.403 were not significance. Thus, comparable to Experiment 1 and Experiment 2, there was no evidence that the sequential adjustment of task order control is task-specific or specific for particular task orders. The interaction of Order Transition N and Task Order, $F(1, 39) = 8.102$, $p = .007$, $\eta p^2 = 0.17$, demonstrated asymmetrical task-order switch costs; these costs were smaller under the preferred task order, $F(1, 39) = 62.191$, $p < .001$, $\eta p^2 = 0.62$, in comparison to the non-preferred task order, $F(1, 39) = 126.361$, $p < .001$, $\eta p^2 = 0.76$. The interaction of Task and Task Order, $F(1, 39) = 221.018$, $p < .001$, $\eta p^2 = 0.85$, demonstrated that oculomotor responses were faster in the preferred task order (oculomotor-pedal) compared with the non-preferred task order (pedal-oculomotor), $F(1, 39) = 168.963$, $p < .001$, $\eta p^2 = 0.81$, while pedal responses were slower in the preferred task order compared with the non-preferred task order, $F(1, 39) = 88.530$, $p < .001$, $\eta p^2 = 0.69$. None of the other main effects and interactions were significant, $Fs(1, 39) < 1.442$, $ps > .237$, $\eta p^2\text{s} < 0.04$.

4.2.2. *Analyses of directional errors*

The repeated-measures ANOVA revealed main effects of Task, $F(1, 39) = 34.006$, $p < .001$, $\eta p^2 = 0.47$, Order Transition N – 1, $F(1, 39) = 6.752$, $p = .013$, $\eta p^2 = 0.15$, and Order Transition N, $F(1, 39) = 14.639$, $p < .001$, $\eta p^2 = 0.27$. As illustrated in Fig. 8, directional error rates were higher in the oculomotor task ($M = 4.4$ %) in comparison to the pedal task ($M = 1.6$ %), higher for order repetitions in Trial N – 1 ($M = 4.3$ %) in comparison to order switches in Trial N - 1 ($M = 2.7$ %), and higher for order switches in Trial N ($M = 3.5$ %) in comparison to order repetitions in Trial N ($M = 2.5$ %); thus indicating task-order switch costs. This latter finding replicates findings of other studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were not modulated by the task order transition in the previous trial, $F(1, 39) < 1$, or by the task order transition in the previous trial and Task, $F(1, 39) = 2.352$, $p = .133$, $\eta p^2 = 0.06$, BF01 = 2.441. Thus, as in the directional error rates of Experiment 2, there was no evidence for a general or task-specific sequential adjustment of task order control in the error rates. However, the combination of Order Transition N – 1 and Order Transition N was modulated by the factor Task Order, $F(1, 39) = 6.134$, $p = .018$, $\eta p^2 = 0.14$, BF01 = 0.593 (BF10 = 1.685). This modulation showed that there was no interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) < 1$, under conditions of oculomotor – pedal task order. Under conditions of the pedal – oculomotor task order, the interaction of Order Transition N – 1 and Order Transition N was significant, $F(1, 39) = 8.890$, $p = .005$, $\eta p^2 = 0.19$, with reduced task-order switch costs after previous order switches in comparison to after task order repetitions. The significant four-way interaction of Task, Task Order, Order Transition N – 1, and Order Transition N, $F(1, 39) = 4.780$, $p = .035$, $\eta p^2 = 0.11$, BF01 = 1.063 (BF10 = 0.940), showed that this reduction is exclusively present in the pedal task. Thus, except for the pedal task under the pedal-oculomotor task order, there was no evidence for sequential modulation of task order control that is specific for certain task dominances or task-order preferences. The only other significant interaction of Task, Task Order, and Order Transition N, $F(1, 39) = 9.715$, $p = .003$, $\eta p^2 = 0.19$,

