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DEPLETION OF EXECUTIVE CONTROL DURING RISKY DECISION MAKING REVEALS A CORRESPONDENCE BETWEEN THE REFLECTION EFFECT AND TRIAL-BY-TRIAL STRATEGY FORMATION

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According to dual process theories, depletion of executive resources may amplify decision-making biases. Psychological studies investigating the influence of executive control on risky decision making typically employ dual task paradigms, e.g. a risky decision-making task in parallel with an executive task. However, these paradigms often reveal relatively weak to null effects. In this study, we designed a novel task to determine the influence of executive control on risky decision making directly, and simultaneously separating gains and losses using a block design. Contrary to other tasks, risk taking, and executive control occurred during the same decision. When risky decisions were conditioned on high executive control, participants demonstrated a reflection effect: higher risk taking for loss blocks, compared to gain blocks. Further exploration revealed that the gain-domain specific influence of executive control on risky decisions occurred due to the influence of trial-by-trial decision-making strategies.

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INTRODUCTION

Dual process theory implies that decision-making biases occur when executive control resources become depleted [Kahneman, 2003; Kahneman, Frederick, 2007; Kahneman, 2011]. The reflection effect is a bias in which individuals are more likely to gamble when the choices are prospective losses, as compared to when mathematically equivalent choices are prospective gains [Kahneman, 1979; Tversky, Kahneman, 1981; Fagley, 1993]. The reflection effect is one example of decision making bias that has been shown to be directly caused by depletion of executive resources, exemplified by increasing time pressure [Kirchler et al., 2017] or by increasing stress [Porcelli, Delgado et al., 2009]. Executive control is an essential component of cognition that enables us to evaluate and plan decisions by retrieving relevant information, inhibit irrelevant information and flexibly adjust to goal-oriented demands [Miyake et al., 2000; Diamond, 2013]. In light of this, some have attempted to test dual process theory by administering various risky decision-making tasks in parallel with a 2-back working memory task [Whitney et al., 2008; Starcke et al., 2011; Farrell et al., 2012; Pabst et al., 2013; Gathmann et al., 2014 a,b]; an inhibitory task such as the Go-No Go task [Verdejo-García et al., 2007; Yeomans, Brace, 2015; Ba et al., 2016; Welsh et al., 2017]; or a set-switching paradigm [Verdejo-García et al., 2007; Fröber, Dreisbach, 2016]. However, studies investigating the influence of executive control on risky decision making using dual tasks have only revealed relatively weak effects [Whitney et al., 2008; Pabst et al., 2013; Starcke et al., 2011; Deck, Jahedi, 2015]. Perhaps employment of two tasks in succession (e.g. a decision-making task following a 2-back working memory task) may not take into account that executive control and decision-making often operate in parallel, subsequently yielding relatively weak behavioural differences.

For this research article, we aim to investigate the influence of executive control depletion on risky decision making directly by using a task that examines risk–taking and executive control within a single event. In a previous study we designed a task that combines the voluntary task-switching paradigm [Arrington, Logan, 2004; Kiesel et al., 2010] with binary lotteries [Selton et al., 1999; Engelmann, Tamir, 2009; Harrison et al., 2013; also see Yaple et al., 2017, 2018a,b]. In this paradigm, participants selected between risky and safe options depending on the choice to switch or repeat task-sets. This paradigm allows one to examine the interaction of risk taking with simultaneously implemented executive control, such that both cognitive processes occur in parallel during a single behavioural response. Using this task paradigm, we expect to demonstrate that risky decisions would be influenced by the depletion of executive control during task set switching.

METHODS

Participants

Thirty-three right-handed (16 females; mean age 21.4 years; age range 18–35 years; SD = 5.04) subjects with normal or corrected to normal vision and with no neurological disorders were recruited and provided a small amount of compensation (equivalent to $7–15 US dollars). Participants either taking drugs or prescribed with medications were excluded from the participant pool. All participants provided a written consent approved by a local ethics committee – the HSE Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research – in accordance with the Declaration of Helsinki.

Task Design and Procedure

Participants performed the Rewarded Voluntary Switch Task [Yaple et al., 2017] – a modified version of the voluntary task-switching paradigm [Arrington, Logan, 2004], which allows subjects to select between risky or safe options by simultaneously switching or repeating task-sets between trials. Voluntarily switching and repeating task-sets has traditionally been used to measure the ability to flexibly adjust to goal-oriented demands [Arrington, Logan, 2004: Kiesel et al., 2010] and was used in the current experiment to measure exertion of high and low executive control, respectively. Importantly, in each trial of the task an act of executive control may involve switching from one task to another.

