Dynamic cognitive flexibility: Influences of time and personality traits on voluntary task selection

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Abstract

Cognitive flexibility, or the ability to flexibly switch between different task sets, is often operationalized using performance on voluntary task switching (VTS) paradigms. In VTS paradigms, performance is commonly measured by examining reaction time, accuracy, the effects of switching tasks on reaction time and accuracy, and the rate at which participants choose to switch tasks. Previous literature has frequently examined these measures in terms of overall task averages. Instead, the current work examines whether these measures change during task performance, as well as the degree to which individual differences in these changes might inform individual differences in external measures. A series of three experiments, two of which utilized publicly available datasets from previous publications, examined changes in these measures throughout the performance of different VTS paradigms administered by different labs. In the first two experiments, significant group-level declines in switch rates were present, consistent with increased effort avoidance and early fatigue effects. In the third experiment, no such decline was present at a group level; however, subject-level changes in switch rates were related to scores on BIS/BAS subscales, while subject average switch rates were not. The current work suggests that examining changes in switch rates throughout a task might provide valuable information not captured by average switch rates that future VTS studies might wish to explore. Future work should attempt to clarify the conditions in which group-level declines in switch rate can be produced as well as which cognitive mechanisms might underlie these declines.

Keywords: cognitive flexibility; practice; fatigue; individual differences; effort avoidance

Public Significance Statement: While measures of cognitive flexibility are often examined as subject or group level averages, we find that there are robust changes over time. These declines appear to be due to effort avoidance or fatigue and can't be explained by practice effects.

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Dynamic cognitive flexibility: Influences of time, motivation, and personality traits on voluntary task selection across three independent studies

Cognitive flexibility, or the ability to adaptively switch between multiple activities or task sets, is often considered a core aspect of executive functioning (Miyake et al., 2000; Miyake & Friedman, 2012). In experimental settings, flexibility is often operationalized using task switching paradigms, whereby participants switch between simple tasks such as color or letter categorization. In a classical cued task switching paradigm, the task a participant performs depends upon a cue, such as a letter or symbol. The primary measures of interest in cued task switching are generally the difference in reaction time and/or accuracy between trials on which a participant switches tasks (switch trials) and trials on which a participant repeats tasks (repeat trials)—known as RT switch cost and accuracy switch cost, respectively (Koch, 2001; Monsell, 2003; Rogers & Monsell, 1995; Schmitz & Voss, 2014). More recently, voluntary task switching (VTS) paradigms, which allow participants to choose when and how frequently to switch between two possible tasks, have allowed for the possibility of analyzing task choice (measured as the percent of trials on which participants choose to switch tasks, or switch rate) as a measure of flexibility in addition to switch costs (Arrington & Logan, 2004, 2005; Mayr & Bell, 2006).

Despite the relative popularity of research examining VTS performance (see Arrington et al., 2014 for a review; Braem, 2017; Braun & Arrington, 2018; Fröber et al., 2019; Fröber & Dreisbach, 2017; Mittelstädt, Dignath, et al., 2018; Mittelstädt, Miller, et al., 2018), no work to date has focused on how measures of flexibility, such as switch cost and switch rate, might change throughout the course of a session. Instead, subject- or group-level averages of these measures are analyzed—the underlying assumption in these analyses is that that switch costs and switch rates either remain relatively constant throughout the task, or that any changes throughout the task are not meaningful enough to warrant examination. The current work aims to examine 1) which commonly analyzed behavioral measures change throughout performance of standard VTS paradigms, 2) to what degree these changes might

inform us about cognitive processes occurring throughout task performance, and 3) to what degree these changes might inform us about individual differences in participants.

While no previous work has examined changes in performance throughout a simple VTS paradigm, there is a rich body of work documenting the existence of behavioral changes as a result of practice, boredom, fatigue, and effort avoidance in comparable tasks (Benoit et al., 2019; Karayanidis et al., 2003; Khan et al., 2018; Kool et al., 2010; Kool & Botvinick, 2014; Lorist et al., 2000; Nieznański et al., 2020; Otto & Daw, 2019; Plukaard et al., 2015; Rogers & Monsell, 1995). Using this work, we can draw inferences about how each process might affect common behavioral measures in VTS and create sets of predictions about the effects of each process. Below, we outline work done to examine the effects of these four factors on behavioral performance and make predictions about how each might affect voluntary task selection.

Practice effects from accumulated experience performing a task are well-documented and have been reported in a variety of paradigms (Logan, 1992) including cued task switching (Karayanidis et al., 2003; Rogers & Monsell, 1995), as have reductions in accuracy switch cost (Rogers & Monsell, 1995). While manipulations of practice effects often involve multiple sessions, it is possible that experience performing a task during a single session might yield similar reductions in overall RT, RT switch cost, and/or accuracy switch cost throughout the task. Indeed, Koch and colleagues (2018) cite evidence for a reduction of RT switch cost with only a small amount of practice. To date, no studies have examined how practice might influence switch rate; as most VTS studies instruct participants to select tasks equally often and in a random order, one might predict that switch rates will be closer to 50% with practice. However, most studies document a strong repetition bias (Arrington & Logan, 2004, 2005; Mayr & Bell, 2006) suggesting that practice effects do not significantly impact task selection.

Second, an increase in boredom throughout the course of performing the task could affect task performance and task choice. Boredom is typically examined in vigilance tasks that require a participant to monitor for an infrequent target over long periods of time (Kurzban et al., 2013; Scerbo, 2001). However, a series of experiments on a more complex task switching paradigm examined the effects of

restricting available information on subjective feelings of boredom and task switching behavior. The study concluded that the restriction of available information resulted in greater subjective feelings of boredom which were correlated with more frequent task switching (Geana et al., 2016a)—the study has since spawned decision-making models that include the effect of boredom on task choice and exploration (Geana et al., 2016b; Wolff & Martarelli, 2020). While no work to date has examined possible effects of boredom induced through simple task performance (rather than an overt manipulation) on task choice, increases in switch rates during VTS paradigms might indicate an effect of boredom consistent with previous work.

Third, it is possible that participants begin to experience fatigue throughout performance of the task which might affect behavioral performance. However, the majority of work examining the effects of fatigue involve manipulations or periods of time that last much longer than a standard VTS paradigm—while standard VTS paradigms generally last between 20 and 30 minutes, the length of tasks in studies of cognitive fatigue effects are often on the order of hours (Ackerman & Kanfer, 2009; Lorist et al., 2000, 2005; Plukaard et al., 2015). In studies such as these, fatigue results in general decreases in performance; in cued task-switching studies, this has been observed as reductions in overall accuracy (Benoit et al., 2019; Lorist et al., 2000) as well as increases in overall RT and increases in RT switch cost (Plukaard et al., 2015). Therefore, one might predict that these same decrements of performance over time would be present in a VTS study if significant fatigue was present towards the end of the task. Notably, these predictions are in direct contrast with predictions regarding the effects of task experience.

