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ORIGINAL ARTICLE

Exploring the repetition bias in voluntary task switching

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Abstract In the voluntary task-switching paradigm, participants are required to randomly select tasks. We reasoned that the consistent finding of a repetition bias (i.e., participants repeat tasks more often than expected by chance) reflects reasonable adaptive task selection behavior to balance the goal of random task selection with the goals to minimize the time and effort for task performance. We conducted two experiments in which participants were provided with variable amount of preview for the non-chosen task stimuli (i.e., potential switch stimuli). We assumed that switch stimuli would initiate some pre-processing resulting in improved performance in switch trials. Results showed that reduced switch costs due to extra-preview in advance of each trial were accompanied by more task switches. This finding is in line with the characteristics of rational adaptive behavior. However, participants were not biased to switch tasks more often than chance despite large switch benefits. We suggest that participants might avoid effortful additional control processes that modulate the effects of preview on task performance and task choice.

In many multitasking situations, people face complex environments with an enormous amount of potentially relevant tasks. Although people usually decide how to schedule the order of multiple tasks (i.e., sequential multitasking), task selection is guided not only by internal goal-directed intentions, but also by external influences (e.g., Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010). In the present study, we explored how the interplay of these top-down and bottom-up factors might contribute to the central finding of a repetition bias in studies using the *voluntary task-switching* (VTS) paradigm (Arrington & Logan, 2004). We suggest that this repetition bias and the incorporation of bottom-up factors into task selection behavior provide evidence for a reasonable adaptation of our cognitive system to multitasking environments as created by the VTS paradigm.

The VTS paradigm introduced by Arrington and Logan (2004, 2005) is a prominent variant of task-switching procedures (e.g., Jersild, 1927; Rogers & Monsell, 1995; Meiran, Chorev, & Sapir, 2000; for reviews see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010) used to examine factors that influence task selection strategies (for a recent summary see Arrington, Reiman, & Weaver, 2014). In this paradigm, participants decide which of the two tasks they want to perform in a given trial. Importantly, it is also stressed in the instructions that participants should choose tasks *randomly*. More precisely, participants are instructed to imagine that a coin flip decides on each trial which task to perform so that they perform each task and each transition (i.e., repetition and switch) equally often (e.g., Arrington & Logan, 2004). In one version of this paradigm, each task is mapped on a specific hand and task choice and task execution is simultaneously registered by pressing the appropriate response key (e.g., Arrington & Logan, 2004). In another version, the *double-registration paradigm*, participants first have to indicate which task they want to perform by pressing one of two keys with the finger of one hand. Subsequently, task-relevant stimuli are presented and participants perform the selected task by using the fingers of

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the other hand (e.g., Arrington & Logan, 2005; Demanet & Liefooghe, 2014; Dignath, Kiesel, & Eder, 2015). Both the standard VTS and the double-registration procedure reveal two key findings.

First, task performance is worse in switch trials compared to repetition trials. Similar to standard cued task-switching procedures (e.g., Hoffmann, Kiesel, & Sebald, 2003; Koch, 2001; Meiran, 1996), switching between two tasks produces in particular profound *switch costs* in reaction times (RTs) (e.g., Arrington & Logan, 2004, 2005). Second, task choice is biased toward task repetitions (i.e., *repetition bias*). Although participants choose tasks equally often, they consistently violate the instruction to select tasks randomly by repeating tasks more often than expected by chance (e.g., Arrington & Logan, 2005; Yeung, 2010). The repetition bias is especially remarkable because it stands in contrast to the finding that when generating random sequences, there is a tendency to alternate more often than to repeat (Nickerson, 2002; Rapoport & Budescu, 1997). Thus, VTS experiments indicate cognitive limitations when switching tasks both in task performance (reflected in switch costs) and in task selection (reflected in repetition biases).

To account for the repetition bias, Arrington and Logan (2005) suggested that task choices result from a competition between the use of an availability heuristic and a representativeness heuristic. Specifically, tasks are either selected on the basis of the most active task set (i.e., availability heuristic; Baddeley, 1996) or on the basis of a mental representation of a random sequence (i.e., representativeness heuristic; Rapoport & Budescu, 1997). According to this *competing-heuristics account*, the repetition bias occurs because participants sometimes fail to comply with the instruction to form a top-down task goal based on the representativeness heuristic and instead guide task selection based on the most active task set (i.e., availability heuristic). Consequently, this results in repeating the task when the efficiency of controlled top-down processes to randomly select a task is not sufficient.

From a rational perspective, however, it seems reasonable for our cognitive system to select tasks based on the availability heuristic. Although complying with the randomness instruction might be of highest importance in VTS studies, it seems fair to argue that participants also strive to improve their task performance in these studies (in terms of speed and accuracy). The idea that people select actions to minimize the time to achieve task goals has received much support in the literature (e.g., Anderson, 1990; Gray, Sims, Fu, & Schoelles, 2006) and some VTS studies explicitly stressed task performance in the instruction (e.g., Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010). Furthermore, a number of studies provided evidence that individuals are biased to select less demanding actions (e.g., Dunn, Lutes, & Risko, 2016; Kool & Botvinick, 2014; Kool, McGuire, Rosen, & Botvinick, 2010), and guiding task selection on the basis of the most available task seems in line with the law of least mental effort (e.g., Kool et al., 2010).

Based on this interpretation, the explanation of a repetition bias via the availability heuristic does not primarily reflect a control deficit, but depicts the flexibility of our cognitive system to adapt to the sequential multitasking environment to balance the goal of randomly selecting tasks with the goals to also minimize time, effort or both. More specifically, we assume that participants avoid task switches because of increased effort and/or time to perform the task (i.e., reflected in switch costs) and thus sometimes guide their task choice based on the availability heuristic typically resulting in task repetitions. Note that this suggests that participants have some metacognitive awareness (Dunn et al., 2016) associated with switching tasks. Although we are not aware of any study that directly examines the introspection of switch costs, recent research suggest that an individual's introspection is sensitive to very small variations in task performance (Questienne, van Dijck, & Gevers, 2017). Furthermore, the probability for task repetitions and thus the repetition bias strongly increase when the instruction to randomly select a task is weakened (e.g., Arrington et al., 2014; Liefooghe, Demanet, & Vandierendonck, 2009), which provides a further hint that participants have some awareness of the costs associated with switching tasks. Consequently, we argue that the race of the two heuristics as suggested by Arrington and Logan (2005) to account for the repetition bias actually describes reasonable task selection behavior due to the opposing goals of participants in a VTS setting (i.e., minimization of effort/time and adherence to select tasks randomly).

