INDIVIDUAL DIFFERENCES IN WORKING MEMORY MODERATES THE RELATIONSHIP BETWEEN PROSACCADE LATENCY AND ANTISACCADE ERROR RATE

by

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(Under the Direction of Jennifer E. McDowell)

ABSTRACT

Cognitive control is required for flexible responses in changing environments and varies in its effectiveness even among healthy people. We evaluated cognitive control using antisaccades in comparison with basic prosaccades. Documented relationships exist between antisaccade error rate and prosaccade latency: individuals with shorter prosaccade latency show more antisaccade errors. Previous studies also suggest that individual differences in working memory may influence saccade performance. The current study investigated the relationships among prosaccade, antisaccade and working memory (assessed by symmetry span) data collected from over 150 healthy young adults. Hierarchical multiple regression analyses were conducted. The results demonstrated that prosaccade latency was a reliable predictor of antisaccade error rate, and working memory moderated the predictability of the two. These results suggested that working memory may contribute strongly to the individual differences observed with respect to differences in cognitive control among healthy people.

INDEX WORDS: cognitive control, working memory, saccades

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CHAPTER 1

INTRODUCTION

Cognitive control can be summarized as the supervisory cognitive process involved in tasks such as attention and memory allocation, goal-setting, task switching, suppression of unwanted and irrelevant thoughts and responses, self-control monitoring, skillful and flexible usage of strategies (Alvarez & Emory, 2006; Miller, 2000; Miller & Cohen, 2001). Cognitive control allows for flexible responses in changing environments, therefore it is important for successful daily functioning. Effective cognitive control is believed to attenuate maladjustment and promote well-being (Moilanen, Shaw, Dishion, Gardner, & Wilson, 2010). In contrast, deficits in cognitive control are often associated with neurological or psychiatric problems, such as schizophrenia, Attention-deficit/hyperactivity disorder (ADHD) and Alzheimer's disease (Perry & Hodges, 1999; Reilly, Harris, Khine, Keshavan, & Sweeney, 2008; Schachar, Mota, Logan, Tannock, & Klim, 2000).

Cognitive control can be assessed by a variety of paradigms in clinical and laboratory settings. One valuable methodology to investigate cognitive control is to measure ocular motor control (Hutton, 2008; Robinson, 1968). Various paradigms exist to assess ocular motor control in the laboratory, for example saccadic eye movement tasks (Hutton & Ettinger, 2006). There are a number of advantages to use saccadic eye movements in studying cognitive control of behavior. First of all, measurements of saccadic eye movements allow for precise control and manipulation of visual stimuli input. Second, the motor output can be accurately recorded and measured by eye tracking equipment. Third, saccadic eye movement tasks are relatively easy to implement, not only in healthy adults but also in samples including children and individuals with mental disorders (McDowell, Dyckman, Austin, & Clementz, 2008). These characteristics make the saccadic system especially valuable in investigating cognitive control.

Saccades are fast redirections of gaze which can be classified into basic visually guided saccades and more cognitively complex volitional saccades (Leigh & Zee, 1999; Sweeney, Takarae, Macmillan, Luna, & Minshew, 2004). Basic visually guided saccades are also referred to as prosaccades, which are reflexive redirections of gaze toward a cue. Prosaccades are exogenously triggered by external stimuli. An initial glance toward a place other than the cue location is defined as a prosaccade error. The prosaccade error rate is calculated as the percentage of error trials over the total number of trials, which is usually low because the task is simple. Prosaccade latency is defined as the time interval between when the stimulus is presented and when the eye starts to move, which is considered as a measure of visual processing speed of an individual (Everling & Fischer, 1998).

In contrast to prosaccades, volitional saccades are elective saccades made as part of purposeful behavior (Leigh & Zee, 1999). In addition to the visual-spatial attention and saccade generation required by prosaccades, volitional saccades additionally require inhibition and working memory (Hallett, 1978; Roberts, Hager, & Heron, 1994). One of the most frequently used volitional saccade paradigms is an antisaccade task which requires participants to suppress a glance toward a peripheral cue and subsequently generate a saccade to its mirror image location (same amplitude, opposite direction) (Hutton & Ettinger, 2006; Munoz & Everling, 2004). Correct antisaccade performance requires participants to maintain task instructions in mind, to inhibit a reflexive saccade toward the cue, and then to program and generate a saccade to the cue's mirror image location. An antisaccade error is defined as an initial glance toward the peripheral cue, and the error rate is higher than that of prosaccades due to the increased task demand (Leigh & Zee, 1999). Antisaccade latency is defined as the time interval between when the stimulus is presented and when the eye starts to move. Correct antisaccade latency is longer than that of prosaccade, which is believed to reflect inhibitory processing of the reflexive response (Hutton & Ettinger, 2006) .

Antisaccade error rate is a variable of great interest in the literature as it is often used as an index of cognitive control ability (Clementz, 1998; Lasker & Zee, 1997). Many studies in samples with various mental disorders, such as schizophrenia and bipolar disorder, have found that subjects show significant differences in antisaccade error rate compared to healthy participants (Clementz, McDowell, & Zisook, 1994; Katsanis, Kortenkamp, Iacono, & Grove, 1997). In addition, antisaccade error rate varies considerably in healthy participants across studies and laboratories (Hutton & Ettinger, 2006), which motivated the current study to explore cognitive factors that affect antisaccade performance.