Furthermore, a recent study found that fatigue manipulations lasting only 5 or 10 minutes resulted in an increase in accuracy switch cost on a cued task-switching paradigm (Nieżnański et al., 2020). Importantly, this change was interpreted as a compensatory mechanism engaged to combat larger performance decrements such as changes in overall RT and accuracy. The idea that such compensatory mechanisms might be invoked and obscure larger performance decrements is not new (Hockey, 2010; Robert & Hockey, 1997; Wang et al., 2016), although it has not been directly examined in VTS. However, the ability of a participant to choose tasks in a VTS paradigm allows for the reduction of

switching as a possible compensatory mechanism to combat early fatigue-induced performance decrements, as repeating tasks more often would allow for better overall performance. Therefore, we hypothesized that fatigue-induced compensatory behavior might be reflected in a reduction of switch rates over time. This prediction is in direct contrast to predictions about the effects of boredom on performance.

Finally, it is possible that as participants perform the task, they exert less effort during task performance. Prior work suggests that as more effort is exerted, the subjective cost of effort exertion increases (Baumeister, 2002; Baumeister et al., 1998; Kool & Botvinick, 2014). In other words, the effort exerted to perform the task causes a reduction in the desire to exert further effort as the task goes on. In the context of VTS, the well-documented bias towards repeating tasks (Arrington & Logan, 2004, 2005; Mayr & Bell, 2006) has been interpreted as an avoidance of effort (Mittelstädt, Dignath, et al., 2018). Therefore, one might expect an increase in effort avoidance as a participant performs the task, operationalized as a reduction in switch rates. While this prediction converges with predictions regarding compensatory mechanisms resulting from fatigue, prior work has suggested that effort avoidance can be offset by the presence of monetary reward (Kool et al., 2010); therefore, the sensitivity of any possible switch rate reductions to reward manipulations might help discern between overall effort avoidance and fatigue-induced compensatory behavior.

The current work examined changes in performance over time in three experiments, each involving different VTS paradigms across three independently collected datasets. The first experiment involved a large sample ($n = 100$) and was intended to test the competing predictions one might expect of each possible cognitive process to see which might occur during a standard VTS task (Imburgio & Orr, 2020). Improvements in RT, accuracy, RT switch cost, and accuracy switch cost would indicate significant practice effects, while decrements in these measures would indicate significant effects of fatigue. Increases in switch rate would indicate significant effects of boredom, while decreases in switch rate would indicate either compensatory behavior to combat fatigue-related decrements or a reduction in effort expenditure over time.

The second experiment involved a performance-contingent reward manipulation with varying magnitudes (Fröber et al., 2019). This experiment was intended to replicate the declines in switch rate and evidence of practice effects found in Experiment 1, as well as examine the effect of the performance-contingent reward manipulation on these effects. In particular, examining the effect of reward and motivation on switch rate reductions present in Experiment 1 was intended to rule out either fatigue-related compensatory behavior or effort avoidance as possible mechanisms underlying the reduction.

The third experiment was intended primarily to examine the effects of reward-induced motivation on the significant reduction in switch rate over time that was observed in both Experiment 1 and Experiment 2 (Braem, 2017b). Experiment 3 involved reward conditions that were originally meant to manipulate participants' average switch rates; here, the reward manipulation was used to test the effects of motivation on switch rate changes rather than overall average switch rates. Additionally, Experiment 3 included BIS/BAS scores for each participant, which allowed us to examine whether individual changes in switch rates over time could meaningfully inform individual differences in approach/avoidance behavior that prior work found to be related to sensitivity to effort exertion (Storbeck et al., 2015). Experiment 3 found additional evidence for practice effects, but no evidence for a decline in switch rates at a group level found in Experiments 1 and 2; however, individual differences in changes in switch rates over time were related to individual BIS and BAS Fun-Seeking (BAS-Fun) scores, suggesting that change in switch rate might be a valuable measure to examine even when no significant group-level change is present.

Experiment 1

Method

Participants

The sample consisted of 114 undergraduate students who completed the study for course credit. Participants who switched tasks on greater than 80% of trials or less than 20% of trials were removed from analyses ($n = 14$). The final sample of 100 had a mean age of 19.31 ($SD=1.52$) and included 60 females and 40 males. The same data from this sample was analyzed in a separate paper focused on the

effects of interval length manipulations (Imburgio & Orr, 2020). All study procedures were approved by the Texas A&M University Institutional Review Board.

Paradigm

Participants performed a modified version of a number Stroop task. Each trial was composed of a task choice phase followed by a task stimulus phase as depicted in Figure 1. In the task choice phase, participants were presented with a ‘?’ in the center of the screen. The ‘?’ indicated that participants were to choose which of two tasks to perform: a physical comparison or a numerical comparison. Participants indicated their task choice with a key press (either ‘d’ or ‘f’), with task choice mapping counterbalanced across participants. In line with classical voluntary task switching paradigm designs (Arrington & Logan, 2004), participants were instructed to choose tasks randomly. Participants were instructed that this meant they should choose each of the two tasks about equally often throughout the experiment. Participants were also instructed that they should repeat the same task as the previous trial and choose to switch to a new task about equally often. Finally, participants were told not to use a pattern to adhere to these guidelines, but to choose randomly as though they were flipping a coin in their head to decide on each trial. There was no time limit on task choices.

Figure 1. Depiction of paradigm in Experiment 1. RCI = task response-cue interval, CSI = task choice-stimulus interval

In the task stimulus phase, participants were presented with two numbers that differed in both numerical size and physical size, one number above the fixation cross and one below the fixation cross. If participants had indicated in the choice phase that they chose to perform a numerical comparison, they

were to choose the number that was numerically larger in the stimulus phase (ignoring the physical size of the numbers). If the participant had indicated in the choice phase that they chose to perform a physical comparison, they were to choose the number that was physically larger in the stimulus phase (ignoring the numerical value of the numbers). Participants indicated their response in the stimulus phase with a key press ('j' for the top number and 'n' for the bottom number).

The task response-cue interval (RCI) and task choice-stimulus interval (CSI) were either 100 and 1000ms. Each length was equally likely to occur, and the effects of these interval conditions are not analyzed here; these effects are analyzed in a separate manuscript (Imburgio & Orr, 2020). Congruent trials (numerically larger number is also physically larger) and incongruent trials were equally likely. The task consisted of 6 blocks of 65 trials each for a total of 390 trials per participant.

Prior to the full task, participants completed a practice version of the task, beginning with single task practice blocks, then a shortened version of the full task. If a participant failed to reach 60% accuracy on a given portion of practice, they were required to repeat that portion of practice until the accuracy criterion was reached. Participants were given feedback after the final practice phase that displayed their task accuracy, switch rate, and percent of trials where they chose each task. If participants switched tasks on less than 20% of trials or greater than 80% of trials, they were asked to repeat that portion of practice. Similarly, if participants chose one of the tasks more than 80% of the time, they had to repeat that portion of practice. Accuracies and RTs are presented along with demographic information in Table 1.

Analyses

All analyses were conducted in R version 4.0.0 (R Core Team, 2020). The first trial of each block (neither a switch trial nor a repeat trial) was removed from analyses. Trials following errors were also removed from analyses to account for post-error slowing. Trials with task RTs less than 200ms or greater than three standard deviations from the mean task RT were also removed. Normality of RT distribution was determined via visual inspection, as a Shapiro-Wilke test would be overpowered for the number of data points to detect inconsequential deviations from normality (Ghasemi & Zahediasl, 2012). Because

RTs were not normally distributed, they were log transformed for analyses; the transformation yielded an adequately normal distribution.