In the present study, we aim to test the interpretation of the competing-heuristic account in terms of adaptive task selection behavior in more detail. For this purpose, we selectively manipulated the availability of stimuli that are *associated with potential task switches*. Numerous studies have shown that task choice in VTS is influenced by bottom-up factors (e.g., Arrington & Reiman, 2015; Arrington & Weaver, 2015; Demanet & Liefooghe, 2014; Mayr & Bell, 2006; Yeung, 2010). For example, Arrington (2008) observed that participants were more likely to choose the task associated with the first stimulus when stimulus availability was randomly manipulated between switch and repetition stimuli (i.e., two stimuli were presented with variable stimulus-onset asynchrony). We expected that exclusively increasing switch stimulus availability should increase performance in task switch trials, so that the perceived effort and objective costs in performing these transitions should be reduced. Importantly, an increase of switch task performance should be also reflected in a reduction of repetition rates if participants adapt their task choice behavior to their task performance.

Importantly, this rather functional interpretation of the competing-heuristic account and our manipulation of switch stimulus availability make some critical assumptions about the underlying mechanisms involved in task-switching and task selection behavior. Specifically, we argue that in VTS studies with two tasks, both task sets are held active throughout the experiment so that in each trial stimuli for each task are—at least to a certain degree—simultaneously processed. Response congruency effects found in many task-switching studies can be seen as a manifestation of this kind of dual task processing (e.g., Koch & Allport, 2006; Schneider, 2015; Yeung, 2010). Importantly, however, stimuli that are associated with a task repetition (i.e., repetition stimuli) are usually processed faster because the task set applied in task *n* probably increases the task activation for this task in trial $n + 1$ (e.g., Allport, Styles, & Hsieh, 1994; Koch, 2001; Koch & Allport, 2006). Thus, when selecting trials based on the availability heuristic, our cognitive system might accumulate (in parallel) evidence of the responses associated with the two tasks in each trial. One of the two tasks is only selected as soon as a certain processing threshold is reached and then the final task processing takes place. Obviously, in usual VTS settings, repetition stimuli will often win this race. However, when we provide switch stimuli a head start by increasing the availability of these stimuli in a trial *n*, evidence accumulation can proceed on the corresponding switch task stimuli on trial $n + 1$. Consequently, it is more likely that switches are selected based on the availability heuristic. As described before, we assume that processing the switch stimulus to a degree that is reflected in performance data is crucial to select the corresponding switch task.

To assess task selection under conditions that differentially enable task processing, we manipulated the availability of task switch stimuli using three different *preview groups* in a modified double-registration VTS paradigm (see Fig. 1). Preview was manipulated between participants to ensure that there was no contamination of task choice and performance in one preview condition by prior experience with another preview condition. In each preview group, participants had to choose first which of two tasks they wanted to perform on a given trial. After they indicated their task choice, they had to perform the corresponding task. Importantly, however, a non-chosen stimulus in trial *n* remained the same in the next trial $n + 1$ and the benefit of preview associated with task switch stimuli differed between groups. Participants were presented with both tasks during task choice only (i.e., *choice-preview*), during task choice and task execution (i.e., *execution-preview*) or during task choice and task execution plus an additional viewing time after task execution (i.e., *extra-preview*). To systematically assess the impact of preview for each preview group, we added a *baseline task display condition* in each preview group in which participants performed a regular VTS setting without any preview in addition to the *experimental task display condition* with preview. To investigate if benefits in task performance impact on task selection, it is important to consider both the difference in task performance between switch and repetition trials (i.e., switch costs) and the selection of task transition (i.e., repetition rate).

In the task display conditions without preview (i.e., baseline), we expected to replicate the standard key findings in the VTS paradigm, switch costs and the repetition bias (e.g., Arrington, Reiman & Weaver, 2014). However, in the experimental task display conditions, switch costs should decrease with increased preview possibility because participants could process a potential switch task on trial *n* before they select this task on trial $n + 1$. For the choice-preview group, task processing during task choice should occur only to a minor degree. In contrast, the execution-preview and extra-preview condition were implemented to foster task processing of switch stimuli. Here, we assume that participants with extra-preview benefit more than participants in the execution-preview condition and thus their performance in switch trials should especially profit. The main question was whether an improvement of performance in switch trials as a marker of the processing degree of switch stimuli is accompanied by a parallel reduction of repetition rates. Thus, we expected that the repetition bias is smaller (meaning the switch rates are higher) when switch costs are smaller (i.e., preview benefit is larger). Consequently, we hypothesized finding no repetition bias if switch costs are eliminated in task performance and even a switch bias if preview times result in switch benefits (i.e., negative switch costs).

It is important to note that preview benefits can vary across the three different preview groups, but also within participants in all preview groups. For example, Reissland & Manzey (2016, Experiment 1; see also Brüning & Manzey, 2017) demonstrated individual differences in the preference for strictly serial vs. overlapping processing in an alternating-run task-switching paradigm with preview on switch task stimuli (i.e., *task switching with preview paradigm*). Thus, we assume that differences in individual preview benefits due to the degree the switch stimulus is processed should also be reflected in the size of the repetition rate. For this purpose we also computed the correlation between switch costs and repetition rate. We expected to observe that these two measures would correlate because participants with larger switch costs (i.e., smaller preview benefit) should repeat tasks more often.

