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The relationship between anxiety, mind wandering and task-switching: A diffusion model analysis

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THE RELATIONSHIP BETWEEN ANXIETY, MIND WANDERING, AND TASK-SWITCHING: A DIFFUSION MODEL ANALYSIS

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The Relationship between Anxiety, Mind Wandering and Task-switching: A Diffusion Model Analysis

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ABSTRACT

Although the negative impact of anxiety on task-switching has been documented, little is known about the extent or mechanisms of this impairment primarily because of the complex nature of task-switching and difficulty in probing the occurrence of worries within participants. To address this issue, we employed a stochastic diffusion model analysis along with a novel thought-probe technique in task-switching paradigm. Across 152 participants, we found state anxiety was linked to higher switch costs in nondecision time but not drift rate parameter of diffusion model, which indicates that the locus of task-switching impairment in anxious individuals is pertinent to the efficiency of task-set reconfiguration but not proactive interference processes. Furthermore, we found boundary separation parameter – which quantifies conservative decisional styles – heightened as a function of anxiety, supporting the existence of compensatory strategy in anxious individuals. We also found anxiety increased mixing costs in task-switching paradigm, which extends the implication of anxiety to global sustained control mechanisms in task-switching. Interestingly, we found that impaired performance by anxiety was not attributed to the frequency of worrisome thoughts during task-switching. These findings elucidate several theoretical assumptions on the relationship between anxiety and task-switching.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

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CHAPTER 1: INTRODUCTION

Anxiety is a common human experience which is characterized by aversive emotional state due to perceived threatening circumstances. It has been known to be hugely disruptive to cognitive functioning even when the task is non-threatening (Edwards, Edwards, Lyvers, 2015). In particular, the influence of anxiety on task-switching—the ability to switch back and forth between multiple tasks, operations, or mental sets (Monsell, 2003)—has received a fair amount of attention. Despite frequent experience of anxiety and daily engagement in task-switching in our daily life, however, little is known about the extent or mechanisms of the negative effect of anxiety on task-switching (Eysenck & Derakshan, 2011). For instance, although task-switching has been demonstrated to implicate multiple components of cognitive processes (Mayr & Kliegl, 2003; Ruthruff, Remington, & Johnston, 2001), there is no study to date that has examined the specific component of task-switching that is disrupted by anxiety. Similarly, the assumption that anxious individuals employed compensatory strategy to maintain their task-switching accuracy (Eysenck, Derakshan, Santos, & Calvo, 2007) has not been directly demonstrated in the previous literature. Furthermore, it is not clear whether the negative effect of anxiety on task-switching efficiency is purely driven by heightened worrisome thoughts in anxious individuals. With these issues in mind, I aim to elucidate the extent and mechanism underlying the negatively effect of anxiety on task-switching by using a novel thought-probe method (Stawarczyk, Majerus, Maj, Van der Linden, & D' Argembeau, 2011; Unsworth & McMillan, 2014) and the stochastic diffusion model analysis (Ratcliff, 1978).

Anxiety can be conceptualized in terms of either personality aspect (i.e., trait anxiety) or emotional state (i.e., state anxiety; Spielberger, 1972). State anxiety is characterized by experience of apprehension that occurs in response to subjectively threatening events with an uncertain outcome. It can be elicited by everyday events such as having to speak in the public or waiting to receive an examination result. Trait anxiety, on the other hand, is a stable individual's tendency to experience anxiety across various context and events. According to previous studies, both high trait and state anxiety have been shown to be associated with impaired task-switching performance, but this effect was evident only when performance was assessed in terms of reaction times (RT) but not in accuracy (Ansari, Derakshan, & Richards, 2008; Edwards et al., 2015; Derakshan, Smyth, & Eysenck, 2009).

Attentional control theory (Eysenck et al., 2007) is the most well-known approach to explain why trait and state anxiety affect task-switching (for a theoretical review on the effect of anxiety on cognitive performance, see Derakshan & Eysenck, 2009). The theory postulates that both trait and state anxiety reduce attentional focus during task-switching because attentional resources are allocated to internal threat-related stimuli (e.g., worrisome thoughts). As a result, task-switching performance should be compromised owing to lesser attentional resources available to switch between concurrent tasks. The theory also explains why anxiety affects RT (i.e., speed) but not task-switching accuracy (Ansari et al., 2008; Edwards et al., 2015; Derakshan et al., 2009). Importantly, the theory distinguishes performance effectiveness from processing efficiency. Specifically, performance effectiveness relates to the quality of performance that is typically assessed by outcome measures such as the accuracy of the task, whereas processing efficiency relates to the extent to and manner in which processing resources are invested in doing the task, and thus is typically measured by the time spent. The theory predicts that anxiety will influence efficiency assessed by RT, but not effectiveness assessed by accuracy because anxious individuals are motivated to compensate performance effectiveness at the cost of efficiency, i.e., increased processing time. In other words, anxiety is more likely to entail the use of a compensatory strategy which leads to a trade-off between efficiency (speed) and effectiveness (accuracy; Eysenck et al., 2007).

Although the attentional control theory (Eysenck et al., 2007) has received considerable supports for the notion that trait and state anxiety impair task-switching performance in terms of RT but not accuracy (Ansari et al., 2008; Goodwin & Sher, 1992), many of its underlying assumptions have not been directly tested. For instance, attentional control theory (Eysenck et al., 2007) assumes that the negative effect of trait or state anxiety on the transient cost of task-switching (i.e., switch costs) is due to impaired efficiency in exerting attentional control of task-set reconfiguration (i.e., a process of replacing a task with a new task; Rogers & Monsell, 1995). Although this assumption appears to be supported by previous studies which have found higher switch costs among individuals with high trait anxiety (Ansari et al., 2009) or state anxiety (Derakshan et al., 2009), it is noteworthy that switch costs arises from not only task-set reconfiguration but also proactive interference (i.e., a general slow down after switching to a new task due to an interference from a previous task; Wylie & Allport, 2000). Thus, without dissociating the effect of anxiety on task-set reconfiguration from the effect of anxiety on proactive interference of switch costs, it is still unclear which specific component of task-switching is directly affected by anxiety. This is critical since Pacheco-Unguetti, Acosta, Callejas, and Lupiáñez (2010) suggested that trait and state anxiety could affect different aspects of mechanisms underlying selective attention. Specifically, the authors showed that trait anxiety was associated with deficiencies in the goal directed top-down control processing (i.e., executive network), whereas state anxiety was associated with bottom-up processing which increases sensitivity to task-relevant stimuli. Given these findings, it is plausible to argue that trait anxiety are associated with impaired task-set reconfiguration processes which mainly implicate top-down cognitive processes (Rogers & Monsell, 1995), whereas state anxiety can be associated with impaired proactive interference which implicate bottom-up processing (Wylie & Allport, 2000). This view, however, contradicts the assumption of attentional control theory that trait and state anxiety would impair task-switching in a similar manner, specifically by influencing task-set reconfiguration. Thus, without decomposing switch costs into either task-set reconfiguration or proactive interference, it is not possible to verify the theory's critical assumption and identify the locus of impaired switch costs by state and trait anxiety.

Another crucial assumption of the attentional control theory (Eysenck et al., 2007) which needs to be tested is whether anxious individuals in both trait and state anxiety compensate performance effectiveness by sacrificing processing efficiency. This assumption indicates that anxious individuals are motivated to be conservative in their decisional styles. However, the assumption seems inconsistent with existing findings on the positive relationship between anxiety and impulsivity (Bellani et al., 2012; Torrubia, Avila, Moltó, & Caseras, 2001). Although previous findings that anxiety typically affects RT but not accuracy (e.g., Derakshan et al., 2009) appear to support the presence of a compensatory strategy, this should be interpreted with caution because overall accuracy on the task is potentially vulnerable to ceiling effect (Dixon, 2008) and less reliable (Hartanto, Toh, & Yang, 2016). Moreover, given that individual differences in task-switching performance are typically observed in RTs rather than accuracy – for example, aging (Kramer, Hahn, & Gopher, 1999; Kray, Li, & Lindenberger, 2002) and developmental disorders (Gargaro, May, Sheppard, Bardshaw, & Rinehart, 2015) — the absence of the effect of anxiety on accuracy may simply reflect an artefact in measurement but not necessarily the presence of a compensatory strategy. Therefore, it is essential to examine the presence of a compensatory strategy in anxious individuals using a more direct indicator of a compensatory strategy.