To test whether any of the measures of interest changed over time, we utilized Bayesian multilevel regressions via the ‘brms’ R package (Bürkner, 2017) using trial number as an independent variable. Convergence for all models was confirmed both by visually inspecting chains and by examination of $\hat{R}$ statistics (all $\hat{R}$ ’s ≤ 1.01). An effect was considered significant if the coefficient’s 95% credible interval (CI) did not contain zero. All coefficients are reported as standardized coefficients followed by 95% CI.

We first tested for changes in RT switch cost over time by testing an interaction between alternation and trial number on log-transformed RTs. Here, a significant interaction would indicate a change in RT switch cost over time (the difference between switch RT and repeat RT would change as a function of trial number). In this model, the subject-level main effects of alternation (repeat, switch) and trial number were also included. However, a subject-level interaction term was not included as it prevented model convergence and subject-level changes in RT switch cost were not central to the research questions in Experiment 1. Next, we tested for changes in overall RT over time using a regression model that included main effects for alternation and trial number, but not an interaction term, as group-level and subject-level IVs. Log-transformed RTs were again the DV in this model.

To examine changes in switch rate and accuracy over time, we used a logistic regression in which task choice or accuracy (switch/correct coded as 1 and repeat/incorrect coded as 0) was the DV. In models examining switch rate, trial number was a group- and subject-level IV. Here, a significant change over time in the probability of choosing to switch tasks would be indicated by a significant regression coefficient for the trial number. A positive coefficient would indicate that participants are more likely to switch tasks as the experiment progressed.

In models examining accuracy, the alternation was also included as a group- and subject-level IV. The model examining changes in accuracy switch cost included interactions between switching and trial number; a significant interaction would indicate a significant change in accuracy switch cost. To examine

changes in overall accuracy, a model including no interaction term, but main effects of both switch/repeat and trial number, was also generated.

Results

Changes in switch rate, overall RT, RT switch cost, overall accuracy, and accuracy switch cost throughout the task are depicted in Figure 2.

Figure 2. Group-level changes in switch rate (left), RT by switch condition (middle) and accuracy by switch condition (right). Main effects of trial number on switch rate and RT were significant; effect of trial number on accuracy was only significant within switch trials. Shaded areas represent 95% CI.

The interaction between alternation and trial number did not significantly predict RT at the group level ($\beta = -0.008 [-0.016, 0.002]$), indicating there was no group-level change in RT switch cost over time. When the interaction term was removed, the main effect of switching was significant ($\beta = 0.07 [0.06, 0.08]$), indicating the expected presence of a RT switch cost. Further, the main effect of trial number was significant ($\beta = -0.07 [-0.08, -0.06]$), indicating a significant reduction in overall RT throughout task. This effect was consistent with practice effects and inconsistent with fatigue effects.

Trial number also significantly predicted task choice ($\beta = -0.21 [-.29, -.14]$). Participants were less likely to switch tasks as trial number increased, indicating an overall decline in switch rate as the task progressed. This pattern was consistent with the predictions related to effort avoidance and fatigue-related compensatory mechanisms, but inconsistent with increases in boredom.

There was a significant interaction between trial number and alternation in predicting accuracy ($\beta = 0.13 [0.02, 0.24]$). This interaction was explored by centering trial number 1.5 standard deviations

above and below the mean, then comparing the effect of switching (accuracy switch cost) in each model to compare switch cost in early and late stages of the experiment. Accuracy switch cost was larger towards the beginning of the experiment ($\beta = -0.60 [-0.82, -0.39]$); towards the end of the experiment, the effect was reduced to non-significance ($\beta = -0.21 [-0.43, 0.02]$). In the model with no interaction term, the expected accuracy switch cost was present ($\beta = -0.41 [-.57, -.26]$). However, overall accuracy did not change significantly throughout the task ($\beta = 0.02 [-.04, .08]$). The overall improvements in accuracy switch cost over time were consistent with practice effects.

Discussion

In Experiment 1, we identified several changes that occurred throughout performance of the task. Reductions in overall RT and accuracy switch cost were consistent with the effects of practice and inconsistent with fatigue-related performance deficits. Reductions in switch rate over time were inconsistent with increases in boredom but consistent with both reductions in effort expenditure and compensatory changes resulting from fatigue.

The reduction in overall RT, consistent with practice effects, was somewhat unsurprising—as most studies that found eventual increases in RT as a result of fatigue involve much longer manipulations, practice-induced improvements seemed more likely intuitively. However, the fact that RT switch cost did not improve even though overall RT did suggest that the practice effects seemed to work at a general level of task performance rather than at a higher level of cognitive control; in other words, participants got better at both the numerical and physical comparisons, but not necessarily better at set shifting more generally.

Given this pattern, though, the results that accuracy switch cost improved but overall switch cost did not was surprising. However, an examination of the effect revealed that accuracy was selectively improved over time for switch trials, but not repeats. This pattern does align with the general idea of performance increases as a result of practice if accuracy was near ceiling for repeat trials—as the mean accuracy for repeats was very high ($M = 95.30\%$), this seems like a likely explanation.

While the large sample in Experiment 1 was well-suited to detect changes in switch rates or switch costs over time, there was no manipulation meant to examine the mechanism underlying the change in switch rate that was detected—reductions in effort expenditure and compensatory changes to protect fatigue-related declines are both possible.

Further, it is not possible from the results of Experiment 1 alone to rule out the influence of task-specific factors in producing the decline in switch rate rather than a more general process such as fatigue or effort avoidance that would occur in other voluntary task switching paradigms. For example, while the number Stroop has been used previously in task switching literature (Orr et al., 2012, 2019; Orr & Banich, 2014; Petruo et al., 2019), it introduces more conflict than other task switching paradigms due to stimulus congruency effects and the use of bivalent stimuli; the resulting demands on cognitive load might affect the rate of fatigue or the rate at which effort expenditure is reduced. Therefore, generalizing the results of Experiment 1 to a different voluntary task switching paradigm which did not include these additional sources of conflict would be fruitful in helping to rule out the possibility of task-specific factors as an underlying cause of switch rate declines.

Experiment 2

In Experiment 2, we analyzed a publicly available dataset originally examined in a 2019 manuscript (Fröber et al., 2019, Experiment 1). Participants in Experiment 2 first performed a standard double-registrant voluntary task switching paradigm. However, unlike in Experiment 1, participants then performed the same task with performance-contingent rewards.

Importantly, the dataset provided an opportunity to replicate the results of Experiment 1 in a different, commonly used version of a double registrant voluntary task switching paradigm; Experiment 2 utilizes a letter-digit classification rather than a number Stroop and univalent rather than bivalent stimuli. Therefore, Experiment 2 partially served to replicate the results of Experiment 1 in a smaller sample from a separate population using a slightly altered task.

Experiment 2 also served to help rule out either effort avoidance or fatigue. Because previous work has suggested that effort avoidance can be mitigated by monetary reward (Kool & Botvinick, 2014),

we hypothesized a reduction or elimination of switch rate decline would support the idea that the decline was related to effort avoidance. If the rate of decline was unaffected by reward, the decline was more likely a fatigue-induced compensatory mechanism.