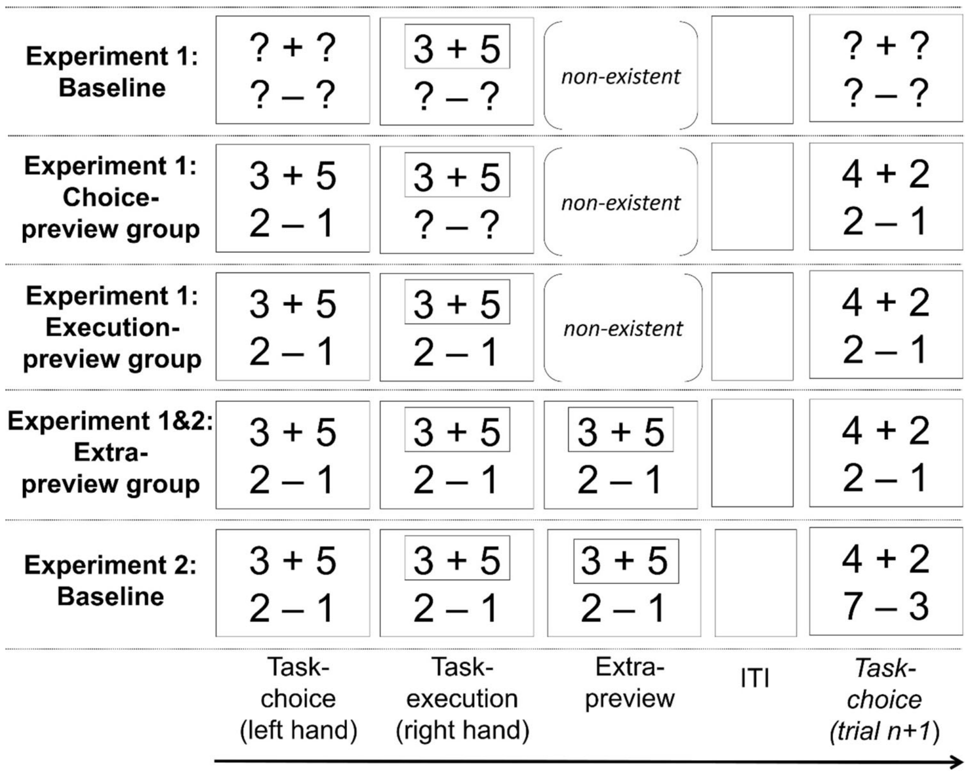

Fig. 1 Trial sequence in the baseline and experimental task display conditions of Experiment 1 (i.e., choice-preview group, execution-preview group, extra-preview group) and Experiment 2 (i.e., extra-preview group). Extra-preview was only provided in the experimental task display blocks of the extra-preview groups of Experiment 1 and 2 and extra-preview on discretionary stimuli was provided in the baseline task display blocks of Experiment 2

Experiment 1

In this experiment, we used a double-registration version of the voluntary task-switching paradigm with an addition and subtraction task. In each trial, participants had to first select a stimulus of the addition task stack or a stimulus of the subtraction task with their left hand. Participants were instructed to select tasks randomly and to perform the tasks as fast and accurately as possible. Different participants were tested in each preview group, but all participants were also tested in a similar baseline task display condition in addition to the experimental task display condition with preview (see Fig. 1).

Method

Participants

Seventy-two native German speakers (56 female) were individually tested at the University of Freiburg, Germany. Participants were mainly psychology students and they were compensated with either course credit or money. They ranged in age from 17 to 34 years ($M = 22.2$)[1] and 61 were right-handed. Participants were equally assigned to one of the three preview groups (i.e., choice-preview, execution-preview and extra-preview). Five additional participants were also tested, but three participants were not included in the analysis due to switches on less than 10% of the trials. We replaced these participants with new participants to ensure counterbalanced preview groups and task display condition sequences. The two other participants did not understand the instructions (assessed by self-report after the experiment) and they were replaced by new participants during data collection (i.e., prior to any data analyses).

Apparatus and stimuli

Stimulus presentation and recording of responses were controlled by E-Prime Software 2.0 (Psychology Software Tools, Pittsburgh, PA, USA) running on a Fujitsu EPrimo P920 computer. All stimuli were presented in white font on the black background of a 24-in. computer monitor, which was viewed from a distance of approximately 60 cm. Target stimuli consisted of two numbers connected by a plus or minus sign. Participants were required to either add (i.e., addition task) or subtract (i.e., subtraction task) these numbers. For the addition task, a combination of the numbers one to eight with possible solutions between two and nine was used. For the subtraction task, a combination of the numbers two to nine with possible solutions between one and eight was used. There were 36 different combinations of calculations (i.e., stimuli) per task. The numbers were approximately 6 mm in height and 4 mm in

[1] Age from one participant was missing.

thickness. Two question marks of the same size served as placeholders. Tasks were presented one above the other (i.e., at a distance of approximately 10 mm) at the center of the screen. For half of the participants, the addition task was always presented at the top, and the subtraction task was always presented at the bottom. For the other half of the participants, the task positions were reversed. Participants indicated their task choice by pressing the "A" key (i.e., upper task) and "Y" keys (i.e., lower task) of a QWERTZ keyboard (marked with color patches) with the index and middle fingers of the left hand and they responded to the task with the right hand on the keys of the numeric keypad.

Procedure

Each participant performed seven consecutive blocks with the baseline task display and seven consecutive blocks with the preview group-specific experimental task display (i.e., choice-preview, execution-preview or extra-preview). The sequence of task display conditions (i.e., baseline-experimental vs. experimental-baseline) was counterbalanced across participants. In each of the 14 blocks, participants performed 72 trials (1008 trials in total). The order of the specific stimuli of each task was randomly predefined at the beginning of each block. If participants worked on all 36 stimuli of one task stack, this task stack was refilled with another random order of these stimuli.

The experiment started with visually presented instructions describing the basic procedure (i.e., task choice and task execution) in each trial and the requirement to be as fast and accurately as possible but to choose tasks randomly. Specifically, participants were instructed to choose each task equally often without applying any strategy. Participants were also told to imagine a coin flip for every task choice (see Arrington & Logan, 2004). The experimenter ensured that participants had fully understood the written instructions. Participants were not informed about the preview manipulation.

In the experimental task display blocks of all preview groups (see Fig. 1), two task stacks (e.g., "2 + 4" vs. "7-2") appeared on the screen and participants had to indicate which task they wanted to perform (i.e., task choice screen). Then, the stimulus for the selected task was surrounded by a rectangle until participants responded (i.e., task execution screen). For the choice-preview group, task stacks were only uncovered during task choice, but the non-selected task was covered during task execution. For the execution-preview group, task stacks were uncovered during both task choice and task execution. For the extra-preview group, task stacks were uncovered and in addition the task execution screen was shown for another 500 ms after a response was made. In case of correct responses, a blank black screen (i.e., intertrial interval, ITI) was displayed for 100 ms. Then, the same stimulus of the previously non-selected task was presented in the next trial. In case of an error, an error tone was played and the task execution screen was shown for another 1500 ms before the ITI started.

In the baseline task display blocks (see Fig. 1), two covered task stacks (i.e., "?+?" vs. "?−?") appeared on the screen and only the stimulus for the selected task (surrounded by a rectangle) was presented during task execution. After task execution, a blank black screen (ITI) was presented in all preview groups. For the choice- and execution-preview group, this ITI was still 100 ms. For the extra-preview group, we used an ITI of 600 ms to match the time between trials to the corresponding experimental task display condition (i.e., 500 ms extra-preview + 100 ms ITI). Previous research has shown that repetition rates and switch costs decrease when increasing the response–stimulus interval even if no preview is provided (e.g., Arrington & Logan, 2005). Thus, the prolongation of the ITI in the baseline task display blocks of the extra-preview group was necessary to fairly compare repetition rates and switch costs with the experimental task display blocks with preview.

Breaks between blocks were self-paced and after each block participants received performance feedback (i.e., block duration and block errors) as well as a reminder to continue selecting tasks in a random order.