Furthermore, attentional control theory (Eysenck et al., 2007) postulates that the negative effect of anxiety on task-switching efficiency is driven by the loss of attention resources to worrisome thoughts. To date, however, there is no study that has directly tested the mediating role of worrisome thought in the relationship between anxiety and task-switching. Some studies which have assessed worrisome thoughts either before or after the completion of the task (Harris, 2013; Forster, Elizalde, Castle, & Bishop 2015; Moser, Becker, & Moran, 2012) failed to find any relationship between worry and cognitive performance, although the reliability of quantifying worrisome thoughts either prospectively or retrospectively can be questioned (Nisbett & Wilson, 1977). On the other hand, recent neuroimaging studies (Bishop, 2008; Forster et al., 2015) suggest that trait anxiety is associated with general impoverished attentional control that is not caused by worrisome thoughts. Forster et al. (2015) argued that worrisome and task-unrelated thoughts (TUT) are in general the product of impoverished attentional control caused by trait anxiety. In favour of this, the literature on mind wandering suggests that impoverished attentional control increases mind wandering but not the other way around (McVay & Kane, 2009, 2010). These conflicting findings highlight the critical need to examine the mediating role of worrisome thoughts in the relationship between anxiety and task-switching using an online measure to probe TUT.

In view of these research gaps, the present study pursued five goals. First, I aimed to elucidate the specific processing component of task-switching that is affected by anxiety. To this end, I employed a classical diffusion model analysis (Ratcliff, 1978), which derives a number of meaningful parameters by utilizing information provided by positions, shapes, and sizes of empirical RT distributions (Figure 1). The parameters of my primary interest are drift rate parameter (v) – which quantifies the speed and direction of information accumulation— and nondecision time (t0) parameter –which quantifies the duration of all non-decision processes such as encoding or response execution. Recent studies which employed a diffusion model (Karayanidis et al., 2009; Mansfield, Karayanidis, Jamadar, Heathcote, & Forstmann, 2011; Schmitz & Voss, 2012, 2014) demonstrated that the nondecision time captures an earlier phase of a task switch which reflects task-set reconfiguration processes, while drift rate captures a later phase of a task switch which reflects proactive interference. Therefore, examining nondecision time (t0) and drift rate (v) of a diffusion model allows us to examine whether impaired switch costs by anxiety is attributed to either task-set reconfiguration or proactive interference. Drawing on attentional control theory (Eysenck et al., 2007), I hypothesized that both trait and state anxiety would impair switch costs of nondecision time parameter but not drift rate parameter, as the former reflects efficiency in exerting attentional control in task-set reconfiguration.

Second, I aimed to examine the relation of anxiety to tendency to use compensatory strategies during task-switching. According to the attentional control theory (Eysenck et al., 2007), anxious individuals are motivated to maintain their performance effectiveness of task-switching (i.e., the accuracy of task-switching) from the adverse effect of anxiety – owing to lesser attentional resources – by compensating performance effectiveness with processing efficiency (i.e., slower processing time). In view of this, the parameter called boundary separation (a) – which quantifies the speed-accuracy trade-off in responding—is useful to test the link between anxiety and the presence of compensatory strategies. High boundary separation is characterized by higher accuracy at the cost of slower RT (Starns & Ratcliff, 2010), reflecting a more conservative decisional styles, which is consistent with the notion of a compensatory strategy as suggested by attentional control theory (Eysenck et al., 2007). Thus, I hypothesized that if anxiety maintains performance effectiveness (accuracy) at the expense of processing efficiency (RT) during task-switching, boundary separation should increase as a function of state or trait anxiety in task-switching paradigm. Specifically, anxiety would be positively associated with boundary separation parameters of blocks that require task-switching (mixed blocks), but not in blocks that does not require task-switching (pure blocks). This would ensure that anxious individuals’ conservativeness is related to their strategy to maintain high accuracy during task-switching—which occurs in mixed blocks only—rather than their overall tendency to be conservative in general. Furthermore, if the negative effect of anxiety on task-switching effectiveness was suppressed by a compensatory strategy, I would observe impaired task-switching effectiveness due to anxiety when the compensatory strategy was controlled in the analysis.

Third, I aimed to examine the relationship between anxiety and mixing costs of the task-switching paradigm. Because task-switching has been typically conceptualized as switch costs which implicate transient control processes at a local level where switching from one task set to another occurs (Monsell, 2003), extant literature has focused on the relationship between anxiety and switch costs only (Ansari et al., 2008; Edwards et al., 2015; Derakshan et al., 2009). However, although task-switching entails not only switch costs but also mixing costs that arise from global control mechanisms in monitoring and maintaining two competing task sets (Braver, Reynolds, & Donaldson, 2003; Rubin & Meiran, 2005), little research has examined the relationship between anxiety and mixing costs. Therefore, it is critical to examine whether the adverse effect of anxiety could be extended to global control mechanisms in task-switching, which is essential in facilitating task-switching performance by optimizing preparation to switch in advance (Braver et al., 2003). To this end, I hypothesized that if anxiety impairs processing efficiency of task-switching performances as predicted by the attentional control theory, both state and trait anxiety would also incur greater mixing costs.

Fourth, I aimed to examine the mediating role of TUT in the relationship between anxiety and task-switching. In order to assess TUT without resorting to prospective or retrospective measurement, I employed thought probe technique (Stawarczyk et al. 2011; Unsworth & McMillan, 2014) during task-switching such that participants were asked to report at random points whether their immediately preceding thoughts were on- or off-task. Despite the introspective nature of thought probe technique, previous studies demonstrated that TUT measured by online thought probe technique is reasonably valid and predicts cognitive performances significantly better than other objective markers of mind-wandering reports, such as intra-individual RT patterns (McVay &Kane, 2012). Moreover, to further test predictions of attentional control theory, I modified the thought probe technique to differentiate between non-threatening TUT (e.g., daydreaming) and threatening TUT (e.g., worries). Based the prediction by attentional control theory that anxiety reduces attentional focus during task-switching by increasing internal threat-related worrisome thoughts, I hypothesized that the deleterious effect of anxiety on task-switching would be significantly mediated by the frequency of threatening TUT but not by that of non-threatening TUT. However, if the frequency of threatening TUT does not mediate the effect of anxiety on task-switching, it may support the alternative view from the recent findings in neuroimaging (Forster et al., 2015), which argued that impoverished prefrontal mechanisms in anxious individuals are not caused by worrisome thoughts but instead simply reflects an inherent characteristic of trait anxiety.

Lastly, I aimed to explore the moderating effect of WMC on the relationship between anxiety and task-switching. Although attentional control theory predicts that anxiety impairs processing efficiency, some studies failed to replicate this even when similar tasks were employed (e.g., Harris, 2013; Unsworth et al., 2009). Furthermore, a meta-analysis by Seipp (1991) showed that the negative correlation between anxiety and test performance was heterogeneous, indicating that some studies found null effects of anxiety or even positive association between anxiety and performance. These inconsistent findings suggest potential boundary conditions where anxiety is unthreatening or even beneficial for processing efficiency. We explored WMC—which refers to the ability to maintain task-relevant information in the face of concurrent interference (Miyake et al., 2000)—as a potential moderator. My exploration of WMC was motivated by recent studies which suggested WMC could minimize the cognitive implication of anxiety. For instance, Owens, Stevenson, Hadwin and Norgate (2014) found that WMC significantly moderated the relationship between anxiety and mathematical performance. Specifically, anxiety and mathematical performance were positively correlated (i.e., anxiety benefits mathematical performance) among participants with high WMC, but negatively correlated among participants with low WMC (i.e., anxiety impairs mathematical performance). Similarly, Johnson and Gronlund (2009) found that high WMC individuals were not affected by their trait anxiety when performing on a dual-task which consisted of a highly demanding memory task as a primary task and an auditory probe task as a secondary task. These findings suggest that individual differences in WMC may provide a shield from deleterious effect of anxiety. Given this, it is plausible that WMC moderates the relationship between anxiety and cognitive performance in task-switching. Hence, I hypothesized that anxiety would impair task-switching performances only among individuals with low WMC. In contrast, I expect that anxiety would not impair (or even benefit) task-switching performances among those with high WMC.