Method

Experiment 2 consisted of 30 participants from the University of Regensburg who participated for course credit and an opportunity to win an Amazon gift card based on points earned during the ‘reward’ portion of the experiment. All steps for data preprocessing in the current analyses, as well as criteria for participant exclusion based on performance, were consistent with the original publication in which these data were reported (Fröber et al., 2019), resulting in the exclusion of two participants on the basis of excessively low voluntary switch rates. As a result, the final analyses included 28 participants.

Paradigm

Participants performed a double-registration voluntary task switching paradigm in which, as in Experiment 1, each trial consisted of a task choice phase followed by a task stimulus phase. However, unlike in Experiment 1, the participants chose to respond to either the size of a number (smaller or larger than 153) or whether a letter was nearer to A or nearer to Z in the alphabet.

During the task choice phase, participants were prompted to choose whether to perform the number task or the letter task. Participants indicated their response using a key press of the right hand with the mapping of key to task counterbalanced across participants. Stimuli presented on the left and right of the screen indicated which key was mapped to which task during the task choice phase. There was no time limit on task choice. As in Experiment 1, participants were instructed to respond randomly such that they chose each task about equally often and that they chose to repeat and switch tasks equally often. Participants were additionally instructed to respond quickly and accurately, again in line with the instructions in Experiment 1. During the task response phase, participants were presented either a number or a letter, depending on their task choice—unlike in Experiment 1, task stimuli were therefore not bivalent. Participants indicated their response to the task stimulus using a key press of the right hand using separate keys from the task choice response. There was no time limit on task stimulus responses.

Participants began the experiment with two single-task practice blocks of 16 trials followed by a voluntary choice practice block of 16 trials—these blocks are not analyzed here nor in the original publication. Following the practice blocks, the ‘baseline’ portion of the experiment was presented. The baseline portion consisted of 174 trials in which no reward was presented for any trials. Reaction times during the baseline portion of the experiment were used to determine subject-specific reward thresholds in the subsequent ‘reward’ portion of the experiment, these calculations are detailed by the authors in the original publication (Fröber et al., 2019).

The reward portion consisted of 352 trials. In the reward portion, a reward cue was presented 500ms prior to the task choice phase of each trial and remained on the screen during the task choice phase. Following correct responses, participants were informed of how many points they had earned on the current trial during a feedback phase. Following incorrect responses, participants were informed during the feedback phase that they did not earn any points. Reward cues consisted of one of four shapes and one of two line-widths. Line width of the shape indicated the magnitude of reward (low or high); the shape itself did not inform reward magnitude but was used to avoid repeats of reward cues in successive trials. Low reward and high reward trials were equally likely. Further, while low reward was only contingent upon correct responses, high reward was also contingent on individually calibrated speed of response (please refer to the original publication for details about how reaction time criteria were calculated). While the magnitude of reward and trial-level transitions between low and high reward were not of interest in the current analyses, they were the primary conditions of interest in the original analyses by Fröber and colleagues (Fröber et al., 2019). For the current analyses, the distinction between reward presence in the reward portion and reward absence in the baseline portion was instead the condition of interest.

Analyses

As noted above, data preprocessing steps for the current analyses matched the preprocessing steps described in the original publication. Two subjects were eliminated from analyses entirely on the basis of excessively low (less than 5%) switch rates during the reward phase. Trials with reaction times greater

than 3 standard deviations from the mean were considered outliers and removed from analyses, as were incorrect trials, trials following errors, and the first trial of each block.

In general, analyses in Experiment 2 matched those conducted in Experiment 1 with the new inclusion of interaction terms involving the presence or lack of reward. All reported regressions are Bayesian multilevel regressions computed via the 'brms' R package (Bürkner, 2017). Convergence for all models was confirmed both by visually inspecting chains and by examination of $\hat{R}$ statistics (all $\hat{R}$'s $\leq$ 1.01). An effect was considered significant if the coefficient's 95% credible interval (CI) did not contain zero. All coefficients are reported as standardized coefficients followed by 95% CI.

As in Experiment 1, changes in switch rates throughout the experiment were assessed using mixed Bayesian logistic regressions for which the DV was task choice (switch was coded as 1, repeat as 0); group- and subject-level IVs in this model were trial number and task phase (baseline vs. reward) as well as the interaction between task phase and trial number. The interaction in this model was intended to assess whether the presence of reward might influence changes in switch rates over time. If the interaction was not significant, we planned to remove it from the model and assess the main effects, comparing the magnitude of switch rate change in Experiment 1 to the magnitude of the same change in Experiment 2 using credible intervals of the regression coefficients.

To examine changes in reaction times and RT switch cost over time, we conducted mixed Bayesian regressions in which log transformed RTs were the DV and trial number, alternation, and task phase (baseline vs. reward) were group- and subject-level IVs, along with all interaction terms between the three IVs. Following inspection of the three-way interaction in the full model to assess possible effects of reward condition on changes in RT switch cost over time, WE removed the three-way interaction terms and assessed the remaining two-way interactions to test for changes in switch cost over time, reward-modulated changes in overall RT over time, and changes in overall RT switch cost. Finally, we examined a model containing only main effects to examine whether overall reductions in RT over time found in Experiment 1 were replicated in Experiment 2, controlling for effects of reward and switching on RT.

Finally, to examine accuracy-related changes, we conducted logistic regressions in which accuracy on each trial was coded as 1 (correct) or 0 (incorrect). We first examined a regression including all three IVs (alternation, trial number, and reward presence) and all possible interaction terms to test whether there were reward-modulated changes over time in accuracy switch cost. As in RT-related models, a model including all three two-way interactions was tested but no three-way interactions was then tested, followed by a model including only main effects.

Results

Changes in switch rate, overall RT, RT switch cost, overall accuracy, and accuracy switch cost throughout the task are depicted in Figure 3. The effects of introducing reward on overall RT, overall accuracy, and switch rate are depicted in Figure 4.

Figure 3. Group-level changes in switch rate (left), RT by switch condition (middle) and accuracy by switch condition (right). Main effects of trial number on switch rate and RT were significant. Shaded areas represent 95% CI.

There was no interaction between trial number and reward presence in predicting task choice ($\beta = -0.04 [-0.33, 0.24]$), indicating that any changes in switch rates over time were not influenced by the presence of performance-contingent rewards. Because the null effect of reward on switch rate decline was crucial to ruling out effort expenditure as a mechanism of action, we conducted a follow-up test to quantify support for the null by calculating a Bayes Factor for the interaction coefficient (Lee & Wagenmakers, 2014). There was strong support for the model without the interaction term compared to the model with the interaction term ($BF = 23.88$), suggesting that there was indeed no effect of the reward manipulation on changes in switch rates over time.

When the interaction term was removed from the model predicting task choice, the main effect of trial number was significant; replicating the results from Experiment 1, participants chose to switch less often as the experiment progressed ($\beta = -0.11 [-0.20, -0.03]$). There was no main effect of reward presence, indicating no effect of reward presence on overall switch rates ($\beta = 0.36 [-0.22, 0.93]$).