Figure 1 illustrates the task design. In each trial participants were presented with a randomly selected single digit number (1, 2, 3, 4, 6, 7, 8, or 9) and instructed to choose one of two games per trial: 1) an odd/even game, to indicate parity; or 2) a high/lower than 5 game, in which subjects responded by pressing the corresponding high or low response button. Participants responded using the left and right index and middle fingers to indicate whether the digit was odd, even, higher or lower than 5.

Subjects were instructed that repeating the same game in succession would yield a safe option (25 monetary units [MU] with a probability of 100%), while switching between games would result in a risky option (50 MU or 0 MU with a probability of 50%). Expected value was equal between gain and loss blocks to avoid confounds associated with probability calculation. The influence of executive control on risky decisions was counterbalanced across blocks. In half of the experiment, switching between games led to risky options (Switch = Risk blocks) and in the other half repeating led to risky options (Repeat = Risk blocks). In addition, subjects received positive or negative monetary incentives in separate blocks represented as gain and loss blocks, respectively. In total, all four block types were administered randomly throughout the experiment. Responses that were incorrect or exceeded 4000 ms generated negative feedback (i.e. 0 MU in the gain blocks and –50 MU in the loss blocks). Feedback for safe options consisted of 25 MU and –25 MU in gain and loss blocks, respectively. When subjects chose the risky option, feedback would either yield 50 MU or 0 MU randomly within the gain blocks, and 0 MU or –50 MU in the loss blocks; each with 50% probability, determined by a random generator. Trial feedback lasted for 1000 ms.

Due to complexity of task and to reduce learning effects subjects received two rounds of training, which consisted of eight blocks of 10 trials resulting in 80 trials in total. After training, subjects received 12 blocks of 30 trials, totalling to 90 repetitions for each block type. Feedback was given per trial and at the end of the experiment total cumulative feedback was shown on the computer screen. Subjects received 500 MU for participation and an additional bonus, between –300 and +300 MU (approx. 10 USD), based on the feedback outcomes of six randomly selected trials. Response buttons were counterbalanced across subjects. Block type were presented in pseudorandom order and counterbalanced. Presentation of stimuli and data collection were controlled by E-Prime 2.0 software [Schneider et al., 2002]. After the experiment, subjects were debriefed and asked about their strategies during the game.

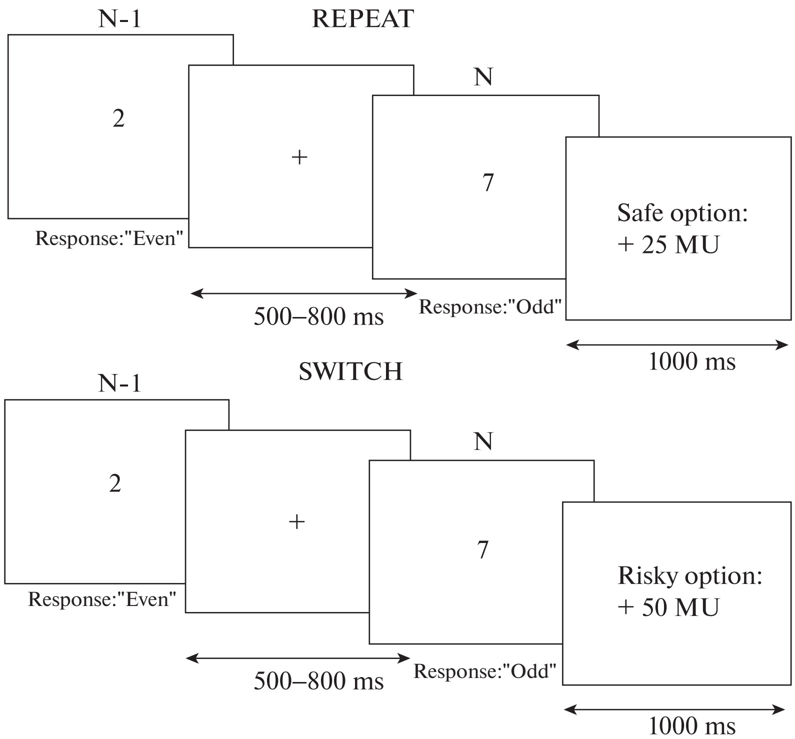

Fig. 1. The Rewarded Voluntary Switch Task combines the voluntary task-switching paradigm with monetary risk prospects. Participants make selections between the safe option (25 MU with a probability of 100%) or the risky option (50 MU or 0 MU with a probability of 50%) depending on whether to switch or repeat task-sets between trials. Figure represents a switch and a repeat between two consecutive trials in the Switch = Risk gain blocks.