CHAPTER 2: METHOD

Participants

One hundred and sixty undergraduates (female = 119) from a local university in Singapore participated in the study for extra course credits. Two participants were excluded due to technical error during the switching task. Five participants who reported feeling unwell (e.g., gastric, vertigo, or headache) during the data collection were also excluded from the analysis. The exclusion resulted in a total sample of 152 participants (female = 113), with an average age of 20.9 years (*SD* = 1.74, range = 18–26). These participants came from varying socioeconomic status (SES) levels, as indexed by their monthly household income in Singapore dollars: less than $2,500 (8.6%), $2,500-S$4,999 (17.8%), $5,000-S$7,499 (20.4%), $7,500-S$9,999 (15.8%), $10,000-S$12,499 (12.5%), $12,500-S$14,999 (7.9%), $15,000-S$17,499 (7.2%), $17,500 -S$19,999 (3.3%), and more than S$20,000 (6.6%).

Materials

Task-switching paradigm with thought probing. The task-switching paradigm (Rubin & Meiran, 2005) was employed to examine switch costs and mixing costs. In the task-switching paradigm, participants were asked to respond as fast and accurately as possible to either the color (red or green) or shape (circle or triangle) of a bivalent stimulus (i.e., red triangle and green circle), according to the cue given. Participants responded by pressing either the left key, marked “red” and “circle,” or the right key, marked “green” and “triangle” with these keys counterbalanced across participants. Participants were instructed to complete one practice block (comprising 30 trials) and eight experimental blocks including two pure blocks at the start—pure-color and shape blocks, the order of which was counterbalanced across participants—and four mixed blocks, and another two pure blocks at the end, all of which were presented in this fixed order. Pure blocks consisted of only one task cue, and thus, did not require task-switching. Mixed blocks, however, consisted of two possible cues and therefore required task-switching in an unpredictable manner. Mixed blocks involved either repeat or switch trials. In repeat trials, a task which was same as the previous one was repeatedly presented, whereas in switch trial, a task which was different from the previous task (e.g., color task) was presented, which in turn required task-switching. Switch costs were calculated by subtracting performance index (mean RTs, accuracy) on repeat trials from that on switch trials, whereas mixing costs were calculated by subtracting the relevant index of performance on pure trials in pure blocks from that of repeat trials in mixed blocks (Rubin & Meiran, 2005).

Each pure block is comprised of 40 trials, while mixed-block is comprised of 80 trials. For the mixed blocks, half of the trials involved task-switching, while the other half did not; these trials were randomly presented with a maximum of four consecutive trials of the same task. As such, there were 160 trials for each type of trials (pure, repeat, and switch trials). Color gradient and a row of small black shapes were used as cues to indicate color and shape tasks, respectively. There were two possible targets (i.e., a red triangle or a green circle). For each trial, a fixation cross appeared for 350 ms and was followed by a blank screen for 150 ms. Subsequently, the cue appeared for 250 ms and was followed by the target. During the switching task, participants were periodically prompted by probing questions and asked to press one of seven keys to indicate what they were thinking immediately prior to the presentation of the probe. Thought-probing questions are as follows; (1) I am totally focused on the current task; (2) I am thinking about my performance on the task or how long it is taking; (3) I am thinking about some of my concerns, troubles, or fears; (4) I am thinking some important stuff or recent worries; (5) I am distracted by information present in the room (sights or sounds); (6) I am having some fantasies that are disconnected from reality; (7) I am thinking some unimportant stuff. Of these seven options, option 1 was coded as on-task thoughts, while option 2 was coded as task-related interference (TRI). We distinguished between on-task thoughts and TRI as the latter was argued to reflect a form of lapse in attention as the participant is not fully focused on the task (Smallwood et al., 2004). We further coded option 3 and 4 as threatening TUT, option 5 as external distraction, and option 6 and 7 as non-threatening TUT.

Thought probe randomly occurred toward the end of 15% of the trials in both pure and mixed blocks. Thought-probe prompts were pseudo-randomized to occur equally before each type of trials (e.g., repeat and switch trials). Since it is believed that thought probe questions likely incur proactive interference during task-switching, all of my later analysis removed those trials that were preceded by thought probes.

Complex span tasks. Rotation-span and symmetry-span tasks were employed to measure WMC (Foster et al., 2015). In the rotation-span task, participants were instructed to judge whether a rotated letter mirrored the target letter. Subsequently, an arrow of either short or long length pointing in one of eight different directions appeared and participants were asked to remember both the length and the direction of the arrow. The rotated letter and arrow sequence would be repeated from two to five times for each trial with unpredictable length.

In the symmetry-span task, participants were instructed to judge whether a displayed shape is symmetrical along its vertical axis. Subsequently, a red square appeared in a 4x4 grid and participants were asked to remember the location of the red square. The symmetry and location sequence was repeated from two to five times for each trial with unpredictable length. In both rotation- and symmetry-span tasks, the set size (i.e., the total number of arrows to remember) varied from two to five per trial. Scores in each task were computed by using the partial-credit unit (PCU) method, in which the participant’s score was expressed as the proportion of the total number of correct recall responses in a set (Conway et al., 2005). Subsequently, PCU scores from rotation-span and symmetry-span tasks were summed to compute participant's WMC.

State-Trait Anxiety Inventory (STAI). State and trait version of STAI (Spielberg, Gorsuch, Lushene, Vagg, & Jacobs, 1983) were employed to measure participants' state and trait anxiety, respectively. The scale contained 20 items to measure state anxiety ($\alpha = .90$) and 20 items to measure trait anxiety ($\alpha = .90$) on a 4-point Likert scale. Scores for the 20 items were summed to compute the score for state anxiety and trait anxiety.

Procedure

Participants were seated individually in an open cubicle and then asked to sign an informed consent form. Subsequently, participants were asked to complete a state version of STAI before proceeding to the switching task with thought probing. Upon the completion of this, participants were instructed to complete rotation- and symmetry-span tasks. Finally, participants completed a demographic survey and trait version of STAI. The entire task took approximately 70 minutes to complete.

CHAPTER 3: Results

Switch Costs

Accuracy and RT. Ordinary least squares (OLS) regression analyses were conducted to examine the predictability of state and trait anxiety in the effectiveness (accuracy) and efficiency (RT) of switch costs in task-switching. For the analysis in RT, the accurate responses that were either 2.5 *SD* above or below an individual's mean were excluded separately for pure blocks and mixed blocks.

I found that state anxiety marginally predicted switch costs in RT (B = 1.94, SE = 1.04, Beta = .15, 95% CI [-0.12, 4.00], t = 1.87, p = .064), but not switch costs in accuracy (B = 0.00, SE = 0.00, Beta = -.06, 95% CI [0.00, 0.00], t = -0.75, p = .453). Trait anxiety also marginally predicted switch costs in RT (B = 1.66, SE = 1.00, Beta = .14, 95% CI [-0.30, 3.63], t = 1.67, p = .097), but not switch costs in accuracy (B = 0.00, SE = 0.00, Beta = .04, 95% CI [-0.00, 0.00], t = 0.51, p = .608). These results suggest that state and trait anxiety influence processing efficiency but not performance effectiveness of task-switching.