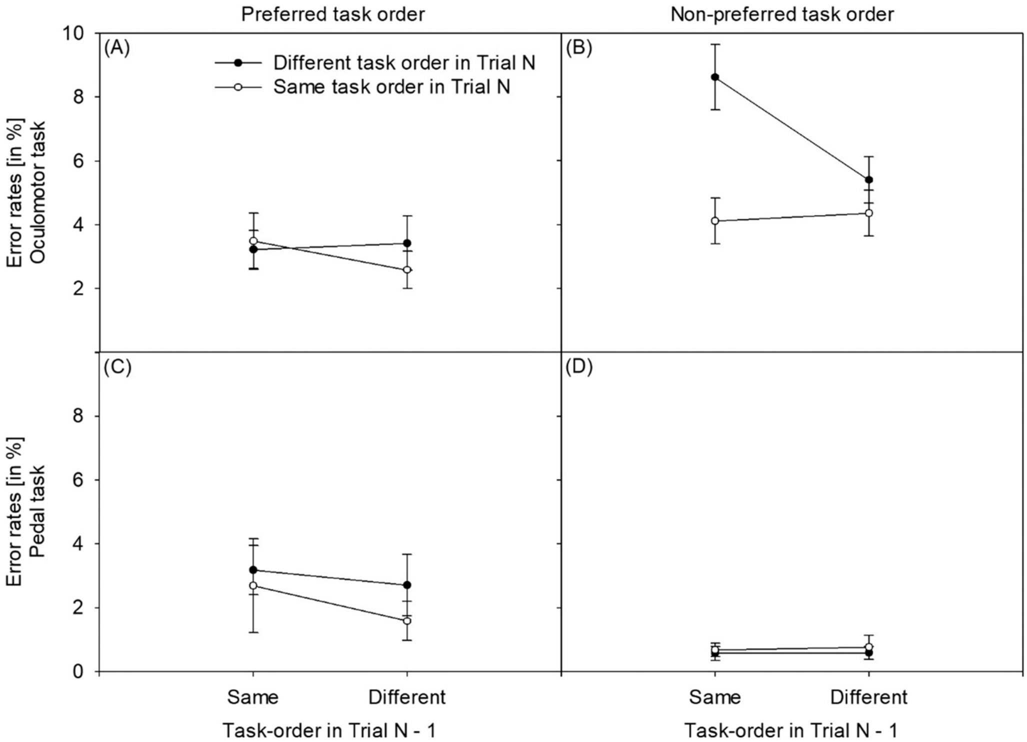

Fig. 8. Directional error rates of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 3. Panel (A): Oculomotor task with "preferred task order" (i.e., oculomotor-pedal). Panel (B): Oculomotor task with "non-preferred task order" (i.e., pedal-oculomotor). Panel (C): Pedal task with "preferred task order" (i.e., oculomotor-pedal). Panel (D): Pedal task with "non-preferred task order" (i.e., pedal-oculomotor). Error bars represent standard errors of the mean.

demonstrated that task-order switch costs are present only in the oculomotor task for the non-preferred task order, while there were no such costs in the other conditions. None of the other main effects or interactions were significant, $Fs(1, 39) < 3.891$, $ps > .056$, ηp^2s < 0.09.

4.2.3. Analyses of reversal errors

The repeated-measures ANOVA revealed main effects of Task Order, $F(1, 39) = 28.262$, $p < .001$, $\eta p^2 = 0.42$, Order Transition N – 1, $F(1, 39) = 9.661$, $p = .004$, $\eta p^2 = 0.20$, and Order Transition N, $F(1, 39) = 34.286$, $p < .001$, $\eta p^2 = 0.47$. As illustrated in Fig. 9, reversal rates were higher in trials with the preferred task order ($M = 12.6$ %) in comparison to trials with the non-preferred order ($M = 5.9$ %), reversal rates were higher for order repetitions in Trial N – 1 ($M = 10.2$ %) in comparison to order switches in Trial N – 1 ($M = 8.3$ %), and reversal rates were higher for order switches in Trial N ($M = 11.9$ %) in comparison to order repetitions in Trial N ($M = 6.6$ %), indicating task-order switch costs. The latter finding is consistent with the RTs and error rates, and it replicates findings from other studies on task order control (e.g., Kübler et al., 2018; Szameitat et al., 2006). Importantly, the task-order switch costs were modulated by the task-order transition in the previous trial, as indicated by the significant interaction of Order Transition N – 1 and Order Transition N, $F(1, 39) = 16.737$, $p < .001$, $\eta p^2 = 0.30$. This interaction replicates findings of a sequential adjustment of task-order control in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022). The first set of planned simple main effect contrasts demonstrated that the task-order switch costs in Trial N were significant, $F(1, 39) = 6.906$, $p = .012$, $\eta p^2 = 0.15$, but numerically smaller ($M = 2.4$ %) after a task order switch in Trial N – 1 in comparison to the significant, $F(1, 39) = 37.832$, $p < .001$, $\eta p^2 = 0.49$, and larger ($M = 8.1$ %) costs after a task-order repetition in Trial N – 1. The second set of simple main effect contrasts revealed no reversal rate difference in task-order repetitions in Trial N after a task-order switch or repetition in Trial N – 1, F(1,