Design

Reaction times (RTs), percentage errors (PEs) and repetition rates served as dependent variables. To compare as fairly as possible performance between the different experimental and baseline task display conditions, we used the sum of task choice and task execution reaction times for our RT analyses.[2] The independent variables were *preview group* manipulated between participants (i.e., choice-preview group vs. execution-preview group vs. extra-preview group) and *task display* manipulated within participants (i.e., baseline vs. experimental). Thus, for the analysis of repetition rates, we conducted a 3 $\times$ 2 mixed ANOVA with the between-subject factor preview group and the within-subject factor task display. For PE and RT analyses,

[2] In all experimental task display blocks with preview, for example, it is possible that participants worked on a task before they actually selected a task. Indeed, separate analyses for choice and execution reaction times (RTs) in Experiment 1 indicated that participants in the preview conditions worked on task stimuli before they selected a task. This was reflected in longer choice RTs and correspondingly shorter execution RTs in the preview conditions compared to the baseline conditions. These analyses provided further support for our approach to use the sum of task choice and task execution reaction times as a measure for task performance.

we additionally considered *task transition* (i.e., switch and repetition) and we thus conducted a 3 × 2 × 2 mixed ANOVA with the between-subject factor preview group and the within-subject factors task display and transition.

Results

The first block of each task display condition and the first trial of each block was considered practice and excluded from all analyses. For all analyses, we eliminated trials following errors (3.7%). For choice probability and reaction time analyses, we additionally removed error trials (3.7%) and excluded trials with RTs that exceeded more than three standard deviations from the individual's mean for each condition (1.9%) for these analyses. We decided for the same exclusion criteria for choice data and reaction time data to compare these measures as fairly as possible.

Choice probability analyses

The overall probability of performing the subtraction task was .48. This probability differed from chance (.50), $t(71) = 4.49$, $p < .001$. An ANOVA with the within-subject factor task display (i.e., baseline vs. experimental) and the between-subject factor preview group (i.e., choice-preview vs. execution-preview vs. extra-preview) revealed no significant differences in the preference for choosing this task, all $ps > .280$.

The mean repetition rate was .57. Participants repeated tasks more often than was expected by chance, $t(71) = 4.16$, $p < .001$. The first row in Table 1 shows the mean repetition rates in the baseline and experimental task display conditions separately for the three preview groups. These means were analyzed with an ANOVA with the factors task display and preview group. The main effect of task display was significant, $F(1,69) = 5.11$, $p = .027$, $\eta^2 = .07$. Participants repeated tasks slightly more often in the baseline (.58) than in the experimental task display blocks (.56). The main effect of preview group was also significant, $F(2,69) = 3.29$, $p = .043$, $\eta^2 = .09$. Pairwise comparisons (i.e., post hoc analyses using the Scheffé post hoc criterion for significance) revealed that the repetition rate was lower—although not significantly—in the extra-preview group (.51) than in the execution-preview group (.61), $p = .051$, but the repetition rates in the extra-preview group and in the choice-preview group (.58) did not differ significantly, $p = .214$. The rates of the choice-preview and execution-preview groups also did not differ significantly, $p = .775$. Most important, the analysis also revealed a significant interaction between task display and preview group, $F(2,69) = 3.21$, $p = .047$, $\eta^2 = .09$. Separate *t* tests for each preview group revealed that the tendency to repeat tasks was significantly reduced in the experimental task display condition compared to the baseline task display condition for the execution-preview group, $t(23) = 2.85$, $p = .009$, and for the extra-preview group, $t(23) = 2.40$, $p = .025$, but not for the choice-preview group, $p = .530$. The repetition rates were higher than expected by chance in the baseline, $t(23) = 2.50$, $p = .020$, and experimental, $t(23) = 2.98$, $p = .007$, task display conditions for the choice-preview group and in the baseline, $t(23) = 4.58$, $p < .001$, and experimental, $t(23) = 2.77$, $p = .011$, task display conditions for the execution-preview group. For the extra-preview group, these values did not differ significantly from the instructed value of .5 for both the baseline ($p = .173$) and the experimental ($p = .787$) task display conditions.

RT analyses

Table 1 shows the mean RTs in switch and repetition trials, and the corresponding switch costs (i.e., switch RT − repetition RT) in the baseline and experimental task display conditions as a function of preview group. Positive switch cost values indicate that participants were on average faster in repetition compared to switch trials.

An ANOVA with the within-subject factors task display (i.e., baseline vs. experimental), transition (i.e., switch vs. repetition) and the between-subject factor preview group (i.e., choice-preview vs. execution-preview vs. extra-preview) on mean RTs yielded a significant main effect of task display, $F(1,69) = 18.99$, $p < .001$, $\eta^2 = .22$. Mean RTs were lower in the experimental (1160 ms) than in the baseline task display blocks (1235 ms). The main effect of preview group was also significant, $F(2,69) = 9.80$, $p < .001$, $\eta^2 = .22$. Scheffé post hoc tests indicated that participants of the extra-preview group responded faster (1020 ms) than both participants of the choice-preview group (1327 ms, $p < .001$) and participants of the execution-preview group (1244 ms, $p = .011$). The difference between the latter two preview groups was not significant, $p = .512$. All two-ways-interactions were significant (i.e., the interaction between task display and preview group, $F(2,69) = 9.23$, $p < .001$, $\eta^2 = .21$, the interaction between transition and preview group, $F(2,69) = 17.10$, $p < .001$, $\eta^2 = .33$, and the interaction between task display and transition, $F(1,69) = 7.33$, $p = .009$, $\eta^2 = .10$). Most important, the three-way-interaction between these factors was also significant, $F(2,69) = 14.36$, $p < .001$, $\eta^2 = .29$. Separate ANOVAs for each preview group were conducted to examine these interactions in more detail.