Diffusion model analysis. We performed a diffusion model analysis to decompose switch costs into task-set reconfiguration and proactive interference. In my analysis, drift rate (v), nondecision time (t0), and boundary separation (a) were allowed to vary freely across pure, repeat, and switch trials. Following the recommendation by Voss, Nagler, and Lerche (2013), starting point (zr) was fixed in the middle between the two response barriers (i.e., zr = 0.5). Similarly, variability parameters and response-execution differences (d) were fixed to zero, except for the inter-trial variability of nondecisional components (st0), which were held constant across trials (Hartanto & Yang, 2016; Voss et al., 2013). Parameters were estimated using Fast-dm for each participant, with Kolmogorov-Smirnov (KS) statistic for optimization of parameters (Voss, Voss, & Lerche, 2015). Following Weeda, van der Molen, Barceló, and

Huizinga (2014), I conducted a series of simulations to estimate decision time parameters that were purely driven by drift rate but not by boundary separation. First, I performed simulations to estimate the parameters of diffusion model (e.g., drift rate and nondecision time) by fixing the value of each participant's boundary separation parameter in switch trial to the value of each participant's boundary separation parameter in repeat trial. Subsequently, using the value I obtained from the simulation, I further simulated estimated RTs for each participant in both repeat and switch trials. The values of nondecision time parameter in repeat and switch trials were then subtracted from the estimated total RT in repeat and switch trials respectively to compute the values of decision time in each participant. Later, switch costs in decision time that is driven purely by drift rate parameter – which captures proactive interference processes – were calculated by subtracting the decision time of repeat trials from that of switch trials, while switch costs in nondecison time parameter – which captures task-set reconfiguration processes – were calculated by subtracting nondecision time of repeat trials from that of switch trials.

Similar to the above analyses for accuracy and RT, a new set of regression analyses was conducted to elucidate the specific component of task-switching that is associated with state and trait anxiety. As shown in Figure 2, I found that state anxiety significantly predicted switch costs in nondecision time (B = 2.18, SE = 0.96, Beta = .18, 95% CI [0.29, 4.08], t = 2.27, p = .024), but not switch costs in decision time (B = 0.05, SE = 0.92, Beta = .00, 95% CI [-1.77, 1.86], t = -0.05, p = .960). In contrast, trait anxiety significantly predicted neither switch costs in nondecision time (B = 1.52, SE = 0.92, Beta = .13, 95% CI [-0.31, 3.34], t = 1.64, p = .102), nor decision time (B = 0.49, SE = 0.88, Beta = .05, 95% CI [-1.24, 2.22], t = 0.56, p = .575). These findings suggest that only state anxiety was associated with impaired task-set reconfiguration during task-switching.

Boundary Separation

To examine anxious individuals' use of compensatory strategies during task-switching, regression analyses were conducted to predict boundary separation parameters of a diffusion model with state or trait anxiety as predictors. We found that state anxiety was a significant predictor of boundary separation in repeat trials (B = 0.01, SE = 0.00, Beta = .22, 95% CI [0.00, 0.02], t = 2.81, p = .006) and switch trials (B = 0.01, SE = 0.00, Beta = .18, 95% CI [0.00, 0.02], t = 2.19, p = .030), but not in pure trials (B = 0.00, SE = 0.00, Beta = .10, 95% CI [-0.00, 0.01], t = 1.28, p = .202). Similarly, trait anxiety was a significant predictor of boundary separation in repeat trials (B = 0.01, SE = 0.00, Beta = .16, 95% CI [0.00, 0.02], t = 2.00, p = .047) and switch trials (B = 0.01, SE = 0.00, Beta = .16, 95% CI [0.00, 0.02], t = 1.98, p = .049), but not in pure trials (B = 0.00, SE = 0.00, Beta = .07, 95% CI [-0.00, 0.01], t = 0.91, p = .367). These findings suggest that individuals with greater state or trait anxiety were more conservative only during tasks which required task-switching, and they compensated performance effectiveness by sacrificing processing efficiency (see Figure 3).

Furthermore, I conducted hierarchical regression analyses to examine whether compensatory strategy suppressed the negative effect of anxiety on performance effectiveness of task-switching. In the first step, anxiety was included in the model to predict performance effectiveness of task-switching. In the second step, boundary separation in both repeat and switch trials were included in the model to estimate the unique effect of anxiety on performance effectiveness without the influence of compensatory strategy. State anxiety and trait anxiety were analysed in a separate model. Switch cost in accuracy was used as an indicator of performance effectiveness of task-switching. Other than switch costs in accuracy, I also calculated switch costs by using rank-ordering binning procedure that combines speed and accuracy to form a single, comprehensive score of task-switching performance (Hughes, Linck, Bowles, Koeth, & Bunting, 2014; see Draheim, Hicks, & Engle, 2016, for details on calculating switch costs by using the binning procedure). As the binning procedure takes into account accuracy in calculating switch costs, it can be used as another proxy indicator of performance effectiveness which has higher reliability than typical switch costs in accuracy (Hughes et al., 2014). As shown in Table 2, in the first step, state anxiety did not significantly predict switch costs of accuracy (p = .453) and binning procedure (p = .114). However, after controlling for boundary separations in repeat and switch trials in the second step, state anxiety marginally predicted switch costs in accuracy (p = .063) and significantly predicted switch costs calculated by the binning procedure (p = .002), suggesting that compensatory strategy as indicated by boundary separation parameters of a diffusion model suppressed the relationship between state anxiety and indicators of performance effectiveness in task-switching. Nevertheless, the suppressing effect of compensatory strategy was not evident in trait anxiety.

Mixing Costs

We conducted regression analyses to investigate the predictability of state and trait anxiety on the effectiveness and efficiency of mixing costs in the task-switching paradigm. Similar to the above analyses for switch costs, accurate responses that were either 2.5 *SD* above or below an individual's mean were excluded separately for pure blocks and mixed blocks. As shown in Figure 4, we found that state anxiety was a significant predictor of mixing costs in RT (B = 3.76, SE = 1.48, Beta = .20, 95% CI [0.84, 6.68], t = 2.55, p = .012), but not in accuracy (B = 0.00, SE = 0.00, Beta = -.03, 95% CI [0.00, 0.00], t = -0.38, p = .701). However, I found that trait anxiety was not a significant predictor of mixing costs in both RT (B = 1.86, SE = 1.43, Beta = .11, 95% CI [-0.97, 4.69], t = 1.30, p = .196), and accuracy (*B* = 0.00, *SE* = 0.00, Beta = -.04, 95% CI [-0.00, 0.00], *t* = 0.54, *p* = .592). These results suggest that only state anxiety is associated with impaired efficiency of mixing costs.

Task-unrelated Thoughts

We conducted mediation analyses to examine whether threatening or non-threatening TUT significantly mediated the relationship between anxiety and task-switching. Here, I focused solely on state anxiety as my independent variable (IV) due to the fact that most of my analyses failed to find any significant relationship between trait anxiety and either switch or mixing costs. Three potential mediators were analysed, including (1) threatening TUT, (2) non-threatening TUT, and (3) total TUT (threatening TUT + non-threatening TUT). Note that I also considered the total TUT because most of previous studies on TUT and cognitive performance did not take into account the difference between threatening and non-threatening TUT (see Table 3 for the proportion of each type of conscious experience during thought-probe). Lastly, only criterions that were found to be significantly associated with state anxiety were considered, including (a) nondecision time (t0) of swich costs, (b) mixing costs in RT, (c) boundary separations of repeat trials, and (d) boundary separations of switch trials. Multiple mediation models were estimated through the PROCESS macro (Hayes, 2009) with bias-corrected bootstrapping of 10,000 samples for all of the analyses. Mediation is considered significant if the 95% bias-corrected confidence intervals for indirect effects do not encompass zero (Preacher & Hayes, 2004). As shown in the Table 4, state anxiety was positively associated with TUT, which is mostly driven by threatening TUT. However, threatening TUT, nonthreatening TUT, and total TUT did not significantly predict any of my criterions (e.g., switch costs of nondecision time, mixing costs of RT). As a results, across 12 mediation models, the indirect effect of state anxiety on indicators of task-switching performance through TUT as mediator was not significant.