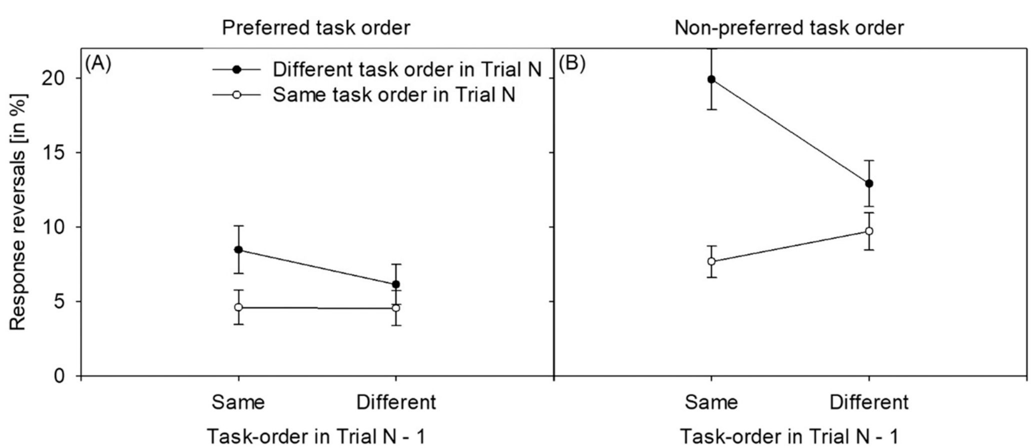

Fig. 9. Rates of response reversals of task-order transition conditions in Trial N – 1 (Order Transition N – 1; same task order versus different task order) and of task-order transition conditions in Trial N (Order Transition N; same task order versus different task order) in Experiment 3. Panel (A): "Preferred task order" (i.e., oculomotor-pedal). Panel (B): "Non-preferred task order" (i.e., pedal-oculomotor). Error bars represent standard errors of the mean.

39) = 1.540, p = .222, while there were significantly higher reversal rates in task-order switches in Trial N – 1 after a task-order switch (vs. a task-order repetition) in Trial N - 1, $F(1, 39) = 21.351$, $p < .001$, $\eta p^2 = 0.35$. Crucially, however, the three-way interaction of Order Transition N – 1 and Order Transition N with Task Order was significant, $F(1, 39) = 10.643$, $p = .002$, $\eta p^2 = 0.21$, BF01 = 0.567 (BF10 = 1.763). This interaction demonstrated that the sequential modulation of task order switch costs was significant under the condition of pedal-oculomotor task order, $F(1, 39) = 31.799$, $p < .001$, $\eta p^2 = 0.45$, while it was not under the condition of oculomotor-pedal task order, $F(1, 39) = 1.508$, $p = .227$, $\eta p^2 = 0.04$. Thus, there was some small evidence that the sequential adjustment of task order control is specific for particular task orders in reversal rates. The only other significant interaction of Order Transition N and Task Order, $F(1, 39) = 18.414$, $p < .001$, $\eta p^2 = 0.32$, demonstrated smaller task-order switch costs for the preferred task order in comparison to the non-preferred task order. None of the other interactions were significant, $Fs(1, 39) < 1.141$, $ps > .292$, $\eta p^2 s < 0.03$.