In the model predicting RT, the three-way interaction between trial number, alternation, and reward presence was not significant ($\beta = 0.00 [-0.02, 0.02]$). When the three-way interaction term was removed, two-way interactions between trial number and alternation ($\beta = -0.003 [-0.008, 0.003]$), trial number and reward presence ($\beta = -0.017 [-0.001, 0.033]$), and alternation and reward presence ($\beta = -0.01 [-0.04, 0.03]$) were all nonsignificant. When all interaction terms were removed, all three main effects were significant; RTs were longer for switch trials than repeat trials ($\beta = 0.015 [0.008, 0.022]$), unexpectedly slower when rewards were present than when they were not ($\beta = 0.47 [0.39, 0.55]$), and decreased throughout the experiment ($\beta = -0.01 [-0.02, -0.005]$).

The three-way interaction between trial number, alternation, and reward presence did not significantly predict accuracy ($\beta = -0.10 [-1.07, 0.85]$). Removing the three-way interaction revealed no significant two-way interactions (trial number x switch/repeat: $\beta = 0.00 [-0.19, 0.19]$; trial number x reward: $\beta = 0.41 [-0.07, 1.00]$, switch/repeat x reward: $\beta = 0.07 [-1.02, 1.03]$). A model including only main effects revealed no main effect of trial number ($\beta = 0.11 [-0.04, 0.25]$) or switching ($\beta = -0.13 [-0.30, 0.05]$) on accuracy rates. However, accuracy was unexpectedly worse during the rewarded phase than the unrewarded phase ($\beta = -1.17 [-1.91, -0.22]$). Combined with the slowing of RT for the rewarded vs. the unrewarded phase, there is no support for a speed-accuracy trade-off.

Figure 4. Group-level effects of reward phase on switch rate (left), RT (middle) and accuracy (right). Reaction times and accuracies were unexpectedly worse following the introduction of reward. Error bars represent 95% CI.

Discussion

As in Experiment 1, there was a significant reduction in overall RT as the task progressed, consistent with practice effects. Also consistent with Experiment 1, there was a significant decline in the rate of task switches as the experiment progressed. This decline was not affected by the introduction of a performance contingent reward, consistent with compensatory behavioral changes resulting from fatigue rather than effort avoidance. However, there were also unexpected performance decrements in overall RT and accuracy when performance-contingent reward was introduced compared to the initial non-rewarded phase of the experiment¹; therefore, this performance decrement is also inconsistent with practice effects.

¹ Fröber & Dreisbach (2019) did not analyze data from the non-rewarded phase of the experiment as it wasn't relevant to their aims.

The results of Experiment 2 indicate that declines in switch rate over time are 1) replicable, 2) detectable in a small sample ($n = 28$) and 3) robust across fairly different voluntary task switching paradigms. There were a number of notable differences between the two paradigms; most notably, Experiment 1 involved conflict-induced cognitive load due to the possibility of incongruent number Stroop stimuli and bivalent stimuli while Experiment 2 used univalent stimuli with no incongruent condition. Therefore, the presence of a switch rate decline seems robust to different variations of double-registrant voluntary task switching paradigms.

The fact that introducing a performance-contingent reward did not influence this decline in switch rate suggests that they might not be due to declines in effort over time; presumably, the reward would help sustain motivation throughout the task, particularly because the rewards were linked to the possibility of winning an Amazon gift card, and such rewards have previously been found to offset effort reductions due to previous effort exerted (Kool et al., 2010). However, the introduction of reward seemed to harm, rather than facilitate, performance in terms of both overall reaction time and accuracy. It's possible that these effects are a result of fatigue, as the rewarded phase always occurred second; therefore, the presence of reward was confounded with time spent performing the task (the authors of the original experiment did not intend to examine fatigue effects or differences across rewarded and non-rewarded conditions). However, the main effect of trial number revealed a reduction in RT over time while controlling for rewarded vs. nonrewarded phase, which is inconsistent with fatigue.

In any case, the decrements in performance during the reward phase suggest that it is possible that the reward manipulation was not sufficient to motivate performance in participants. Crucially, previous work that has found effort avoidance to be modulated by reward is generally built upon the idea that increasing the benefit of exerting effort (i.e., increasing motivation to perform well) offsets the otherwise present effort avoidance (Kool et al., 2010; Kool & Botvinick, 2014; Otto & Daw, 2019). If the monetary reward in Experiment 2 was not sufficient to motivate participants, the lack of effects on reward on switch rate decline in Experiment 2 should not be considered sufficient evidence to rule out effort avoidance as an underlying mechanism.

Another possible confound is the fact that reward in Experiment 2 was tied to performance in terms of accuracy and RT, but not to task choice. While accuracy and RT criteria for reward were calibrated to participant switch and repeat trials individually, this information was not made known to participants. Therefore, it is possible that introducing the reward might have actually encouraged repeating tasks independent of fatigue or effort avoidance; instead, participants might have been motivated to repeat more often because it is easier to respond quickly and accurately on repeat trials than switch trials.

Experiment 3

Experiment 3, which includes publicly available data originally reported by Braem (2017) aims to address these limitations. In contrast to Experiment 2, the original analysis by Braem compared rewarded and non-rewarded conditions and found expected effects of reward; therefore, it is likely that reward in Experiment 3 did sufficiently motivate participants. Further, reward in Experiment 3 was tied to task choice rather than task response, with some participants being conditioned to switch more often and some being conditioned to switch less often. The original publication reported an effect of reward condition on mean switch rates; however, if participants who are conditioned to switch more (i.e., motivated by reward to switch tasks) also decline *less* in switch rate (or even increase), the decline (increase) is likely not related to fatigue, but due to effort considerations. Additionally, rewarded trials in Experiment 3 were intermittent throughout the task rather than only in the second half; therefore, unlike Experiment 2, trial number and reward presence were not confounded in Experiment 3.

Further, Experiment 3 included BIS/BAS scores for each participant. This allowed for the examination of individual differences in switch rate changes in relation to approach/avoidance behavior; examining the relationship between effort avoidance and BIS/BAS scores was specifically mentioned as a suggestion for future work in the seminal 2010 manuscript on effort avoidance due to previous effort exertion by Kool and colleagues (2010). Since then, higher scores on the BIS subscale have been linked to greater aversion towards cognitive effort exertion (Storbeck et al., 2015). Therefore, if declines in switch rate are related to increased aversion to effort expenditure *due to* previous effort exertion, one

might expect steeper declines in those scoring higher on the BIS subscale. Therefore, Experiment 3 examined correlations between subject-level switch rate changes and BIS/BAS subscale scores. Importantly, we also examined relationships between subject-level average switch rates and BIS/BAS scores to determine if any relationships were indeed related only to the change in switch rate rather than an overall task choice tendency.

Method

Participants

Experiment 3, conducted at Ghent University, consisted of 49 participants who participated for monetary compensation (10 € as well as a chance to win a 50 € gift card based on performance during ‘reward’ trials). As in Experiment 2, data preprocessing and exclusion criteria were identical to the original publication (in this case, preprocessed data was openly available on Open Science Framework (Braem, 2017a). Eleven participants were excluded by the authors because of excessively low voluntary switch rates. As a result, the final analyses included 38 participants. Details about sample size determination can be found in the original publication (Braem, 2017b).

Paradigm

Each participant performed twelve practice trials of the task followed by 4 blocks of the full task, each block consisting of 80 trials. The first half (40 trials) of each block consisted of cued choice trials, while the second half of each block consisted of voluntary choice trials.