Working Memory

We performed a series of moderation analyses using process macro (model 1; Hayes, 2012) to examine whether WMC significantly moderated the effect of state or trait anxiety on indicators of task-switching performance. Due to a technical problem, one participant's data from rotation-span and symmetry-span tasks separately were excluded from moderation analyses. As shown in Table 5, the interaction terms between anxiety and WMC did not significantly predict any of indices of task-switching performance, indicating that WMC did not moderate the effect of state or trait anxiety during task-switching.

CHAPTER 4: DISCUSSION

My experiment revealed five major findings on the extent and mechanisms of the relationship between anxiety and task-switching (switch and mixing costs). First, I elucidated the specific component of task-switching that is affected by anxiety. Using a diffusion model analysis, I decomposed switch costs into parameters of nondecision time and drift rate (i.e., decision time) – which primarily reflect task-set reconfiguration and proactive interference processes respectively (Schmitz & Voss, 2012, 2014). I found that state anxiety was associated with higher switch costs of nondecision time parameter but not switch costs of drift rate (i.e., decision time) parameter, suggesting that state anxiety impaired task-set reconfiguration but not proactive interference processes of task-switching. This finding supports the assumption of attention control theory (Eysenck et al., 2007), in which the adverse effect of anxiety on switch costs is argued due to impaired efficiency of exerting attentional control during task-set reconfiguration. In contrast, regarding the effect of trait anxiety on switch costs, I found either marginally significant or null results. While this result may contradict some studies which have found significant relationship between trait anxiety and switch costs (Edwards et al., 2015; Derakshan et al., 2009), it is important to note that attentional control theory assumes that trait anxiety is simply a predisposition toward experiencing state anxiety (Eysenck et al., 2007; Spielberger et al., 1970). Thus, it is plausible that impaired processing efficiency in task-switching is more directly related to state anxiety than trait anxiety (see Booth & Peker, 2016 for similar findings).

Second, I found a direct evidence supporting the existence of compensatory strategy related to anxiety. According to attentional control theory (Eysenck et al., 2007), anxious individuals are motivated to retain their performance effectiveness of task-switching from the adverse effect of anxiety by compensating the performance effectiveness with processing efficiency. The compensatory strategy explains why anxiety is not associated with impaired task-switching accuracy. Using a diffusion model, I argued that the compensatory strategy as illustrated by attentional control theory could be reflected by a high boundary separation parameter – which characterize higher accuracy at the cost of slower RT. Consistent with my hypothesis, I found that both state and trait anxiety were positively associated with boundary separation parameters of mixed-block but not pure-block of task-switching paradigm. The results suggest that anxious individuals selectively compensate performance effectiveness by sacrificing processing efficiency when the tasks are demanding and require extra attentional control to switch from one task to another. More importantly, I demonstrated that the adverse effect of state anxiety on indicators of performance effectiveness of switch costs emerged when boundary separation in mixed-block was controlled in the analyses. The result supports attentional control theory and provides evidence that compensatory strategy ameliorates the adverse effect of state anxiety on indicators of performance effectiveness in task-switching. My result also casts doubt on possible argument that differential effects of anxiety on performance effectiveness and processing efficiency are simply due to measurement artefact caused by lower reliability and ceiling effects in accuracy measures of task-switching.

Third, I extended current understanding of cognitive consequences of anxiety in mixing costs of task-switching. Unlike previous studies which have focused solely on switch costs (Edwards et al., 2015; Derakshan et al., 2009), the switching task used in the present study was also designed to measure mixing costs, which reflect global sustained control mechanisms in monitoring and maintaining two competing task sets (Rubin & Meiran, 2005). To this end, I found that state anxiety was associated with higher mixing costs in RT but those in accuracy. The result shows that anxiety does not only impair task-set reconfiguration processes, but also the processing efficiency of maintaining multiple task sets and resolving interference or conflicts arising from competing task sets. It is noteworthy that the efficiency in maintaining two competing task sets is essential in facilitating successful completion of task-switching, as it optimizes the preparation to switch in advances (Braver et al., 2003).

Fourth, although threatening TUT was significantly higher in anxious individuals, I did not find any mediating role of threatening or non-threatening TUT on the relationship between anxiety and task-switching performances. This finding is consistent with recent studies that failed to find any relationship between worry and cognitive performance (Harris, 2013; Forster et al., 2015; Moser et al., 2012). It is noteworthy, however, that TUT in the present study was associated with slower RT in all types of trials in task-switching paradigm, pure (r = .221, p = .006), repeat (r = .221, p = .006), and switch (r = .189, p = .020), suggesting that the occurrence of TUT could indiscriminately impairs processing efficiency in general across all types of trials, possibly due to lapse of attention during mind wandering (McVay & Kane, 2009). As the adverse effect of TUT frequency is not trial-specific, its effect on task-switching could be neutralized when switch costs or mixing costs were calculated using difference scores between two different types of trials (e.g., switch trials and repeat trials). Alternatively, it is also plausible that switch costs and mixing costs of task-switching paradigm are more likely to be affected by the intensity rather than merely the frequency of worrisome thoughts. As argued by attentional control theory (Eysenck et al., 2007), impaired task-switching by anxiety is due to the preferential allocation of attentional resources to worrisome thoughts, which resulted in the loss of attentional resources for ongoing task-switching. Given this argument, it is plausible that the proportion of attentional resources that is distributed between ongoing task-switching and worrisome thoughts could vary across different intensity of worrisome thought. For instance, worrying about failing on an official exam might consume more attentional resources than worrying about failing on a mock exam. If this is the case, future research should consider the intensity of worrisome thought in examining the mediating role of TUT on the relationship between anxiety and task-switching.

The insignificant mediating role of TUT on the relationship between anxiety and task-switching could also relate to recent neuroimaging studies which have found that high trait anxious individuals showed impoverished prefrontal mechanisms in the brain that govern attentional control (Bishop et al., 2008; Forster et al., 2015). The neuroimaging findings proposed that the anxiety-related deficit in prefrontal mechanisms does not arise from state anxiety or worrisome thoughts but reflects an underlying characteristic of trait anxiety. However, these findings are not consistent with current findings that impaired processing efficiency in task-switching in terms of switch costs and mixing costs is more directly related to state anxiety than trait anxiety. Thus, more research should be conducted to examine whether state anxiety could also temporarily impair the recruitment of prefrontal mechanisms underlying task-switching performance.

Lastly, I found that WMC did not moderate any relationship between anxiety and task-switching performance. My exploration on the moderating role of WMC in the relationship between anxiety and task-switching performance was motivated by recent studies that found WMC attenuated the adverse effect of trait anxiety on performance on mathematical problems (Owens et al., 2014) and memory task in the dual-task paradigm (Johnson & Gronlund, 2009). However, the moderating effect of WMC on task-switching performance was not conceptually replicated, demonstrating that WMC does not prevent the detrimental effect of anxiety during task-switching. My result suggests that the beneficial effect of WMC in attenuating deleterious effect of anxiety can be task specific. Specifically, it is plausible the interaction between anxiety and WMC can only emerge when the participants are examined by using cognitive tasks that highly demand the ability to maintain task-relevant information in the face of concurrent interference, such as mathematical tests and dual-task paradigm with high memory load (Raghubar, Barnes, & Hecht, 2010; Redick et al., in press). In contrast, although task-switching and WMC are often categorized under the umbrella of executive functions, research has demonstrated that task-switching costs (i.e., switch costs and mixing costs) implicate many aspect of cognitive processes that are distinct from WMC (Miyake et al., 2000; Rubin & Meiran, 2005). This could explain why the interaction between anxiety and WMC was not observed in the current study.