4.2.4. Discussion

We can conclude that switching to a different task order resulted in task-order switch costs in the RT, directional error, and reversal data (similar to Experiments 1 and 2). Further, we demonstrated that these task-order switch costs are sequentially modulated in a way that they are smaller after previous task-order switches in comparison to task-order repetitions in RTs and reversal error rates (but not in directional error rates). This reduction of task-order switch costs was caused by an improved performance in order switches (in RTs and reversal rates) and a deteriorated performance in order repetitions in RTs after a task-order switch (vs. a task-order repetition). Importantly, and equivalent to Experiments 1 and 2, the specific tasks and task orders that are usually known to be responsible for strong task dominance and task-order preference effects (e.g., Hoffmann et al., 2019; Pieczykolan & Huestegge, 2014) had no effect on the sequential modulation of task-order switch costs in the RTs. In detail, sequential adjustments of task-order control were neither stronger (nor weaker) for participants when switching to their preferred task order vs. their non-preferred task order nor they differ between tasks of different dominance (i.e., the dominant oculomotor and the non-dominant pedal tasks). This RT finding again suggests that sequentially adjusting task-order does not take specific task and task order characteristics into account, which is consistent with the general control modulation hypothesis. Again, we also found a performance advantage for task order repetitions after a previous task order repetition (vs. switch).

The error rates generally did not show sequential adjustments of task-order switch costs, except for the pedal task under the pedal-oculomotor task order. This pedal-oculomotor task order was also the condition under which the reversal errors demonstrated sequential adjustments of task-order switch costs while the reversed task order did not show such adjustments. Thus, Experiment 3 does not allow us to completely exclude the assumption that sequential adjustments of task-order control does not take task-order preference conditions into account. In particular, this modulation might be adjusted by task dominance, as indicated by the existence of this modulation in the pedal task error data, but not in the oculomotor task error data. Note, however, that the Bayesian follow-up analyses indicated only “barely worth mentioning” evidence *for* a specific modulation in directional errors and reversals while evidence *against* such a modulation in RTs was substantial.

5. General discussion

5.1. Summary of the main findings

The main findings of the present study can be summarized as follows. Unsurprisingly (with regard to the original study of Huestegge et al., 2021), we found significant task-order switch costs in RTs, directional error rates, and reversal error rates. More importantly, however, we here replicated previous findings of a sequential modulation of task-order switch costs by previous task-order control demands (order switch vs. order repetition in the *previous* trial). In particular, all three experiments revealed a significant reduction in task-order switch costs after a task-order switch in the previous trial compared with a task-order repetition in the previous trial. This pattern was observed in both RTs and reversal error rates (in all experiments), as well as in directional errors (only in Experiment 1).[2]

The reduced task-order RT switch costs after a task-order switch were caused by improved performance in task-order switches in the *current* trial (faster responses, fewer reversals) and by worse performance in task-order repetitions in the *current* trial (slower responses, more reversal errors) after a task-order switch (vs. repetition) in the *previous* trial. These particular findings differ from previously observed RT patterns of sequential modulations of task-order control, in which responses in both task-order repetitions and (but to a lesser extent) in task-order switches were slowed after a previous task-order switch (vs. repetition, see Strobach et al., 2021; Strobach & Wendt, 2022). Potential reasons for these specific differences will be discussed later (see below).

The present results suggest that task-order switch costs were generally affected by previous task order transition types. However, it is also important to keep in mind that any manipulation of sequential task orders is always accompanied by corresponding changes in task sequences on a component task level (e.g., a switch in task order from one trial to the next, e.g., from A➔B to B➔A also involves a specific pattern of component tasks to be executed, e.g., a repetition of the component task B in-between the task pairs). According to this view, repetitions on the component-task level should lead to a reduction of task-order switch costs in comparison to switches on the component-task level across trials: Specifically, order-switch trials (e.g., at the task-pair level: manual - oculomotor ➔ oculomotor - manual, see Table 1) imply repetitions at the component-task level across trials (i.e., manual – [oculomotor ➔ oculomotor] - manual), whereas order repetition trials (e.g., at the task-pair level: manual – oculomotor ➔ manual – oculomotor) imply switches at the component-task level (i.e., manual – [oculomotor ➔ manual] – oculomotor). However, since our data show impaired performance in order switch trials (i.e., involving repetitions at the component-task level across trials) in comparison to order repetition trials (i.e., involving switches at the component-task level across trials), this data pattern is inconsistent with the assumption that differences in task-order switch costs are solely driven by component-task transitions across trials (Note that there is a variant of this paradigm that controls the local component-task repetitions by using three tasks, Hirsch et al., 2018; Hirsch et al., 2021).