For the choice-preview group, only the main effect of transition was significant, $F(1,23) = 11.08$, $p = .003$, $\eta^2 = .33$ (all other $ps > .246$). Participants were on average slower on switch compared to repetition trials (Δ switch costs = 47 ms). For the execution-preview group,

Table 1 Mean overall reaction time (RT) in milliseconds (ms) and percentage error (PE) as a function of trial transition (i.e., task switch vs. task transition), mean switch costs (i.e., task switch RT − task repetition RT) and repetition probabilities in the baseline and experimental conditions separately for each group (i.e., choice-preview, execution-preview and extra-preview) in Experiment 1

Measure	Group					
	Choice-preview		Execution-preview		Extra-preview	
	Baseline	Experimental	Baseline	Experimental	Baseline	Experimental
Repetition rate	.58 (.03)	.59 (.03)	.64 (.03)	.59 (.03)	.54 (.03)	.49 (.03)
Switch costs in ms	32 (16)	62 (22)	6 (13)	8 (29)	0 (5)	−157 (28)
Task switch RT in ms	1347 (70)	1355 (80)	1267 (44)	1228 (62)	1109 (34)	853 (44)
Task repetition RT in ms	1315 (65)	1293 (63)	1261 (45)	1220 (44)	1109 (35)	1010 (33)
Task switch PE	3.8 (.6)	3.2 (.5)	3.8 (.6)	3.5 (.5)	3.5 (.5)	2.8 (.4)
Task repetition PE	3.7 (.5)	3.3 (.5)	3.5 (.4)	4.1 (.6)	3.8 (.5)	4.8 (.6)

Standard error of the means in parentheses

there were no reliable effects (all $ps > .227$).[3] For the extra-preview group, a significant main effect of task display indicated that participants were faster in the experimental (932 ms) compared to the baseline task display blocks (1109 ms), $F(1,23) = 64.19$, $p < .001$, $\eta^2 = .74$. The main effect of transition was also significant, $F(1,23) = 26.48$, $p < .001$, $\eta^2 = .54$. Mean RTs were shorter on switch trials than on repetition trials (i.e., negative switch costs, Δ switch costs = −78 ms). However, the overall switch costs were modulated by task display, $F(1,23) = 36.48$, $p < .001$, $\eta^2 = .61$. Separate t tests revealed that the switch benefit (Δ switch costs = −157 ms) in the experimental task display blocks was reliable, $t(23) = 5.65$, $p < .001$, whereas there was no significant difference between switch and repetition trials in the baseline task display blocks (Δ switch costs = 0 ms, $p = .923$).

PE analyses

Overall, accuracy was very high (96.4%) and an ANOVA parallel to that conducted on the RTs was also conducted on the PEs (see Table 1). This ANOVA yielded only a significant interaction between the factors task display and transition, $F(1,69) = 8.44$, $p = .005$, $\eta^2 = .11$, all other $ps > .080$. Separate t tests revealed that PEs did not differ between switch (3.7%) and repetition trials (3.7%) in the baseline task display condition, $p = .907$, but PEs were significantly higher in repetition (4.1%) than in switch trials (3.2%) in the experimental task display condition, $t(23) = 2.72$, $p = .008$. This indicates that preview benefits in the experimental task display blocks were also reflected in accuracy.

Relation of repetition rates with switch costs

Finally, we checked whether individual differences in the use of preview were also reflected in choice behavior. For this purpose, we computed the correlations between switch costs and repetition rates in the experimental task display blocks separately for each preview group. Figure 2a–c shows the scatter plots of the individual mean repetition rates and mean switch costs of each participant of the corresponding preview group. As can be seen in Fig. 2b, c, there were substantial relations between these variables within the execution-preview group, $r = .59$, $p = .002$, and within the extra-preview group, $r = .52$, $p = .009$. Figure 2a shows that these variables were independent of each other in the choice-preview group, $r = .08$, $p = .699$. For completeness, we also computed the correlations between switch costs and repetition rates in the corresponding baseline task display blocks. These correlations were weak and not significant, all $rs < .3$ and all $ps > .167$.

Discussion

In summary, repetition biases were observed for the baseline and experimental task display conditions of the choice and execution-preview groups, but not for the extra-preview group. The corresponding repetition rates were reduced in the experimental task display conditions compared to a baseline task display condition in the execution-preview and extra-preview groups, but not in the choice-preview group. When relating performance in switch trials and thus potential preview benefits to task selection behavior, it becomes obvious that the reduction of

[3] We noticed that one participant of this preview group had very high switch costs in the experimental (Δ switch costs = 567 ms), but not in the baseline task display condition (Δ switch costs = −21 ms). This participant was not excluded from our reported analyses, but we conducted additional analyses for the execution-preview group without this participant. These analyses still revealed no reliable effects on mean RTs (all $ps > .113$) and the difference in repetition rates between the baseline and experimental task display blocks was still significant ($p = .013$).