My study is not without its limitations. Given that current study focused on naturally occurring variations in state anxiety, the causality aspect of the study was not well-established due to the lack of manipulation in state anxiety. Although my study is based on attentional control theory that theorized the impaired task-switching performances is caused by anxiety (Eysenck et al., 2007), the conclusion of the current study could be strengthened by future studies which experimentally manipulate state anxiety before instructing participants to complete task-switching paradigm. Furthermore, given that I only employed colour-shape variant of task-switching paradigm, it is worthwhile for future study to examine the robustness of my findings using other variants of task-switching paradigm in computing switch costs and mixing costs. Employing more than one variant of task-switching paradigm would allow future study to circumvent possible task impurity issue in task-switching paradigm (Miyake et al., 2000).

In summary, the current study contributes to elucidating several theoretical assumptions on the relationship between anxiety and task-switching. Consistent with attentional control theory (Eysenck et al., 2007), I identified the locus of task-switching impairment in state anxious individuals is pertinent to task-set reconfiguration processes. I also presented a direct evidence demonstrating the presence of compensatory strategy among anxious individuals when performing demanding task-switching. With regards to mixing costs, my result extends the implication of anxiety not only to transient control of task-set reconfiguration but also to global sustained control mechanisms in monitoring and maintain two competing task sets during task-switching. However, my further mediation analyses indicate that the frequency of TUT does not mediate the adverse effect of state anxiety on task-switching performances. Lastly, I did not find any evidence that support the possibility that WMC could shield the negative effect of anxiety on task-switching performances. These findings contribute to my understanding on the extent and mechanism underlying the relationship between anxiety and task-switching.

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Table 1. Descriptive Statistics of Anxiety, Task-switching, and Working Memory Measures

	M	*SD*	Range	Skewness	Kurtosis
Anxiety (STAI)					
State	40.04	8.77	23.00 – 69.00	0.64	0.85
Trait	46.70	9.19	27.00 – 71.00	0.14	-0.59
Boundary separation (a)					
Pure trials	1.26	0.31	0.50 – 2.38	0.65	0.72
Repeat trials	1.90	0.44	0.80 – 2.87	0.12	-0.41
Switch trials	1.80	0.44	0.83 – 2.94	0.47	-0.22
Switch costs					
Accuracy (%)	-0.08	0.05	-0.25 – -0.03	-0.94	0.72
RT (ms)	234	113	-22 – 620	0.73	0.90
Decision time (ms)	112	99	-265 – 366	-0.06	1.16
Nondecision time (ms)	148	105	-78 – 520	0.80	1.03
Mixing costs					
Accuracy (%)	-0.01	0.04	-0.19 – 0.22	0.08	11.31
RT (ms)	311	162	3 – 935	0.93	1.20
Working Memory					
Rotation-span[1]	5.72	1.39	0.53 – 8.25	-1.00	1.36
Symmetry-span[1]	6.21	1.27	1.73 – 8.00	-1.30	2.16
Total score[2]	11.94	2.22	3.73 – 15.45	-1.24	1.93

[1] Data from 1 participant was missing

[2] Data from 2 participants were missing

Table 2. Summary of Multiple Regression Analyses for Predicting Switch Costs in Accuracy and Binning Procedure

	Step 1		Step 2	
	B (SE)	*p*	*B* (SE)	*p*
Model 1: DV = Switch costs (accuracy)				
State anxiety	.000 (.000)	.453	-0.001 (.000)	.063
Boundary separation (repeat trials)	-	-	0.025 (.014)	.061
Boundary separation (switch trials)	-	-	0.025 (.014)	.083
Model 2: DV = Switch costs (binning)				
State anxiety	0.021 (.013)	.114	0.037 (.012)	.002
Boundary separation (repeat trials)	-	-	0.301 (.356)	.399
Boundary separation (switch trials)	-	-	-1.677 (.362)	.000
Model 3: DV = Switch costs (accuracy)				
Trait anxiety	0.000 (.000)	.514	0.000 (.000)	.786
Boundary separation (repeat trials)	-	-	0.021 (.014)	.138
Boundary separation (switch trials)	-	-	0.026 (.014)	.065
Model 4: DV = Switch costs (binning)				
Trait anxiety	0.007 (.012)	.571	0.017 (.012)	.148
Boundary separation (repeat trials)	-	-	-1.555 (.367)	.000
Boundary separation (switch trials)	-	-	0.282 (.365)	.441

Note. Higher values reflect better performance in switch costs of accuracy while lower values reflect better performance in switch costs of binning procedure.

Table 3. Proportions of Each Type of Conscious Experience during Task-switching across Pure and Mixed-blocks

	On-task	TRI	Threatening TUT	Non-threatening TUT	ED
Total	0.55 (0.31)	0.28 (0.25)	0.08 (0.17)	0.07 (0.12)	0.03 (0.06)
Pure	0.62 (0.33)	0.23 (0.26)	0.07 (0.18)	0.06 (0.11)	0.03 (0.06)
Mixed	0.51 (0.34)	0.30 (0.28)	0.08 (0.18)	0.07 (0.14)	0.04 (0.07)

Note. *SD*s are shown in parentheses. TRI = task-related interference, ED = external distraction.

Table 4. Summary of Mediation Analyses with State anxiety as the Independent Variable (IV)

Mediator (M)	Dependent Variable (DV)	Effect of IV on M (*a*)	Effect of M to DV (*b*)	Total Effect (*c*)	Direct Effect (*c*')	Indirect Effect	95% CI for Indirect Effect	Kappa-squared
Threatening TUT	Switch costs (t0)	0.007 (0.002)**	-56.04 (51.68)	2.18 (0.96)*	2.57 (1.02)*	-0.39 (0.36)	-1.347, 0.085	0.03
	Mixing costs (RT)	0.007 (0.002)**	69.92 (79.61)	3.76 (1.48)*	3.28 (1.58)*	0.48 (0.69)	-0.940, 1.888	0.03
	BS of repeat trials	0.007 (0.002)**	0.08 (0.22)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.004, 0.003	0.01
	BS of switch trials	0.007 (0.002)**	-0.02 (0.22)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.005, 0.003	0.03
Non-threatening-TUT	Switch costs (t0)	0.002 (0.001)	99.99 (71.63)	2.18 (0.96)*	2.02 (0.96)*	0.16 (0.22)	-0.107, 0.826	0.01
	Mixing costs (RT)	0.002 (0.001)	103.06 (110.56)	3.76 (1.48)*	3.60 (1.49)*	0.16 (0.26)	-0.120, 0.893	0.01
	BS of repeat trials	0.002 (0.001)	0.45 (0.30)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.000, 0.003	0.01
	BS of switch trials	0.002 (0.001)	0.35 (0.30)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.000, 0.003	0.01
Total TUT	Switch costs (t0)	0.009 (0.002)**	-3.06 (44.09)	2.18 (0.96)*	2.21 (1.03)*	-0.03 (0.45)	-1.016, 0.783	0.00
	Mixing costs (RT)	0.009 (0.002)**	89.04 (67.42)	3.76 (1.48)*	3.00 (1.58)	0.76 (0.61)	-0.399, 2.026	0.04
	BS of repeat trials	0.009 (0.002)**	0.22 (0.18)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.001, 0.005	0.04
	BS of switch trials	0.009 (0.002)**	0.11 (0.19)	0.01 (0.00)*	0.01 (0.00)*	0.00 (0.00)	-0.003, 0.005	0.02

Note. *SE*s are shown in parentheses. State anxiety was included as the independent variable for all of the analyses. Analyses were conducted with bias-corrected bootstrapping with 10,000 samples. TUT = task-unrelated thought; switch costs (t0) = switch costs in nondecision times; mixing costs (RT) = mixing costs in response time; BS = boundary separations. * $p < .05$, ** $p < .001$