The main goal of the present study, however, was to determine the potential influence of specific task-order (and component task) characteristics on the sequential modulation of task-order control. In other words, are specific task orders and/or specific component tasks differentially affected by the task-order control demand in the previous trial (task order switch vs. repetition)? Regarding this question, neither Experiment 1 nor Experiment 2 provided any evidence of a significant differential reduction in task-order switch costs when performing (1) a relatively dominant task (i.e., the oculomotor task) compared with

[2] One might wonder why we included the re-analysis of Experiment 1 to test for the possibility of task/task-order specific “second-level” sequential modulation of task-order control since there was no evidence for task-order specific “first-level” asymmetries in task-order switch costs. This was warranted because, as was argued in the original study by Huestegge et al. (2021) that there is no reason to assume fundamentally different mechanisms of task-order control at work in Experiment 1 (vs. Experiments 2 and 3), only, that effects of task order preference on “first-level” task-order switch costs was counteracted by other processes related to oculomotor habits in the specific spatial arrangement of oculomotor and manual responses used in this Experiment.

performing a relatively non-dominant task (i.e., the manual/pedal task) as well as (2) a switch to a preferred task order compared with performing a switch to a non-preferred task order in any of the dependent variables. While the RT data in Experiment 3 paint the same picture, we observed hints toward a task *order* specific control modulation in directional errors and reversals. It is therefore not possible to *completely* rule out the possibility of especially task order specific sequential adjustments to task-order control based on the current data. Note, however, that Bayesian follow-up analyses indicated only weak evidence of the two respective interaction effects while evidence against specific modulation was generally substantial across the remaining analyses. Thus, unlike "first-level" task-order control (i.e., performing an actual order switch vs. an order repetition), which has previously been shown to be affected by specific task characteristics as shown by a general advantage related to switching to the preferred task order (Huestegge et al., 2021), the "second-level" sequential modulation of task-order control (i.e., the reduction in task-order switch costs following a *previous* task-order switch) addressed in the present study is, overall, most likely processed according to the general control modulation hypothesis and appears to be governed by different, more general mechanisms. Taken together, this suggests different underlying control characteristics for these two ("first-level" and "second-level") types of task-order control.

5.2. Sequential modulation of cognitive control

The present results revealed no evidence for sequential task-order control adjustments that depend on specific task and task order characteristics, rendering a general attention- (or other cognitive capacity-) related mechanism most likely. As outlined in the introduction, this idea of allocating more "mental capacity" to certain aspects of task-related processing in response to increased processing demands is a common notion in research on cognitive control (Kahneman, 1973) and has been modelled by Norman and Shallice (1986) by referring to different states of control.

A more formal version of this mechanism of sequential modulation of cognitive control has been used to explain the reduction of congruency effects following an incongruent trial (vs. following a congruent trial) in conflict paradigms such as the Flanker effect (Gratton et al., 1992). In the influential conflict monitoring theory by Botvinick et al. (2001), the cognitive system is assumed to monitor for conflict (as induced by incongruent trials). Upon detection of conflict (i.e., upon encountering an incongruent trial), an upregulation of cognitive control is triggered to increase the activity of task-relevant information or to decrease the activity of task-irrelevant information. Increased cognitive control then also facilitates the resolution of conflict in a subsequent incongruent trial. Applying this idea to the present setting, the system could be expected to monitor for conflict caused by the requirement to switch task-order (instead of dealing with an incongruent stimulus) and upon detection of such a conflict, to increase cognitive (task-order) control.