During the cued trials, participants were first presented with a task cue phase followed by a task stimulus phase. During the task cue phase of cued trials, participants were presented with one of ten possible letters; whether the letter was a vowel/consonant indicated which of the two possible tasks they were to perform (animacy or size, with the cue-to-task mapping counterbalanced across participants). The cue remained on the screen for 1000ms. During the task stimulus phase, subjects were presented with one of 320 possible Dutch words to respond to using a key press (response-button mappings were counterbalanced across participants); the dimension of the word they were to respond to depended on which of the two tasks was indicated during the cue phase. The two possible tasks were ‘animacy’, where

subjects responded to indicate whether the word described something that was animate, or ‘size’, where subjects were to indicate whether or not the word described something that was smaller or larger than a basketball. Subjects had up to 5000ms to respond to the task stimulus. During cued trials, each task was equally probable, as were task switch and task repeat trials. Details about stimulus/cue randomization and counterbalancing, as well as more specific descriptions of task timings, can be found in the original publication (Braem, 2017b) and were not central to analyses here.

Cued trials also included reward. After a correct task response, subjects were presented with a screen that indicated they had earned either a high reward (‘+10’) or a low reward (‘+01’) for that trial. After incorrect responses, subjects presented with the Dutch word for ‘false’ (“FOUT!”) and earned no points for that trial. Subjects were told that they if they earned the most points of any participant during the cued trials, they would win the 50 € gift card.

Unbeknownst to the subjects, the probability of a low or high reward for correct trials depended upon whether the trial was a task switch or task repeat. For participants in the ‘switch reward’ condition ($n = 19$), correct responses on switch trials had an 80% chance to yield high reward and a 20% chance to yield low reward, while the probabilities were reversed on repeat trials. For participants in the ‘repeat reward’ condition ($n = 19$), there was an 80% chance of high reward (and 20% chance of low reward) on repeats and the probabilities were reversed for switch trials. Participants were told that the number of points won on each correct response was random rather than tied to switch or repeat trials.

On voluntary trials, participants were presented with a ‘#’ sign rather than a letter during the task cue portion of each trial, indicating they could respond to either the animacy or size of the word. Unlike Experiments 1 and 2, participants did not have to press a button to indicate which they had chosen. The task stimulus phase was the same on voluntary trials as it was on cued trials. Participants were instructed to choose tasks randomly using similar instructions as in Experiments 1 and 2 (each task should be chosen equally often, and they should choose to repeat and switch tasks equally often). As there was no reward on voluntary trials, they included no feedback; however, participants were told that accurate responses

and an honest attempt to choose tasks randomly on voluntary trials were required for their eligibility in winning the 50€ gift card.

Questionnaires

All participants completed the BIS/BAS scale (Carver & White, 1994), intended to measure disposition towards rewarding and aversive stimuli. The BIS/BAS scale consists of four subscales: BIS, BAS Reward Responsiveness (BAS-Reward), BAS Fun-Seeking (BAS-Fun), and BAS Drive (BAS-Drive).

Analyses

Data obtained from Open Science Framework (Foster, MSLS & Deardorff, MLIS, 2017) for Experiment 3 was preprocessed and had already included participant exclusion markers, RT outlier removal, and removal of trials following errors. Therefore, exclusion criteria for the current analyses matched the preprocessing from the original publication exactly; preprocessing steps were similar to preprocessing steps from Experiments 1 and 2.

The majority of analyses in Experiment 3 mirrored those in Experiments 1 and 2. Changes in RT switch cost, accuracy switch cost, overall RT, overall accuracy, and switch rate over time were analyzed identically to previous analyses using Bayesian mixed regressions using the brms package (Bürkner, 2017) in R version 4.0.0 (R Core Team, 2020)—RTs were again log-transformed and both accuracy and switch rate were again assessed using logistic regressions. However, regressions in Experiment 3 included reward condition as an additional IV, along with interactions between reward condition and all other IVs in all other regressions. Because all participants were in only one of the two possible reward conditions, reward condition was included as only a group-level IV (and not as a subject-level IV) in all regression models. As in the previous experiments, nonsignificant interaction terms were removed from models and main effects were assessed in models that contained no interaction terms. Convergence for all models was confirmed both by visually inspecting chains and by examination of $\hat{R}$ statistics (all $\hat{R}$'s ≤ 1.01). An effect was considered significant if the coefficient's 95% credible interval (CI) did not contain zero. All coefficients are reported as standardized coefficients followed by 95% CI.

Only voluntary trials were analyzed because our main interests were related to changes in behavior during voluntary task switching; in particular, changes in task choice/switch rate over time were the most salient finding from Experiments 1 and 2, and cued trials do not contain a task choice component. Further, the presence of reward on cued trials and lack of reward on voluntary trials would have complicated interpretations of any differences across the trial types for other DVs of interest.

Because our hypotheses related to BIS/BAS scores were motivated specifically by exploration of the mechanism underlying the decreases in switch rate found in Experiments 1 and 2, analyses involving BIS/BAS were restricted only to relationships between BIS/BAS scores and switch rates. Our primary hypothesis here was that high BIS scores—which indicate greater aversion towards negative stimuli and have been linked specifically to greater aversion towards cognitively demanding tasks (Storbeck et al., 2015)—would be related to greater declines in switch rate. To this end, we extracted subject-level trial number coefficients from the regression predicting task choice, which represent subject-level changes in switch rate (more negative coefficients meant greater decline in switch rate over time) and assessed correlations between these subject-level coefficients and subscales of the BIS/BAS.

The normality of the distributions of BIS/BAS subscale scores and subject-level coefficients was assessed using a Shapiro-Wilke test and visual inspection of quantile plots. While subject-level switch rate change coefficients were normally distributed, the distributions of BIS, BAS-Reward, and BAS-Drive scores were significantly different from normally distributed (all p 's $\leq .01$); therefore, Spearman ranked correlations were used to assess relationships between these three subscales and the subject-level switch rate change coefficients rather than Pearson correlations that assume normality. The distribution of BAS-Fun was close to significantly different from a normal distribution ($p = .058$) and a visual inspection of the distribution indicated that it appeared bimodal, therefore, a Spearman rank-based correlation was used here as well to avoid violating the parametric assumptions of a Pearson correlation.

Results

Changes in switch rate, overall RT, RT switch cost, overall accuracy, and accuracy switch cost throughout the task are depicted in Figure 5. Relationships between BIS and BAS-Fun subscales and task choice-related measures are depicted in Figure 6.

There was no significant interaction between reward condition and trial number in predicting task choice ($\beta = -0.02 [-0.18, 0.13]$); Bayes factors indicated support for the model without the interaction term compared to the model with the interaction term ($BF = 5.65$). These results indicate that there was no effect of reward condition on changes in task choice over time.

When the interaction term was removed, there was a main effect of reward condition ($\beta = 0.47 [0.12, 0.83]$); replicating the original studies' findings, participants who received higher rewards on switch trials during cued trials were more likely to choose to switch tasks than participants who received higher rewards on repeat trials. In contrast to experiments 1 and 2, there was no effect of trial number on task choice ($\beta = -0.02 [-0.10, 0.05]$), indicating no significant changes in switch rate over time. Follow-up Bayesian analyses indicated support for the null; there was strong support for a model containing no group effect of trial number compared to a model with the group effect ($BF = 8.04$). Therefore, it was very likely that there was no change in switch rates over time at a group level in experiment 3.