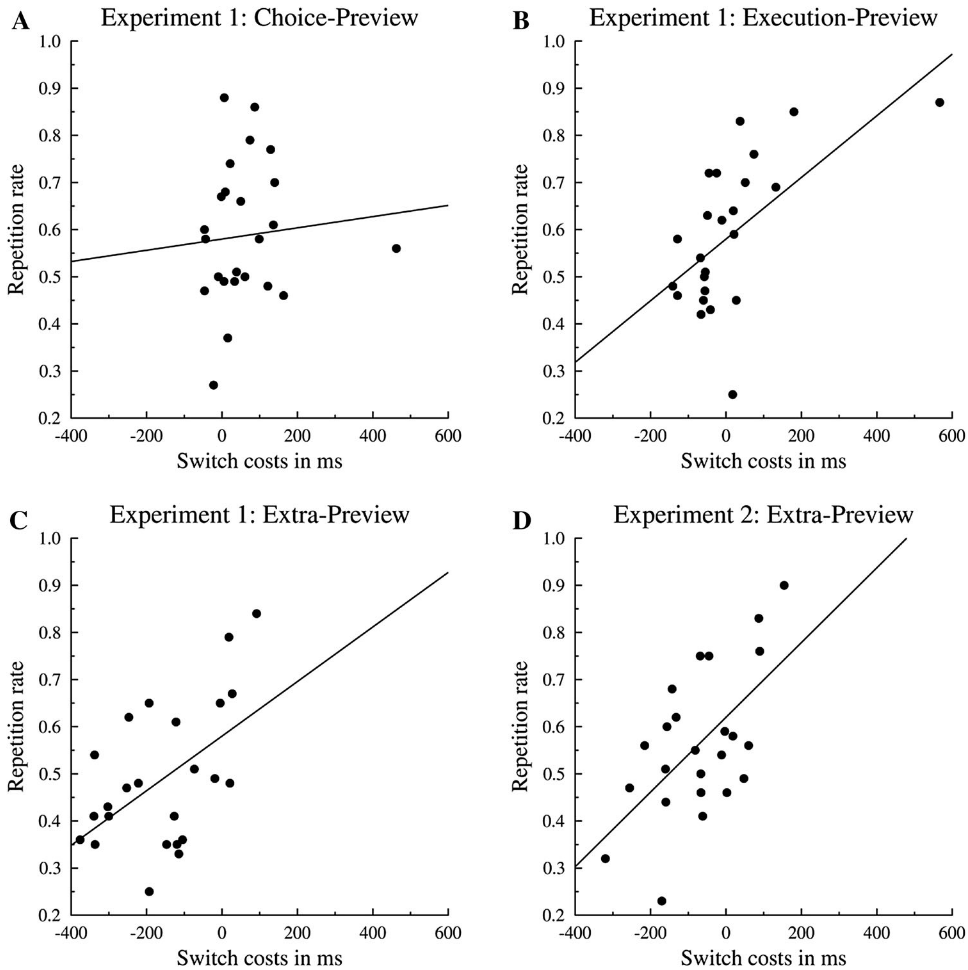

Fig. 2 Scatter plots of individual switch costs (i.e., mean task switch reaction times − mean task repetition reaction times) against repetition rates for the experimental task display conditions of the three groups in Experiment 1 (i.e., choice-preview group, execution-preview group and intertrial-preview group) and for the experimental task display condition in Experiment 2 (i.e., intertrial-preview group). Switch costs showed significant positive correlations (solid lines) with repetition rates in the execution-preview group ($r = .59$, $p < .001$) of Experiment 1 and in the extra-preview groups of Experiment 1 ($r = .52$, $p = .009$) and Experiment 2 ($r = .60$, $p = .002$). The corresponding correlation in the choice-preview group of Experiment 1 was not significant ($r = .08$, $p = .699$). Note that we conducted additional analyses without participants with switch costs higher than 400 ms: there was still a significant correlation in the execution-preview group ($r = .55$, $p = .007$) and the correlation in the choice-preview group was still small and not significant ($r = .21$, $p = .334$)

repetition rates in the extra-preview and execution-preview group was only accompanied by improvements in switch task performance in the extra-preview group, but not in the execution-preview group. However, a closer examination of the individually selected repetition rates as a function of switch costs revealed significant correlations between these measures with both extra-preview and execution-preview. This can be taken as a strong hint that participants incorporated their individual preview benefits in their task selection behavior. It should be also emphasized that the lacking preview benefit in the experimental task display blocks of the choice-preview group is reflected in a similar repetition rate in these blocks compared to the baseline task display blocks.

This combination of findings suggests that participants decide to switch tasks when they have processed the corresponding switch stimuli to a degree that is reflected in task performance. Thus, these findings provide evidence for our argumentation that the repetition bias can be explained by the availability heuristic due to attempts of our system to reduce perceived effort and/or the objective time costs. Interestingly, however, two findings speak against this interpretation of the repetition bias.

First and most strikingly, participants were not biased to switch tasks more often than chance despite the large observed performances advantages in switch compared to repetition trials in the extra-preview group. We argued that switch benefits indicate that task switches are now less effortful and less time-consuming. Thus, participants should be also biased to switch tasks more often than chance when having extra-preview if avoidance of effort and time costs explains the repetition bias. This was clearly not the case. To explain this result within the competing-heuristic account, one could argue that participants were able to selectively focus their attention on the switch stimuli on only a number of trials and/or shielded the influence of switch stimulus availability on the remaining trials. Thus, preview benefits did not have the predicted influence (i.e., initiate some stimulus processing) on every trial so that participants selected a task repetition (as the most active task set) when they selected tasks based on the availability heuristic on these trials. This suggests that additional components need to be considered within the competing heuristic to account for this result and we will turn back to this issue in "General discussion".

Second, switch costs were not present in the baseline task display conditions of the execution-preview and extra-preview group. Interestingly, participants were biased to repeat tasks more often than expected by chance, although there were no switch costs. According to the availability heuristic, one could argue that the last performed task is the most active task so that participants are biased to select this task even though this interfering activation does not result in observable switch costs.

Importantly, however, this suggests an alternative explanation which might at least partially account for reductions in the repetition rates in the execution-preview group and extra-preview group. It is conceivable that participants switched tasks more often simply because they were longer confronted with the corresponding (still visible) stimuli for the alternative task. For example, presenting these stimuli might just increase the salience of this task (Wickens, Gullwitzer, & Santamaria, 2015). Thus, exposition to alternative task stimuli might have an impact on task choice regardless of any switch stimulus processing, because in all baseline task display trials only the selected task was visible. Although this would be also in line with the availability heuristic, our view on the availability heuristic implies that observable performance improvements are critical to select tasks.

Experiment 2

The central goal of this experiment was to further specify the availability heuristic in terms of adaptive task selection behavior. Specifically, we compared task performance and task selection in the same experimental task display condition of the extra-preview group of the first experiment with a new baseline task display condition. In this baseline task display condition, the stimuli of the two tasks were also present during task choice, task execution and for additional time after task execution similar to the experimental task display blocks. The crucial difference to the experimental task display condition was that new task stimuli appeared for both tasks on the next trial and thus participants could not benefit from preview to prepare performance for the next stimulus (see Fig. 1). We again expected that switch costs are lower in the experimental compared to the baseline task display condition, because with the latter task display switch preparation can only occur at an abstract level—if at all. This allows us to check whether the reduction in repetition rates in the experimental task display blocks of the execution-preview and extra-preview groups of Experiment 1 was only due to the exposition of a discretionary switch stimulus that increases the availability of the corresponding switch task in general, but does not initiate some specific stimulus processing. In this case, repetition rates would be similar in the two task display conditions. If, however, the use of the availability heuristic at least partially reflects some kind of rational task selection behavior, then repetition rates should be reduced in the experimental compared to the baseline task display blocks. Note that this also implies that switch task performance is improved in the experimental task display blocks. Second, we aimed to replicate the results in the extra-preview group of the first experiment. That is, we expected that participants would even show performance advantages when switching tasks, but would not switch tasks more often than expected by chance. Further, we expected that individual performance advantages in switch compared to repetition trials again correlate positively with the amount of chosen switches in the experimental task display condition.

Method

A new sample of 24 participants (19 women) participated in the experiment. Their ages ranged from 18 to 29 years ($M = 20.8$) and 23 were right-handed.

The apparatus, stimuli, procedure and instructions were the same as in Experiment 1 except for the following changes. In the baseline blocks (see Fig. 1), the identity of the corresponding stimuli of the two tasks was visible during task choice, task execution and for a further 500 ms after the selected task was performed. In trial $n + 1$, however, new task stimuli were presented for both selected and non-selected tasks on trial n. In the experimental task display condition, the trial procedure was similar to the experimental task display condition of the extra-preview group in Experiment 1. Thus, the stimulus of the non-selected task on trial n was presented again on trial $n + 1$. Note, however, that the specific stimuli were selected randomly from the corresponding task stimuli pool if a new stimulus was required.