Table 5. Summary of Interactions between Anxiety and WMC on Task-switching

Interaction	DV	*B*	*SE*	95% CI	*p*
State anxiety x WMC	SC (RT)	-0.069	0.541	-1.138, 1.000	.899
	SC (accuracy)	0.000	0.000	-0.001, 0.001	.903
	SC (t0)	-0.100	0.491	-0.871, 1.071	.839
	SC (decision time)	-0.549	0.489	-1.516, 0.418	.263
	MC (RT)	0.633,	0.777	-0.902, 2.168	.416
	MC (accuracy)	0.000	0.000	-0.001, 0.000	.069
	BS of pure trials	0.000	0.002	-0.002, 0.003	.852
	BS of repeat trials	-0.001	0.002	-0.005, 0.003	.554
	BS of switch trials	0.000	0.002	-0.005, 0.004	.873
Trait anxiety x WMC	SC (RT)	0.463	0.494	-0.513, 1.440	.350
	SC (accuracy)	0.000	0.000	-0.001, 0.000	.278
	SC (t0)	-0.200	0.453	-1.095, 0.696	.660
	SC (decision time)	0.473	0.445	-0.407, 1.353	.290
	MC (RT)	0.965	0.717	-0.453, 2.382	.181
	MC (accuracy)	0.000	0.000	-0.001, 0.000	.287
	BS of pure trials	0.001	0.001	-0.004, 0.002	.590
	BS of repeat trials	0.002	0.002	-0.002, 0.006	.264
	BS of switch trials	0.002	0.002	-0.001, 0.006	.215

Note. SC = switch costs, MC = mixing costs, BS = boundary separations

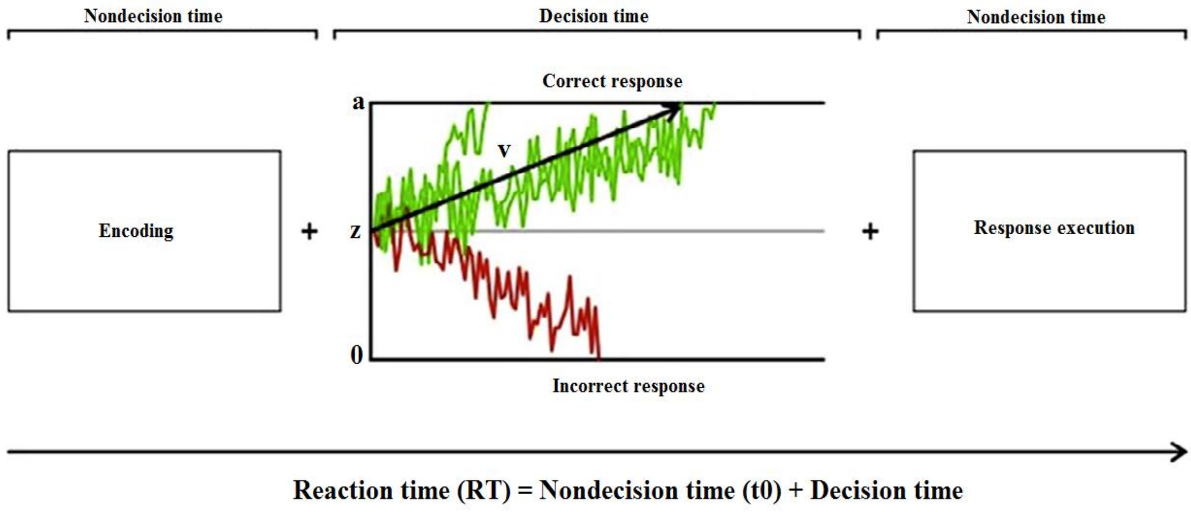

Figure 1. Diffusion process underlying the diffusion model. The model assumes that decisions are based on the accumulation of information over time until a response boundary is reached and a motor response elicited (Ratcliff, 1978; see Voss, Nagler, & Lerche, 2013, for a practical introduction to diffusion models). Adapted from Weeda, van der Molen, Barceló, and Huizinga (2014).

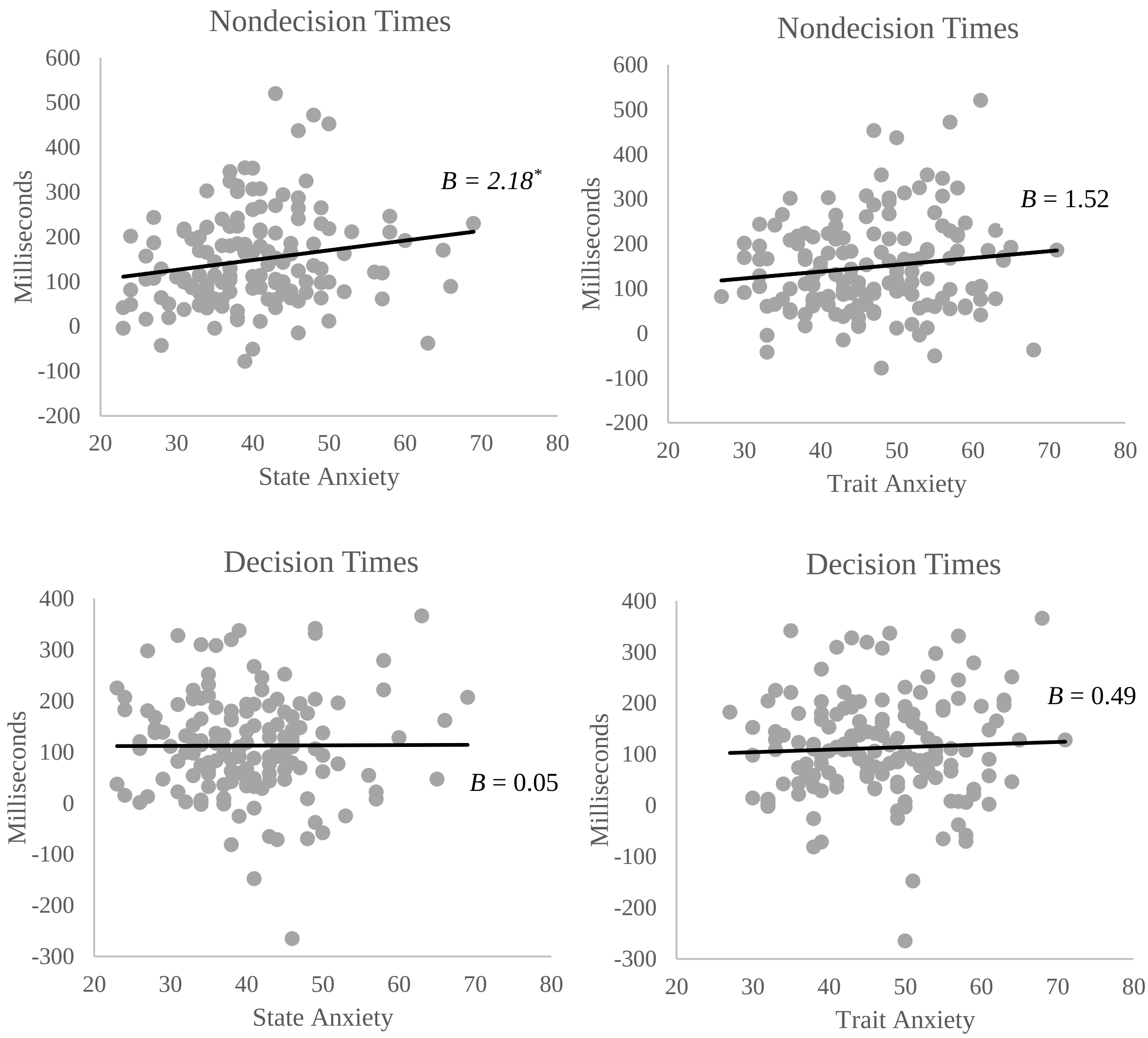

Figure 2. Scatterplots and regression line on the relationship between anxiety and switch costs (in decision time and nondecision time). * $p < .05$, ** $p < .001$