Рис. 1. Пример модифицированной версии парадигмы произвольного переключения между заданиями (Rewarded Voluntary Switch Task, RVST-парадигма). Испытуемые выбирают между рискованной (50 или 0 денежных единиц, ДЕ с вероятностью 50%) или безрисковой (25 ДЕ со 100% вероятностью) альтернативами путем переключения на выполнение другой задачи или повторения текущего задания. На рисунке приведены примеры обеих альтернатив – остаться или переключиться в ситуации, когда переключение сопряжено с рискованной альтернативой.

Statistical Analysis

Incorrect responses and reaction times greater than 2 standard deviations from the mean were removed from the analysis. Using two independent repeated measured ANOVA we tested the effect of Valence (gain blocks, loss blocks) and Switch condition (Switch = Risk blocks, Repeat = = Risk blocks) on (a) mean probability of risky decisions and (b) mean probability of switching of following factors.

Using separate paired sample t-tests we also tested differences in response times between: 1) trials in which participants decided to switch or repeat between task-sets (i.e. a switch cost); and 2) trials in which participants selected risky compared to safe decisions. Switch costs are usually assessed via the time it takes to respond in task-switch trials compared to task-repeat trials as an evidence of time-consuming executive-control [Arrington and Logan, 2004]. Therefore, in our study, the switch cost was used to determine the magnitude of executive control between task-switch and task-repeat trials. Furthermore, we examined within-block effects by assessing whether the switch cost differed between gain and loss blocks by using an additional paired sample t-test. In addition, we examined between-block effects by testing overall mean response times across the four experimental blocks by using repeated measures ANOVA with the independent variables Valence and Switch condition. All repeated ANOVA tests were corrected using a Bonferroni correction. The main analysis was performed using SPSS software version 20 (IBM, Armonk, NY).

General Linear Models Analysis of Behavioural Strategies

Based on participants' self reports during the debriefing phase, we further explored the influence of executive control on decision making strategies (Win-stay, Lose-shift, Win-shift and

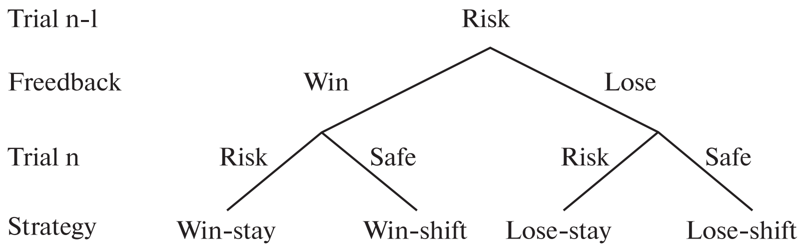

Fig. 2. Tree diagram of strategies based on consecutive selections. After receiving positive or negative feedback (from risky selections) players may either continue to risk in the following trial (stay) or choose the safe option (shift). Winning reflects a feedback that displays +50 MU in gain blocks and –0 MU in loss blocks. Losing reflects a feedback that displays +0 MU in gain blocks and –50 MU in loss blocks.

Рис. 2. Дерево стратегий выбора последовательности решений. В случае выбора рискованной альтернативы под влиянием обратной связи у игрока сохраняется возможность выбора рискованной (остаться) или безрисковой (переключиться) альтернативы. В случае выигрыша в блоке заданий на выигрыш на экране в качестве обратной связи появится информация о нем (например, +50 ДЕ), а в блоке заданий на проигрыш (например, –50 ДЕ).