As in Experiment 1, reaction times (RTs), percentage errors (PEs) and repetition rates served as dependent variables. The independent variable was *task display* manipulated within participants (i.e., baseline vs. experimental). Thus, for the analysis of repetition rates, we conducted a paired *t* test between the two task display conditions. For PE and RT analyses, we additionally considered *task transition* (i.e., switch and repetition) and we thus conducted a 2 × 2 repeated measures ANOVA with the within-subject factors task display and transition.

Results

We followed the same data preparation procedure as in Experiment 1. For PE analyses, we excluded 3.4% post-error trials. For choice probabilities and RT analyses, 3.3% error trials and 2.1% trials that exceeded more than 3 standard deviations from the cell RT means of each condition were excluded.

Choice probability analyses

The overall probability of performing the subtraction task (.47) differed significantly from randomness, $t(23) = 4.09$, $p < .001$. There was, however, no difference between the baseline and experimental task display conditions in choosing this task, $p > .253$.

The mean repetition rate was .59. Overall, participants repeated tasks more often than expected by chance (.50), $t(23) = 2.88$, $p = .009$. The first row in Table 2 shows the repetition rates as a function of task display (i.e., baseline vs. experimental). A paired *t* test revealed that the repetition rate was reduced in the experimental compared to the baseline task display condition, $t(23) = 2.12$, $p = .045$. One-sample *t* tests against the chance level of .50 revealed that the repetition bias was substantial in the baseline task display blocks, $t(23) = 3.43$, $p = .002$, and marginal significant in the experimental task display blocks, $t(23) = 2.02$, $p = .055$. Thus, this suggests that there might be also a repetition bias in the experimental task display condition (if there is any deviation from chance). Obviously, the presence of a repetition bias would imply the absence of a switch bias.

RT analyses

Table 2 shows the mean switch RTs, the mean repetition RTs and the corresponding switch costs (i.e., switch RT − repetition RT) in the baseline and experimental task display blocks. An ANOVA including the factors of task display and transition yielded a significant main effect of task display, $F(1,23) = 6.82$, $p = .016$, $\eta^2 = .23$. Responses were slower in the baseline task display condition (1118 ms) compared to the experimental task display condition (1051 ms). The main effect of transition was not reliable, $p = .438$. Most important, the interaction between these factors was significant, $F(1,23) = 20.90$, $p < .001$, $\eta^2 = .48$. As can be seen in Table 2, there were switch costs of 43 ms in the baseline task display blocks, but switch benefits of 69 ms in the experimental task display blocks. Separate *t* tests revealed that the differences were significant in both the baseline, $t(23) = 2.46$, $p = .022$, and the experimental, $t(23) = 2.90$, $p = .008$, task display blocks.

Table 2 Mean overall reaction time (RT) in milliseconds (ms) and percentage error (PE) as a function of trial transition (i.e., task switch vs. task transition), mean switch costs (i.e., task switch RT − task repetition RT) and repetition probabilities in the baseline and experimental conditions of Experiment 2

Measure	Baseline	Experimental
Repetition rate	.61 (.03)	.56 (.03)
Switch costs in ms	43 (17)	−69 (24)
Task switch RT in ms	1139 (44)	1016 (38)
Task repetition RT in ms	1097 (38)	1086 (32)
Task switch PE	3.1 (.4)	3.3 (.5)
Task repetition PE	3.3 (.3)	3.6 (.5)

Standard error of the means in parentheses

PE analyses

Overall, accuracy was very high (96.7%) and an ANOVA parallel to that conducted on the RTs was also conducted on the PEs (see Table 2). This ANOVA revealed no significant effects, all *ps* > .312.

Comparison of repetition rates and switch costs

Figure 2d shows a scatter plot of the mean switch costs against the mean repetition rates in the experimental task display condition of each participant. As in the previous experiment, there was a significant correlation between these variables, $r = .60$, $p = .002$. The correlation between these variables in the baseline task display condition was small and not reliable, $r = .37$, $p = .073$.

Discussion

In this experiment, we investigated whether the reduced repetition rate in the experimental compared to the baseline task display condition of Experiment 1 can be alternatively explained by presenting a preview on a discretionary switch stimulus. The results provided evidence that only stimulus-specific preview resulted in performance improvement in switch trials and that these processing benefits were accompanied by reduced repetition rates. In addition, participants were again able to incorporate their individual preview benefits in their switching behavior as being indicated by a substantial correlation between switch costs and repetition rates across participants. As in Experiment 1, however, participants were not biased to switch tasks more often than chance as it would be expected if task selection via the availability heuristic functions to minimize time and/or effort. Thus, we suggest that also other factors seem to influence task selection in our setting.

General discussion

In the VTS paradigm, participants are required to randomly select tasks. A key finding is that participants fail to accomplish this and instead show a profound repetition bias (for a review see Arrington et al., 2014). Furthermore, task choice is influenced by bottom-up factors like stimulus availability and this is also in contrast to the instructed goal to randomly choose a task. These findings can be explained with the competing-heuristic account (Arrington & Logan, 2005) assuming that task choice is sometimes based on the availability heuristic when the top-down goal to select a task on the representativeness heuristic fails. The goal of the present study was to examine if the explanation of the repetition bias (and the incorporation of bottom-up factors) via the availability heuristic can be also seen as some rational adaptive behavior because participants balance the goals to minimize time and effort (i.e., avoid switching tasks) and the instruction to choose tasks randomly. We conducted two experiments in which we selectively provided participants with preview on stimuli for potential task switches and investigated if and how participants adapted their task selection behavior to reduced and even reversed switch costs. The main findings of these experiments were that (1) providing preview on specific task switch stimuli in advance of a trial reversed switch costs and led to a reduction of the repetition rate and (2) there were positive correlations between switch costs/benefits and repetition rates (i.e., with preview during a trial and with extra-preview in advance of a trial). Yet, (3) participants were not biased to switch tasks more often than is expected by chance despite large switch benefits due to preview in advance of a trial.

Thus, the former two findings are in line with the assumption that task selection in the VTS paradigm is at least partially driven by attempts to minimize time and/or effort in addition to fulfilling the instructed goal to choose task randomly. As was outlined in the introduction, this suggests that violations of the randomness instruction on task choice (i.e., repetition bias and environmental influences) in the VTS paradigm might reflect reasonable adaptive behavior to balance opposing goals. The competing-heuristic account seems suitable to depict these opposing demands in terms of the representativeness and availability heuristic. Our results, however, imply that selecting tasks based on the availability heuristic is not necessarily an indication of weak control, because this heuristic seems to reflect an important component of adaptive task selection behavior.