Sequential modulations of cognitive control were also discussed by referring to inhibitory processes in the task switching literature. Using a task switching paradigm with different tasks presented sequentially (resulting in switch and repetition trials), Schuch and Grange (2015) applied a N - 2 task repetition cost paradigm in which task sequences of the type ABA (i.e., Task A performed in the final Trial N is the same as the task performed in Trial N - 2) are compared to task sequences of the type CBA (i.e., Task A in the final Trial N is not the same as in Trial N - 2); thus, like in the present study, there is an investigation of the impact of the penultimate trial on the current trial performance and cognitive control status in the N – 2 task repetition cost paradigm. Performance of the final Task A in this sequence is usually worse in ABA sequences than in CBA sequences, presumably due to larger persisting inhibition of the previously inhibited Task A in ABA sequences (Koch et al., 2010; Mayr & Kliegl, 2000). Schuch and Grange (2015) reasoned that, due to this persisting inhibition, ABA trials can be considered as trials with high task conflict relative to CBA trials, and this task conflict increases and adjusts cognitive control in the trial following an ABA sequence. In line with this expectation, performance in trials after ABA sequences was found to be better than performance after CBA sequences. However, it appears unlikely that in our present study the inhibition of a particular task order in Trial N-1 (e.g., inhibition of the "A➔B" order in Trial N-1 for the sequence A➔B, B➔A, A➔B) is responsible for performance in Trial N, as performance in the final trial – in our study – was actually enhanced (representing an order switch after a previous order switch). However, Schuch and Grange also investigated a novel sequential effect of N–2 task repetitions when trial N–3 is taken into account. In particular, performance is better in trials preceded by an n–2 repetition than in trials preceded by an N–2 switch (i.e., performance is better in BABA sequences where trial N–1 was an N–2 repetition than in CABA sequences where trial N–1 was an N–2 switch). It is suggested that this N-3 effect reflects trial-by-trial modulation of cognitive control. The task conflict is higher in N–2 repetitions than in N–2 switches. Therefore, cognitive control is increased in trials following N–2 repetitions, leading to improved performance. This facilitating effect of previous task conflict in the task-switching paradigm shares obvious similarities with the current phenomenon of the sequential trial-by-trial modulation of task-order control. It is however open whether the underlying control mechanisms overlap between both types of situations.

5.3. Specifying the non-specific sequential modulation of dual-task order control

The pattern of results obtained in the current study on the sequential modulation of task-order control shares a striking similarity with the results typically obtained in sequential modulations of cognitive control in conflict tasks (see Braem et al., 2019 for a recent overview). However, the present situation differs from conflict paradigms in an important way. In the sequential reduction of congruency effects, the *content* of a single (i.e., incongruent) trial is the source of conflict triggering the upregulation of cognitive control. Here, in the sequential reduction of task-order switch costs, the *type of transition* between two task-orders (i.e., the switch vs. repetition of task-orders) is the trigger for the adjustment of task-order control. One should therefore probably be careful not to conflate the 'extraordinary' events responsible for a modulation of cognitive control (capacity) in these two paradigms. Rather, a more specific account of the mechanisms underlying a reduction of task-order switch costs is desirable.

Task-order switch costs were consistently reduced after a *preceding* switch of task order (vs. a *preceding* repetition of task order) in RTs and reversal error rates, and this finding was not compromised by any conflicting result pattern in directional error rates (see Figs. 1–9). Crucially, this reduction in switch costs depended neither on the specific task order nor on the specific task that was analyzed. This was interpreted in terms of an adjustment in task-order control (following the demand to switch task-orders) that is non-specific with regard to task and task order characteristics. More specifically, however, performance of a task-order switch (vs. a task-order repetition) was facilitated after a *preceding* switch of task order (vs. a *preceding* repetition of task order) in all performance measures that showed this sequential modulation. At the same time, the present data showed that performance of a task-order *repetition* (vs. a task-order switch) was impaired after a *preceding* switch of task order (vs. a *preceding* repetition of task order), at least in RTs. Thus, the adjustment in task-order control cannot be interpreted as a truly generic improvement of information processing following the precarious task-order switch. Such an adaptation of the system should have led to generally improved performance (for both task order switches *and* repetitions) after a previous task order switch, which we did not observe. Alternatively, previous studies suggested a *general slowing* mechanism (probably representing response caution) after a *previous* task-order switch (vs. repetition) that is only to some extent attenuated in task-order switches in the current trial (Strobach et al., 2021; Strobach & Wendt, 2022). However, this mechanism would not be compatible with our present data either. Here, after a task-order switch (vs. repetition) in the previous trial, the reduced task-order RT switch costs after a task-order switch were caused by *improved* performance in task-order switches in the current trial (faster responses, fewer reversals) and by *worse* performance in task-order repetitions in the current trial (slower responses, more reversal errors).