Lose-stay, see below for details) on a trial-by-trial basis. Decision making strategies were classified based on the choice in the current trial (t) and outcomes of the previous trial (t-1). For example, a Win-stay strategy occurred when participants selected the risky options after receiving positive feedback (i.e. a Win) in the previous trial. Figure 2 illustrates all four strategies. The purpose of this analysis was to examine whether decisions were differentially influenced by previous feedback in different experimental blocks. In total we tested four strategies: Win-stay, Lose-shift, Win-shift and Lose-stay coded as dummy variables and treated as response variables in four separate generalized linear models (GLM) with a logit function. Block types Valence and Switch condition were treated as predictors. Irrespective of Valence, positive feedback was coded as 3 (+50 MU for gain, 0 MU for loss blocks), neutral as 2 (+25 MU for gain, –25 MU for loss blocks), and negative as 1 (0 MU for gain blocks, –50 MU for loss blocks). Wald tests were performed on all levels up to 2-way interactions. Analyses were performed using R software (R Core Team, Vienna, Austria, 2016] with the software package lme4 [Bates et al., 2014] and lmertest [Kuznetsova et al., 2016].

RESULTS

Overall accuracy was 95.89% which did not differ significantly across Valence ($F_{1.32} < 0.001$, $p > 0.999$), Switch condition ($F_{1.32} = 2.946$, $p = 0.096$); nor did they interact ($F_{1.32} = 0.969$, $p = 0.332$). Regarding the percentage of risky decisions, a repeated measures ANOVA revealed a main effect of Switch condition ($F_{1.32} = 7.065$, $p = 0.012$, partial $\eta^2 = 0.181$) on risk taking, indicating an overall decrease in risk taking during Switch = Risk blocks ($\mu = 49.8\%$) compared to Repeat = Risk blocks ($\mu = 57.7\%$). These findings suggest that depletion of high executive control decreases risk taking.

We were also interested in whether Valence would have an influence on risky decisions which would illustrate a reflection effect [Tversky, Kahneman, 1979; 1981; Fagley, 1993]. Although the main effect of Valence was not significant ($F_{1.32} = 1.659$, $p = 0.207$), we found a significant interaction effect between Switch and Valence ($F_{1.32} = 6.039$, $p = 0.020$, partial $\eta^2 = 0.159$). Post-hoc comparisons revealed a significant difference in risky decision making in the Switch = Risk blocks compared to Repeat = Risk blocks within gain blocks ($p = 0.002$), yet not for loss blocks ($p = 0.165$). This suggests that the influence of executive control on risky decision making was specific to the gain domain, indicating a reflection effect. Figure 3 illustrates these differential effects of switch costs on risk taking in gain and loss blocks.

A paired samples t-test comparing reaction time in task-switch trials and task-repeat trials revealed a switch cost effect: $t(33) = -1.656$, $p = 0.107$. Alternations yielded slower response times (1373.18 ms) compared to repetitions (1114.02 ms). Switch costs were not significantly different in the gain blocks (mean = 270.15 ms; SEM = 32.20) or loss blocks (mean = 239.90 ms; SEM = 32.20; $t(33) = 1.185$, $p = 0.245$). An additional paired samples t-test revealed no significant differences in response time during risky and safe decisions ($t(33) = -1.656$, $p = 0.107$). Finally, to assess differences in response time across block types, a repeated measures ANOVA on response time across all decisions revealed a significant

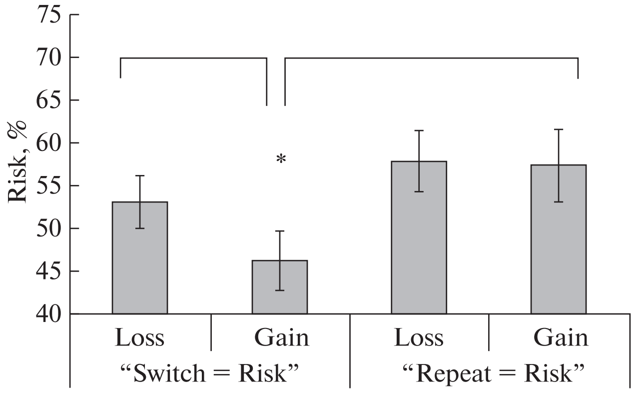

Fig. 3. Mean proportion of risky decisions with standard error bars for all four block conditions. Results of an interaction effect between Valence and Switch condition are demonstrated by a decrease in risky decision making in the Switch = Risk gain blocks. The asterisk indicates a statistically significant difference between conditions ($p < 0.05$).