However, the lack of switch bias suggests that other factors have to be considered to explain the effects of preview within our setting. In general, we hypothesized that providing preview on switch stimuli would initiate some processing of the corresponding tasks. Thus, we reasoned that preview allows some kind of head start in stimulus processing and thus counteracts the strong availability of the last performed task that typically facilitates task repetition performance. Although the present results partially demonstrated the expected effect, it is important to emphasize that we assumed that stimuli automatically initiate task-related processing. However, reconfiguration processes to adopt a new task set are also involved in switching tasks (e.g., Meiran, 1996; Rogers & Monsell, 1995). For example, Meiran (2000) suggested that both stimulus set and response set need to be reconfigured to successfully switch tasks. Thereby, he suggested processes of (re-)weighting of stimulus and response processing for each task, such that a task is always more or less active. Given that the meaning of responses was similar for the two arithmetic tasks, there is probably no response-set reconfiguration necessary. Nevertheless, one might argue that participants need to reconfigure their stimulus set so that switch stimuli can be successfully processed. According to this line of reasoning, the intended effect of switch stimulus availability can only work if the stimulus set for the switch task is sufficiently active. When reconsidering the competing-heuristic account to explain task selection behavior in VTS, one might thus speculate that reconfiguration processes modulate the impact of bottom-up factors via the availability heuristic.

Consequently, the lack of switch bias despite reversed switch costs when having extra-preview time suggests that participants process the switch stimulus to a sufficiently strong degree only for a number of trials. Thus, we speculate that participants avoid the cognitive demand associated with reconfiguring the stimulus set that is needed to successfully process the switch stimulus on the majority of trials. Consequently, the default repetition mode of the cognitive system (Vandamme et al., 2010) cannot be overruled with switch stimulus availability on the remaining trials. However, it should be emphasized that the comparison of the reduced repetition rates in the task display blocks with extra-preview compared to the corresponding baseline task display blocks in the two experiments demonstrate that participants seem willing to apply additional effortful processes when task performance can be improved (i.e., they make use of preview when it is beneficial). We consequently suggest that even within this post hoc interpretation about the effects of preview, the expected task performance is an important component when selecting tasks. Nevertheless, it seems fair to imply that minimizing subjective-oriented effort cost might play a greater role in voluntary task switching than minimizing objective-oriented temporal costs.

In retrospect, the avoidance of cognitive demand in the use of preview might also explain why preview had no overall effect on task performance in the experimental task display blocks of the execution-preview group and in the choice-preview group. Specifically, one might argue that using preview in these conditions requires participants to work on these tasks in parallel. Yet, parallel processing can produce between-task interference. Consequently, effortful control processes are needed to overcome conflict between tasks, but these processes are avoided (e.g., Dignath et al., 2015). Thus, participants might even shield processing of the selected task (e.g., Fischer & Dreisbach, 2015) from potential interfering effects arising from switch stimuli what would reduce or eliminate any preview benefits.

Interestingly, an alternative model provides also plausible explanations for our results. Specifically, the chain-retrieval model (Vandierendonck, Demanet, Liefooghe, & Verbruggen, 2012) assumes that task selection is guided by task sequences retrieved from long-term memory, but with a preference for sequences with more repetitions because of the difficulty of switching tasks. Furthermore, this model suggests that bottom-up factors can override retrieval of a chunked task sequence. The reduced repetition rates in the corresponding extra-preview task display blocks compared to the baseline task display blocks might be explained by this model by assuming that either (a) the preference for sequences with more repetition is reduced because preview provides benefits in switching task (i.e., in terms of switch costs) or (b) switch stimulus availability more often overrides the task choice "predicted" by the task sequence and thus eliciting a task switch or (c) a combination of (a) and (b). Note that additional assumptions that were described within the discussion of the competing-heuristic account can also explain the lack of switch bias within this model. For example, preview could only have an effect on a number of trials due to selective application of control processes. Consequently, switch stimulus availability counteracts chunked task sequences not on every trial.

It should be emphasized that we only observed correlations between repetition rates and switch costs in the corresponding experimental task display blocks with preview, but not in the baseline task display blocks. Similarly, in many other studies the correlations between these measures were only weak (Mayr & Bell, 2006) or absent across participants (Yeung, 2010). This somehow suggests that individuals can only vaguely incorporate their switch costs in their task selection behavior, which is reflected in the typical repetition bias. Currently, we can only speculate why inducing potential switch benefits results in adaptive selection behavior. For example, one might conjecture that in usual VTS settings, switch costs do not vary sufficiently between participants to show strong correlation with repetition rates. Instead by enabling preview, the variation of switch costs increases because participants differ regarding their use of the preview (e.g., Tables 1, 2 indicate higher standard errors of switch costs in the experimental compared to the baseline task display condition).

Indeed, the scatter plots also revealed a considerable amount of individual variability in the use of preview across the execution and extra-preview groups. Recently, there has been a growing interest in the identification of individual characteristics when facing multiple task requirements (e.g., Janssen & Brumby, 2015; Reissland & Manzey, 2016; Umemoto & Holroyd, 2016). We suggest that the variability of the use of preview across participants in our study might further highlight the need to consider individual differences in preferences for serial vs. parallel processing (Brüning & Manzey, 2017; Reissland & Manzey, 2016). Interestingly, Reissland & Manzey (2016, Experiment 2) identified also groups of individuals which applied different sorts of task organization in a voluntary multitasking setting. Specifically, some participants (i.e., group of *blockers*) mainly repeated tasks, whereas two other groups of participants partially (i.e., group of *alternaters*) or often (i.e., group of *switchers*) switched tasks. Thus, individual preferences in task organization might also contribute to the observed repetition rates found in the present study. Indeed, there were strong positive and high correlations (i.e., all rs $> .71$; all ps $< .0001$) between the individual repetition rates of the experiment and baseline task display conditions, demonstrating some stable multitasking preferences within participants and across conditions. In future research, it would seem fruitful to further investigate the stability of the underlying individual strategies across different multitasking paradigms.

Conclusion

In the present study, we investigated if the repetition bias and the influence of bottom-up factors on task choice in VTS studies reflects reasonable adaptive task selection behavior due to minimizing temporal costs and subjective effort in addition to complying with the randomness instruction. We conducted two experiments in which we selectively improved task switch performance by providing preview on switch stimuli. In line with rational adaptive task selection behavior, an improvement of task performance in task switches when having extra-preview in advance of a trial was accompanied by a reduction in repetition rates. Despite large switch benefits, however, participants were not biased to switch tasks more often than expected by chance. This suggests that participants might avoid effortful control processes that modulate the effects of preview on task performance and task choice (e.g., selective use of preview). The VTS paradigm seems an ideal candidate to identify and investigate these processes in a controlled manner.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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

Informed consent Informed consent was obtained from all individual participants included in the study.

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