Instead of a general tendency to slow down or to act more carefully after experiencing a task-order switch (vs. a task-order repetition), participants in the present study must therefore have selectively increased their *readiness to switch* task-order again *at the expense of the readiness to repeat* the task-order they have just switched to, however, without regard for the specific switch to be performed. Probably, the presence of a preferred task order as implemented in the present paradigm renders order switches quite effortful in general, so that cognitive resources are close to their limits, thereby no longer allowing for an increase in the readiness to switch while at the same time being retaining an overall preparedness to benefit from task order repetitions. Overall, the discrepancies in the specific pattern of sequential order switch cost modulations as a result of the particular tasks combined (in the present vs. the previous studies) suggest that one should be careful to infer general mechanisms of task order control solely based on limited situational variability (e.g., with respect to the particular tasks involved).

How could such a heightened “switch-readiness” as envisioned in the previous discussion be attained specifically? Previous studies suggested that *task order* would be represented as part of a higher order task set representation (Hirsch et al., 2017; Hirsch et al., 2018; Kübler et al., 2018). When assuming that in addition to the specific task order, the *task order transition type* (i.e., order repetition vs. order switch) can be stored as a control parameter in such a higher-order task set, there are two conceivable mechanisms underlying the observed pattern of results. On the one hand, a *repetition priming account* would explain the benefits of performing a task-order repetition after a previous task-order repetition and of a task-order switch after a previous task-order switch as a *passive* (partial) repetition benefit of that particular control parameter in the task set (i.e., repetition-repetition and switch-switch) while the specific task order representation changes (see Dignath et al., 2019, for the similar assumption that control states may be integrated in to task representations).

On the other hand, according to a *strategic control adjustment account*, the heightened “switch-readiness” following a previous task-order switch could also represent an *active* strategy adopted by the participants based on the expectancy of the same *task-order transition type* as in the previous trial. As long as the task order repeats, the participants can simply use the information of the previous task order to forego any active specification of task order. In the event of a task-order switch, however, the participant may be “caught off-guard” by the need to actively schedule the tasks (e.g., weighing instructions against effector-based task dominance Pieczykolan & Huestegge, 2019). To avoid being caught off-guard again, the participants might be reluctant to simply rely on the *previous* task-order specification. In a sense, by expecting another task-order switch one becomes “suspicious” of the task order just employed, which would explain both the performance improvement in task-order switch trials and the performance decline in task-order repetition trials following a task-order switch.

Based on the present data, we cannot ultimately disentangle the passive *repetition priming account* from the active *strategic control adjustment account* of the sequential modulation of task-order control. This issue therefore requires dedicated future studies. Nevertheless, we can safely conclude that the sequential modulation of dual-task order control operates in a less task-specific, more general fashion when compared to the specific (“first-level”) implementation of a task-order switch, which was strongly affected by whether participants switch to the preferred (vs. non-preferred) task order.

6. Conclusions

Taken together, the present re-analysis of the dataset collected by Huestegge et al. (2021) extends our knowledge of higher-level task-order control processes in the context of dual-task situations. We provided further evidence for the robustness of sequential adjustment effects of task-order control based on previous task-order control demands. These sequential modulations were caused by improved performance in task-order switches and reduced performance in task-order repetitions following a task-order switch compared to a task-order repetition. Most importantly, however, the results indicated a dissociation of the mechanisms underlying such “second-level” sequential modulations of task-order control from the ones enabling concrete, “first-level” task-order control. The concrete demand of switching task order clearly depends on the exact switch to be made (i.e., to a preferred vs. non-preferred task order). The adaptive increase in task-order control after a previous order switch (vs. a previous order repetition), in contrast, generally did not take aspects of the *specific* switch to be made into account. Further, the adaptive task-order control was similarly evident in the analyses of the dominant (oculomotor) task and the non-dominant (manual/pedal) task. Thus, these results point to the presence of an unspecific, general (active or passive) process of task-order control related to the recruitment of mental capacity.

Ethics approval and consent to participate

All procedures performed in this study 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. Informed consent was obtained from all participants before the commencement of the study.

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Declaration of competing interest

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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The original study of Huestegge et al. (2021) was pre-registered at https://aspredicted.org/fx9dj.pdf.

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