Рис. 3. Распределение средних значений выбора (показано значение стандартной ошибки среднего) для четырех экспериментальных условий. Взаимодействие между факторами Валентности задачи и Переходом (в другую задачу) отражено в процессе уменьшения доли выбора рискованных альтернатив в условии, когда рискованное решение ассоциируется с выбором рискованной альтернативы в блоке заданий на выигрыш. Звездочка отражает статистически значимую разницу между экспериментальными условиями ($p < 0.05$).

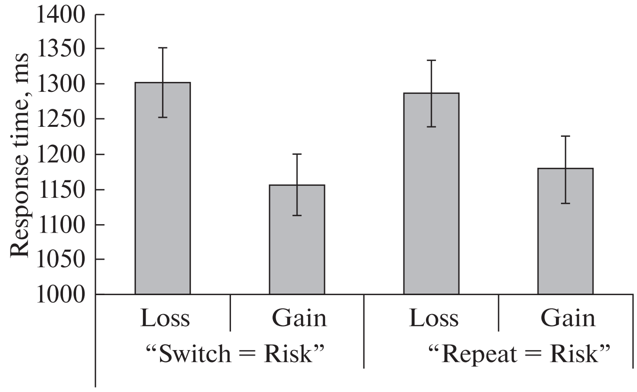

Fig. 4. Mean response times with standard error bars for each block condition.

Рис. 4. Среднее время реакции (показано значение стандартной ошибки среднего) во всех 4 экспериментальных условиях.

main effect of Valence ($F_{1.33} = 45.452$, $p < 0.001$, partial $\eta^2 = 0.579$), yet no other effects were significant. Overall, participants were significantly slower in loss blocks (1294.11 ms) compared to gain blocks (1167.41 ms; $p < 0.001$). Means with standard error bars for reaction time are displayed in Fig. 4.

Analysis of Behavioural Strategies

Lastly, we tested whether outcomes in the previous trials affected behavioural strategies in following trials. No significant differences were found between block type for Win-stay, Lose-shift, and Win-shift strategies. However, the GLM revealed a significant interaction between Switch condition and Valence for the Lose-stay strategy: $\beta = -0.343$; z-score $= 2.485$ $p = 0.012$. This finding is similar to the reflection effect previously revealed by the ANOVA test. While the ANOVA showed an influence of executive control on risk taking specifically in the gain domain, the post-hoc analysis revealed an influence of executive control on Lose-stay strategies in gain blocks. In other words, the aforementioned effect of executive control on risk taking within the gain domain may be linked to the influence of executive control on trial-by-trial strategies; specifically, on repeating risk taking after receiving negative outcomes. Means with standard error bars for each strategy are displayed in Fig. 5.

DISCUSSION

To investigate the influence of depleted executive control on risky decision making we designed a novel task in which decision to voluntary select risky or safe options was conditioned on choice to switch or repeat task-sets. The Rewarded Voluntary Switch Task differed from conventional dual task paradigms that typically employ two tasks in succession. While a dual task may capture two independent cognitive processes operating in parallel, the current experimental paradigm captures a single event by obliging participants to select risky or safe options by switching or repeat task-sets with a single response.

According to dual process theory a decision-making bias should occur when executive control becomes depleted [Kahneman, 2003; 2011; Kahneman, Frederick, 2007; Pujara et al., 2015]. We were able to support this theory by two independent findings. Firstly, a significant difference in reaction time was observed between switching and repeating reflecting a switch cost, which indicated that switching required more executive resources than repeating task-sets. This finding supports the notion that voluntary switching between tasks depletes cognitive resources. Secondly, we found a significant interaction effect between Switch condition and Valence. This effect