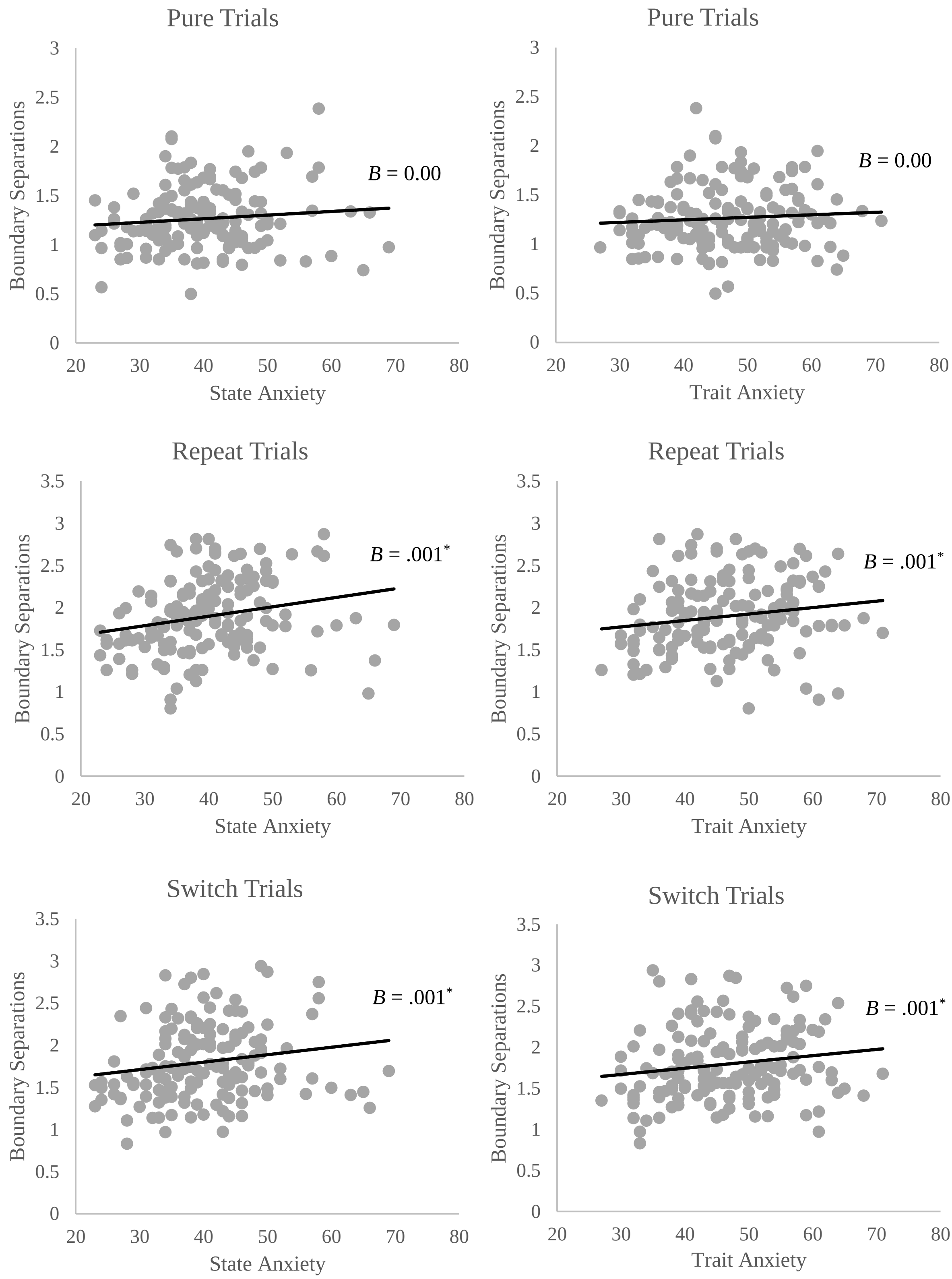

Figure 3. Scatterplots and regression line on the relationship between anxiety and boundary separations across trials. $^{*}p < .05$, $^{**}p < .001$

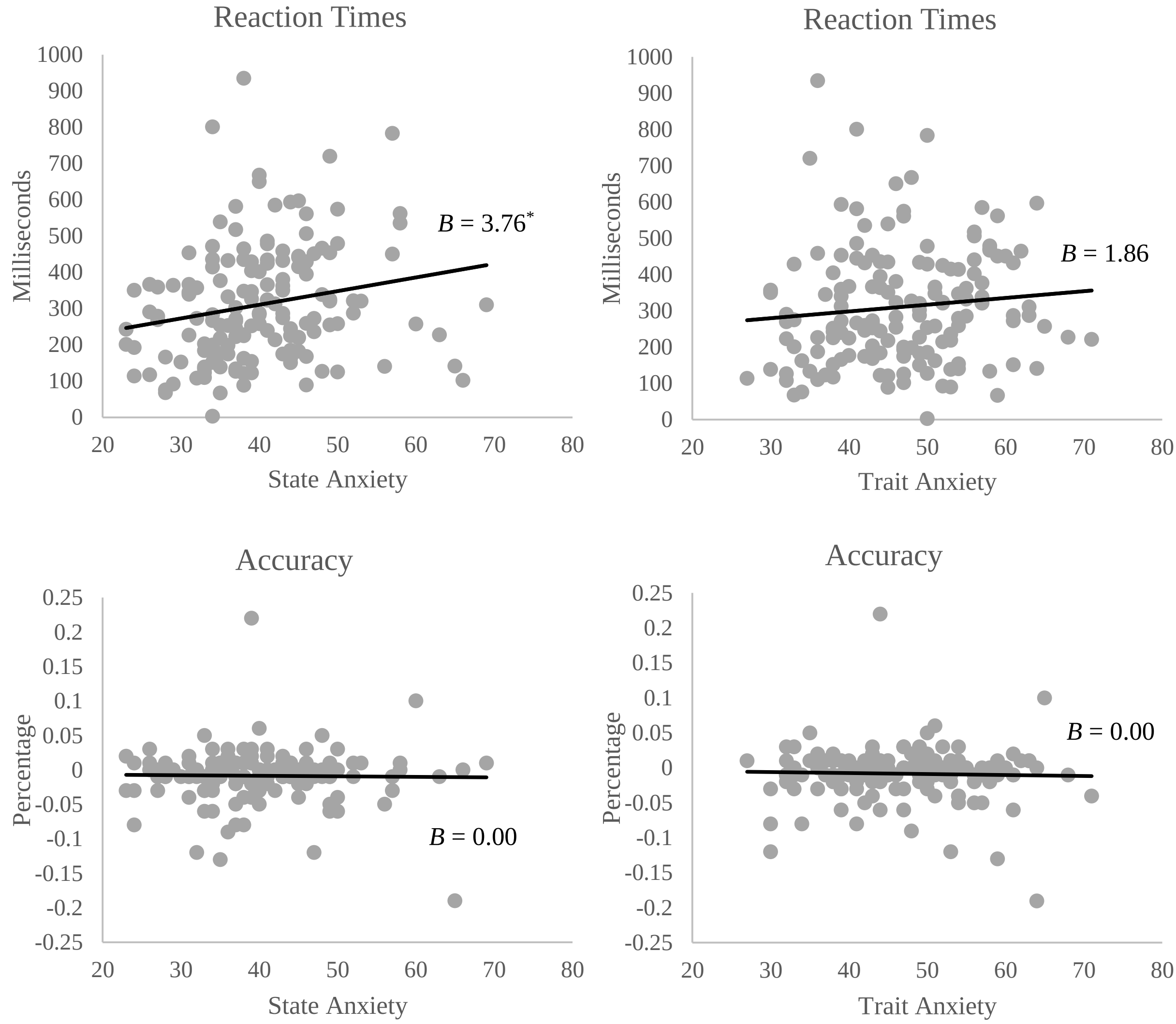

Figure 4. Scatterplots and regression line on the relationship between anxiety and mixing costs (RT and accuracy). * $p < .05$, ** $p < .001$