Figure 5. Group-level changes in switch rate by reward condition(left), RT by switch condition (middle) and accuracy by switch condition (right). Reward condition, but not trial number, significantly affected switch rate. Overall RT, RT switch cost, and overall accuracy improved over time. Shaded areas represent 95% CI.

In predicting RT, the three-way interaction (reward condition x alternation x trial number) was not significant ($\beta = 0.00 [-0.05, 0.05]$). In a model with no three-way interaction term, the interaction

between trial number and alternation was significant ($\beta = -0.025 [-0.046, -0.004]$), indicating that RT switch cost (the difference between switch RT and repeat RT) changed significantly throughout the experiment. To explore the interaction, trial number was centered at 1.5 SDs above and below its mean to quantify RT switch cost (the switch/repeat coefficient in this model) early in the experiment and later in the experiment. RT switch cost was larger earlier in the experiment ($\beta = 0.10 [0.06, 0.14]$) compared to later in the experiment ($\beta = 0.03 [-0.01, 0.06]$), consistent with practice effects. No other two-way interactions were significant (reward condition x alternation $\beta = -0.03 [-0.08, 0.01]$; reward condition x trial number $\beta = 0.01 [-0.02, 0.04]$).

In a model predicting RT with no interaction terms, there was a significant main effect of trial number ($\beta = -0.05 [-0.06, -0.03]$); in line with results from experiments 1 and 2, overall RT decreased throughout the experiment. The effect of alternation on RT was also significant ($\beta = 0.06 [0.04, 0.09]$), indicating that the expected RT switch cost was present throughout the experiment on average. There was no main effect of reward condition on RT, $\beta = 0.10 [-0.03, 0.22]$.

There was no significant three-way interaction (reward condition x alternation x trial number) in the model predicting accuracy ($\beta = 0.32 [-0.41, 1.08]$).). When the three-way interaction term was removed, there were no significant two-way interactions (reward condition x alternation $\beta = 0.07 [-0.61, 0.72]$); reward condition x trial number $\beta = -0.02 [-0.35, 0.31]$; alternation x trial number $\beta = 0.04 [-0.36, 0.43]$). When all interaction terms were removed, there was a significant effect of trial number on accuracy such that accuracy increased over time ($\beta = 0.36 [0.19, 0.52]$); the main effects of alternation ($\beta = 0.01 [-0.35, 0.40]$) and reward condition ($\beta = -0.26 [-0.96, 0.43]$) were not significant.

Figure 6. Relationships between changes in switch rates, average switch rates, and BIS/BAS-Fun scores. While trend lines shown here represent parametric linear model estimates, relationships were tested using spearman rank-correlations (which cannot be depicted) which better account for outliers, leverage points and non-normality. Hence, the trend lines shown here are purely for visualization purposes and do not represent the method by which relationships were tested. Relationships between BIS/BAS-Fun scores and changes in switch rates were significant while relationships involving average switch rates were not.

There was a significant relationship in the predicted direction between BIS scores and subject-level changes in switch rate over time ($\rho = -.48, p = .002$); participants that scored higher on the BIS subscale tended to switch tasks less often as the experiment progressed. There was a significant relationship in the opposite direction between and subject-level changes in switch rate over time and BAS-Fun ($\rho = .37, p = .02$); subjects scoring higher on the fun-seeking subscale tended to switch tasks more often as the experiment progressed. There was no relationship between changes in switch rate and the other two subscales (BAS-Drive: $\rho = -.12, p = .49$; BAS-Reward: $\rho = .09, p = .59$). None of the subscales were significantly correlated with individual mean switch rates (all p 's $> .46$), indicating that BIS and BAS-Fun scores were related specifically to changes in switch rates over time rather than the tendency of a participant to switch tasks on average.

Discussion

Experiment 3 aimed to replicate overall patterns in Experiments 1 and 2 regarding changes in task choice, RT, and accuracy measures over time, as well as test the effect of reward manipulations related to task choice rather than task performance on changes in switch rate. Consistent with the results from Experiment 2, there was no effect of reward on changes in switch rate over time despite replicating the original authors' findings that reward condition significantly affected overall switch rates. However, unlike in Experiments 1 and 2, switch rates did not change over time at a group level in Experiment 3.

Also consistent with previous experiments, overall RT decreased over time; in line with results of Experiment 1, overall accuracy also improved throughout the task. Unique to Experiment 3 here, but consistent with previous work in cued task switching (Koch et al., 2018), RT switch cost decreased throughout the experiment. There was no effect of reward condition on any RT- or accuracy-related measures. Finally, consistent with predictions, higher BIS scores were associated with greater declines in switch rate throughout the task. Higher BAS fun-seeking scores, in contrast, predicted greater increases in

switch rates throughout the task. These patterns were not present when examining subject-level switch rate averages.

The null effect of reward condition on changes in switch rates throughout the experiment provide further support for ruling out reduced effort exertion as a result of previous effort exertion as an underlying mechanism in the switch rate declines present in Experiments 1 and 2. However, this interpretation is complicated by the unexpected lack of overall switch rate decline present in Experiment 3. It is possible that switch rates did not decline in Experiment 3 due to differences in the task itself; for example, while Experiments 1 and 2 found changes in switch rates throughout the continuous performance of voluntary task switching, Experiment 3 involved intermittent cued blocks rather than continuous voluntary choices. Additionally, Experiment 3 included far fewer voluntary choice trials than the two previous experiments-while Experiment 1 included 390 voluntary trials and Experiment 2 included 526, only 160 of the 320 total trials in Experiment 3 were voluntary choice trials. It is possible that with more voluntary trials, a decline in switch rate would be present in a paradigm like the one used in Experiment 3.

Although there was no group-level change in switch rate throughout Experiment 3, results indicate that individual changes in switch rates might provide additionally valuable information about individual differences in behavioral approach and avoidance tendencies. As expected, participants that scored higher on the BIS subscale of the BIS/BAS tended to switch tasks less often as the task progressed; this pattern might indicate that participants who switch less often over time might do so because they view switching as aversive, possibly due to an increased aversion to effort expenditure (Storbeck et al., 2015). Unexpectedly, subjects that scored higher on the BAS fun-seeking scale tended to switch *more* often as the task progressed; because previous work indicates that more frequent switching is indicative of boredom (Geana et al., 2016a), this relationship might suggest that individuals higher on BAS-Fun experience greater boredom throughout the task, causing more frequent exploration behavior in the form of frequent switching. However, it should be noted that the relationship between BAS-Fun and switch rate changes was not predicted and weaker ($p = .37$) than the relationship between BIS and switch

rate changes ($\rho = -.48$); therefore, the relationship between BAS-Fun and changes in switch rate should be interpreted cautiously.

Finally, Experiment 3 provides evidence that changes in switch rates over time and overall switch rate likely measure different mechanisms. The relationships between BIS/BAS subscales were specific to switch rate changes rather than overall switch rate. Similarly, the original publications' effect of rewarding either repeats or switches more often significantly affected overall switch rate, but not changes in switch rate.