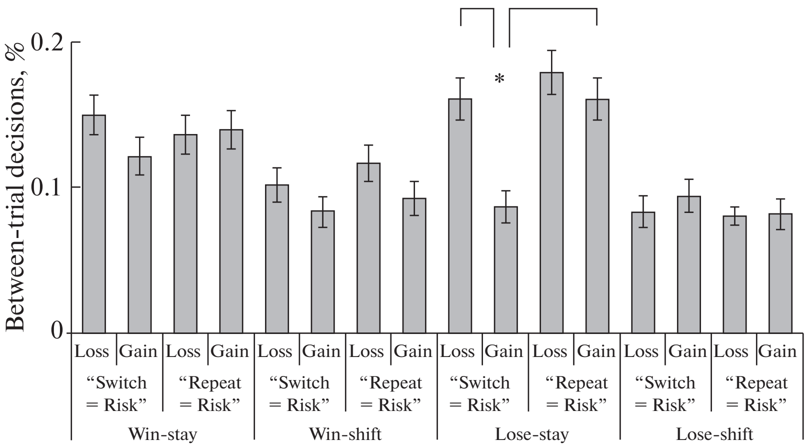

Fig. 5. Mean proportion of between-trial decisions (Win-stay, Win-shift, Lose-stay and Lose-shift) with standard error bars for all four block conditions. A significant difference was observed between gain and loss blocks for the Switch = Risk blocks, specifically for Lose-stay strategy. The asterisk indicates a statistical difference between conditions ($p < 0.05$).

Рис. 5. Распределение стратегий принятия решений о том, чтобы переключиться или остаться по всем типам комбинаций (остаться после выигрыша, переключиться после выигрыша, остаться после проигрыша и переключиться после проигрыша; показано значение стандартной ошибки среднего). Статистически значимая разница наблюдалась между условиями выигрыша и проигрыша в ситуации, когда рискованное решение означало переключение, в случае выбора стратегии “остаться” после проигрыша. Звездочка отражает статистически значимую разницу между экспериментальными условиями ($p < 0.05$).

demonstrated a reflection effect (i.e. higher risk taking in loss blocks as compared to gain blocks) when risky decisions were conditional on exerting high cognitive control (Switch = Risk blocks), yet no reflection effect when risky decisions were conditional on exerting low cognitive control (Repeat = Risk blocks). Although few articles have explored the link between the dual process theory and the reflection effect, it has been suggested that the reflection effect occurs when cognitive resources becomes depleted, thereby allowing automatic and fast decision-making to become the default system [Porcelli, Delgado, 2009; Pujara et al., 2015; Kirchler et al., 2017]. Perhaps evidence from the current study may corroborate this conclusion. Other studies have attempted to use the dual process theory to explain the reflection effect by introducing a time limit for each decision [Svenson, Benson, 1993; Guo et al., 2017; Kirchler et al., 2017]. For instance, Guo and colleagues [2017] demonstrate more frequent selections of sure options for gains and more frequent gamble options for losses when there was greater pressure to make quick decisions. Perhaps our results and the results obtained by Guo and colleagues may illustrate a similar cognitive mechanism that utilizes cognitive resources to make quick decisions.

We further explored our data by examining the effects of outcomes in the previous trial (t-1) on risk taking in the current trial (t). We aimed to test whether the influence of executive control on risky decision making can be explained by its differential influence on trial-by-trial strategies: Win-stay, Win-shift, Lose-stay, or Lose-shift. We found that executive control demands specifically decreased Lose-stay strategies within gain blocks. This particular strategy is described as events in which participants continue to select risky gambles even after receiving negative feedback. If we compare both findings, that: 1) executive control decreases the tendency for participants to select risky decisions in the gain domain, and: 2) that executive control decreases Lose-stay strategies within the gain domain, we may infer that these findings reflect the same behavioural measure. Therefore, the influence of executive control on risky decision-making described by dual process theory may be explained by a decrease in trial-by-trial Lose-stay strategies. In other words, increasing executive control demands motivates participants to reduce risk taking specifically after receiving negative feedback. Perhaps this mechanism may explain how high risky individuals succumb to decision making inertia, e.g. chronic gamblers whom gamble excessively despite receiving negative outcomes may have a lack of executive resources [Roca et al., 2008]. Overall, our findings suggest that depletion of executive control decreases the tendency to select risky decisions specifically after gain omission, i.e. when feedback from the previous trial produces no reward (+0 MU). Furthermore, executive control did not affect decisions in the loss domain; Switch = Risk blocks and Repeat = Risk blocks yielded the same level of risky decisions. Perhaps the difference in behavioural responses for gain omission, yet not losses, may account for the reflection effect. Using the dual process theory framework; as mental effort becomes depleted people tend to make fast automatic decisions, become less sensitive to gain omission from previous negative events and thus, motivating one to continue selecting risky decisions.

To our knowledge, no other studies have directly investigated the influence of executive control on risky decision making using the voluntary switching paradigm, although several studies have investigated the influence of rewards on executive control by using a cued task-switching paradigm with rewarding prospects [Avila et al., 2012; Jonasson et al., 2013; Fuentes-Claramonte et al., 2015; Umemoto and Holroyd, 2015; Etzel et al., 2016]. Only recently have researchers investigated cognitive flexibility and reward processing by taking advantage of the voluntary switching paradigm [Fröber, Dreisbach, 2016]. Interestingly, Fröber and Dreisbach [2016] demonstrated that rewards that changed across time had increased percentage of voluntary switching, compared to stable rewards. They explain these differences in voluntary switching as a mechanism that biases the cognitive system either toward stable or flexible executive control depending on the change in reward expectation.

Perhaps another advantage of the current study was that we used a within-subjects design, in comparison with prior studies that used a between-subjects design [Starcke et al., 2011; Pabst et al., 2013; Gathmann et al., 2014]. Utilizing a within-subjects design may have substantially improved the statistical power of the analysis, thereby resulting to statistical significant differences. Concerns of potential learning effects were taken into account by randomizing block conditions. Perhaps this difference in task design may explain the null effects observed in previous studies [Whitney et al., 2008; Starcke et al., 2011; Pabst et al., 2013; Deck, Jahedi, 2015]. Therefore, our paradigm may be more suitable than dual task paradigms for investigating dual process accounts of decision making.

Perhaps the main limitation of this study is that choices were equal in expected value without varying outcome or probability. However, we limited these choices in order to avoid additional confounds associated with executive control load (e.g. mathematical calculations). Nevertheless, due to large number of trials the Rewarded Voluntary Switch Task may be adapted to investigate lotteries with unequal expected values similar to prior studies [Deck, Jahedi, 2015; Whitney et al., 2008]. Finally, this task may be adapted to investigate executive control simultaneously with other decision-making biases such as delay discounting, which up until now has been investigated in parallel with executive control using the 2-back working memory task [Hinson et al., 2003; Aranovich, et al., 2016]. Overall, our new task is highly adaptable for investigating the influence of executive control on various decision-making processes.

CONCLUSION

Our results support dual process theory by demonstrating a robust influence of executive control on risky decision making. We found a significant decrease in risk taking in the gain domain when executive control resources became depleted. The need to exert more executive resources by task-set switching decreased risky decisions in the gain domain, yet not in the loss domain. This represents a reflection effect that may be explained by changes in (gain-domain specific) trial-by-trial strategies: depletion of executive resources reduced Lose-stay strategies specifically in the gain domain. Overall, the Rewarded Voluntary Switch Task could be used as a novel tool to empirically test the role of executive control in various decision-making biases.

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ИЗУЧЕНИЕ ВЛИЯНИЯ ИСПОЛНИТЕЛЬНОГО КОНТРОЛЯ НА ПРИНЯТИЕ РИСКОВАННЫХ РЕШЕНИЙ В СВЕТЕ ВЗАИМОДЕЙСТВИЯ ТЕОРИИ ОТРАЖЕНИЯ И СТРАТЕГИИ ПРИНЯТИЯ РЕШЕНИЙ

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Согласно представлениям о дуализме мышления, объединяющем рациональные и эмоциональные процессы, лежащие в основе принятия решений, исчерпание ресурсов, регулирующих, контролирующих и управляющих поведением человека, может приводить к накоплению и усилению когнитивных искажений. В предыдущих исследованиях исполнительного контроля на принятие решений в ситуации риска, предлагавших испытуемому параллельное выполнение двух заданий – принятие рискованного решения с целью получить наибольший выигрыш и задачу на исполнительный контроль, наблюдался незначительный или нулевой эффект когнитивного контроля на принятие рискованных решений. Мы разработали новый подход к изучению влияния исполнительного контроля на принятие рискованных решений, благодаря которому стало возможно одновременно модулировать степень контроля и риска при выборе альтернативы. Мы обнаружили, что при сочетании высокой степени риска и высокой степени исполнительного контроля, у испытуемых наблюдался эффект отражения: они чаще принимали рискованные решения в случае потерь по сравнению с ситуацией, когда они получали награду. Дальнейший анализ динамики принятия решений выявил, что изменение отношения к риску под воздействием изменяющегося исполнительного контроля было обусловлено сменой стратегии принятия последующего решения в зависимости от исхода предыдущего выбора.

Keywords: risky decision making, executive control, win-stay lose-shift, reflection effect