General Discussion

The current work sought to examine the degree to which common measures of interest in voluntary task switching paradigms might change throughout task performance. Previous work suggested that there were four mechanisms that might be expected to result in changes throughout task performance: practice effects causing better overall performance, fatigue effects causing worse overall performance or compensatory mechanisms to prevent performance decrements, boredom effects causing increased switching behavior, and decreased effort expenditure because of previous effort expenditure reflected in reduced switching behavior.

The effects of practice on overall RT were consistently present; in all three experiments, overall reaction times declined significantly throughout the experiment. Decline in reaction time on its own might be indicative of reduced effort expenditure; however, overall task accuracy also increased throughout the task in Experiments 1 and 3, with no change in accuracy over time in Experiment 2. If reduced RT was a result of reduced effort rather than practice, one would expect a speed-accuracy tradeoff. Additional improvements in accuracy switch cost in Experiment 1 and RT switch cost in Experiment 3 suggest that participants do display better performance over time consistent with practice effects rather than worse performance over time consistent with fatigue.

In general, there was little evidence for decrements in performance indicative of significant fatigue. The three experiments contained differing numbers of trials (ranging from 320 in Experiment 3 to 526 in Experiment 2); However, it should be noted that reward condition in Experiment 2 was

confounded with time spent performing the task (the second part of the experiment was always rewarded), and there were significant reductions in accuracy and increases in RT attributed to reward condition in Experiment 2. Therefore, it's possible that fatigue-induced decrements in performance were present in Experiment 2 (the longest of the three experiments), although interpretation of these results are complicated by the experiment's design.

It is notable, however, that Experiment 3 was the only of the three in which participants did not decline in switch rates. There are a few possible reasons for this, although the current work is not well situated to compare them directly. Although the overall length of the task in Experiment 3 was comparable to the task length in Experiment 1 (320 trials vs. 390 trials), only half of the trials in Experiment 3 were voluntary choice trials. It's possible that there were too few voluntary trials to detect (or elicit) a change in switch rate at the group level. However, a Bayes Factor analysis indicated strong support for the null (lack of change) rather than inconclusive evidence for the null or alternative, suggesting that the issue is not one of statistical power.

The fact that participants were simply required to make fewer choices in Experiment 3 than the other experiments might underlie the difference in strategy; previous work has found that increasing the ratio of cued to voluntary choice trials, thereby decreasing the number of task choices participants make throughout the task, results in more frequent voluntary switching (Fröber & Dreisbach, 2017). It is possible that this effect might be in part due to a reduction (or abolishment) of an otherwise present reduction in switch rates over time rather than an increase in the overall average tendency to switch tasks. The present findings that changes in switch rates over time are related to BIS and BAS-Fun scores, while mean switch rates are not, suggest that switch rate changes and average switch rate might index different cognitive processes; therefore, future investigation into whether the effect of reducing the number of voluntary trials might be better explained by modulating changes in switch rates rather than average switch rates might prove fruitful in establishing the mechanism by which reducing voluntary choices influences task choices.

In a similar vein, recent work (Dreisbach & Fröber, 2019; Foerster et al., 2020) has distinguished between manipulations that affect task choice at a local, shorter time scale (e.g. trial-level changes in reward prospect) and task choice at a global, longer timescale (e.g. context including ratio of cued to voluntary choice trials). The changes in task choice over time reported in the current work might provide another avenue by which to examine task choice at a global level (whereas previous work has generally focused only on overall average switch rates). Notably, the relationship between individual differences in task choice changes over time significantly predicted BIS and BAS-Fun scores when there was no significant change in task choice over time at a group level, suggesting that changes in task choice might be a valuable measure even for paradigms that do not elicit a group level change.

Limitations and Future Directions

Although the current work suggests that changes in switch rate over time might provide valuable information in future work, the cognitive mechanism underlying the change is still unclear. The reward manipulations intended to provide support for the idea that effort exertion might underly the effect in Experiments 2 and 3 failed to significantly affect the degree of change. However, because there was no group-level change in switch rate in Experiment 3, and because reward was confounded with time spent performing the task, these null effects should be interpreted with caution and do not sufficiently rule out effort expenditure as a possible underlying mechanism.

The fact that BIS scores were negatively correlated with switch rate changes suggests that effort avoidance might play a role in a tendency to switch less over time, given that previous work has found a relationship between BIS scores and sensitivity to effort exertion (Storbeck et al., 2015). Further, the positive relationship between BAS-Fun and changes in switch rate might suggest that another mechanism, possibly boredom (Geana et al., 2016a), could additionally explain the effect. However, future work should seek to replicate these findings, as the relationships were examined within a sample that might be considered small for individual differences research ($N = 38$).

The current work compared the presence of behavioral changes across different voluntary task switching paradigms run by different labs to establish the degree to which changes might be robust across

tasks. However, the relatively large differences across paradigms also makes it difficult to interpret why a specific effect might not replicate across paradigms (for example, why switch rates declined at a group level in Experiments 1 and 2 but not Experiment 3). Future work can expand on the current findings by manipulating individual aspects of a voluntary task switching paradigm to provide more insight into exactly what aspects of a task might moderate the behavioral effects presented here.

Future work using more direct manipulations of effort expenditure and fatigue might be useful to establish the degree to which each mechanism (effort avoidance due to previous expenditure vs. a compensatory strategy meant to combat fatigue) might contribute to changes in task choice over time. However, it is also possible that these two mechanisms overlap—that is, that increases in effort expenditure meant to induce effort avoidance *necessarily* result in greater levels of fatigue resulting in a compensatory strategy—which might make devising a behavioral manipulation that affects one process and not the other very difficult. Previous work does suggest that effort avoidance is uncorrelated with the subjective feeling of fatigue (Benoit et al., 2019), though, suggesting that the two might be separable.

However, it is also possible that, in the case of VTS performance, effort avoidance is itself a compensatory strategy during the early stages of fatigue that might occur prior to subjective feelings of fatigue; if this is the case, the theoretical framework of the current study which places the two processes in theoretical opposition with each other (informed by previous work in similar paradigms) might be flawed. Future work might wish to examine the degree to which individual differences in switch rate declines in VTS paradigms might be related to individual differences in fatigue-related decrements in cued task switching paradigms, where this compensatory strategy cannot be applied, to examine whether the two mechanisms might be related.

Finally, the mechanisms proposed to underlie declines in switch rates in the current work are based in predictions related to the effects of these mechanisms in similar tasks. However, future work that establishes relationships between declines in switch rates and other measures of effort exertion and/or fatigue would be beneficial to support these ideas.

Conclusions

The current work examined the degree to which common measures of interest in a voluntary task switching paradigm change during performance of the task. There was consistent evidence for improvements in performance over time, indicating effects of task practice. In two of the three experiments, there was a group-level reduction in switch rates over time; while this reduction was not present in Experiment 3, analyses of individual differences in BIS/BAS scores suggest that changes in switch rates over time provide information that might prove useful for future work in cognitive flexibility examined using VTS independent of subject average switch costs. The combined results of the three experiments support the use of switch rate changes throughout task performance as a novel dependent variable of interest in future VTS use, although more work is necessary to determine which cognitive mechanisms the effect might index.

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