A direct relationship between antisaccade error rate and processing speed of the reflexive prosaccade had been reported in previous studies: subjects with shorter prosaccade latency tended to have higher antisaccade error rate. For example, Taylor and Hutton reported a highly significant correlation between un-cued prosaccade latency and antisaccade error rate in a healthy undergraduate sample. Individuals who make faster prosaccades toward a cue were more likely to make antisaccade errors (Taylor & Hutton, 2004). Similarly, Ethridge et al reported a strong relationship between speed of visual orienting measured as prosaccade latency and failed inhibition measured as antisaccade errors in an interleaved pro- /anti-saccade condition (Ethridge, Brahmbhatt, Gao, McDowell, & Clementz, 2009). Additional evidence came from a cluster analysis of saccade performance in a large sample of participants, which identified subgroups of participants: increased errors clustered with faster latencies and decreased errors clustered with slower latencies (Li et al., 2012). It has also been reported that shorter prosaccade latency was associated with an elevated antisaccade error rate in a schizophrenia sample (Reilly et al., 2008).

In addition, a range of cognitive characteristics have been shown to influence cognitive control, including working memory (Unsworth, Schrock, & Engle, 2004). Working memory is a mental workspace for the online cognitive manipulation and storage of information (Baddeley, 1992; Goldman-Rakic, 1996; Logie, 2003). Working memory is constantly required in an antisaccade task to maintain task instruction active and accessible, while inhibiting the natural tendency to respond to a prepotent stimulus and instead maintain the spatial location of the to-be-generated response (Hutton & Ettinger, 2006). The relationship between working memory and cognitive control has long been of interest (Braver & Cohen, 2001; Engle & Kane, 2004; Miyake et al., 2000), however, it is still not fully characterized.

Many studies on the relationship between working memory and cognitive control can be summarized to two categories. In the first category, dual-task methodology is used to investigate how different levels of working memory load impacted the execution of cognitive control tasks. A debilitating effect of working memory load on antisaccade performance has been repeatedly reported. For example, in a previous study, healthy subjects performed an antisaccade task and a concurrent sentence span task that varied working memory load (Roberts et al., 1994). The researchers found that antisaccade error rate increased as the working memory load increased, and when working memory load was heavy, healthy participants made errors comparable to those committed by patients with prefrontal dysfunctions. A similar finding has been reported that antisaccade error rate was elevated when working memory load increased as measured using an n-back task (Mitchell, Macrae, & Gilchrist, 2002). Multiple studies have suggested that increased working memory load beyond some threshold can result in decreased inhibition.

In the other category of studies, healthy subjects high and low in working memory capacity were compared on a certain cognitive control task to explore how working memory capacity may contribute to the observed variance in cognitive control. Previous studies found that individuals with low working memory span showed a significant higher antisaccade error rate than those with high working memory span (Kane, Bleckley, Conway, & Engle, 2001). When antisaccade and prosaccade trials were mixed in one task, low span subjects were more likely to make direction errors on both antisaccade and prosaccade trials than high span individuals (Unsworth et al., 2004).

Together, these previous studies have demonstrated that there are considerable individual differences in antisaccade error rate in healthy subjects and working memory is associated with antisaccade performance. It was hypothesized that there might be a correction between antisaccade error rate and working memory capacity. However, few evidence was found in healthy subject samples, and only a couple studies found a weak correlation between the two variables in schizophrenia samples (Gooding & Tallent, 2001; Hutton et al., 2004; Nieman et al., 2000). In sum, previous studies show that working memory have considerable influence on antisaccade error rate; however, the lack of evidence of a direct relationship between antisaccade error rate and working memory suggested that the relationship might not be simple and straightforward. Therefore more sophisticated model is needed to better understand this relationship.

Crawford and colleagues proposed a moderation hypothesis to understand this relationship: working memory capacity mediated the relationships between saccade programming speed and antisaccade errors (Crawford, Parker, Solis-Trapala, & Mayes, 2011). The working memory task used in this study presented blocks of alternating sentences and single key words on a screen. In each block, the participants were instructed to read the sentences out load and keep the key words in mind which they were asked to recall in order later. The working memory span was calculated as the total number of words correctly recalled in the appropriate order. Participants who performed in the upper and lower quartile formed the high- and low-working memory groups, respectively. In addition, participants performed prosaccade and antisaccade tasks. Path analysis was conducted and the results demonstrated that there was a direct relationship between prosaccade latency and antisaccade error ($r=-0.54$ $p<0.05$). However, the results showed that working memory did not mediate the relationship between prosaccade latency and antisaccade error rate.

Altogether, previous studies show that there is a direct relationship between prosaccade latency and antisaccade error, and working memory has considerable influence on antisaccade error rate. It has been ruled out that working memory capacity mediated the relationship between the other two variables. An alternative hypothesis is that working memory moderates the relationship between prosaccade latency and antisaccade error rate. Therefore, the current study explores the role of working memory as a moderator instead of a mediator in the relationship between prosaccade latency and antisaccade error rate. A moderator is a variable that alters the strength of a causal relationship between a predictor variable and an outcome variable. A moderation effect occurs when the magnitude of the effect of a predictor variable on an outcome variable varies as a function of the moderator variable. This is also known as an interaction in multiple regression analyses. In contrast, a mediator is a variable which is influenced by a predictor variable and in turn influences an outcome variable in a causal relationship. Visualizations of a moderation effect and a mediation effect are presented in Figure 1 respectively.

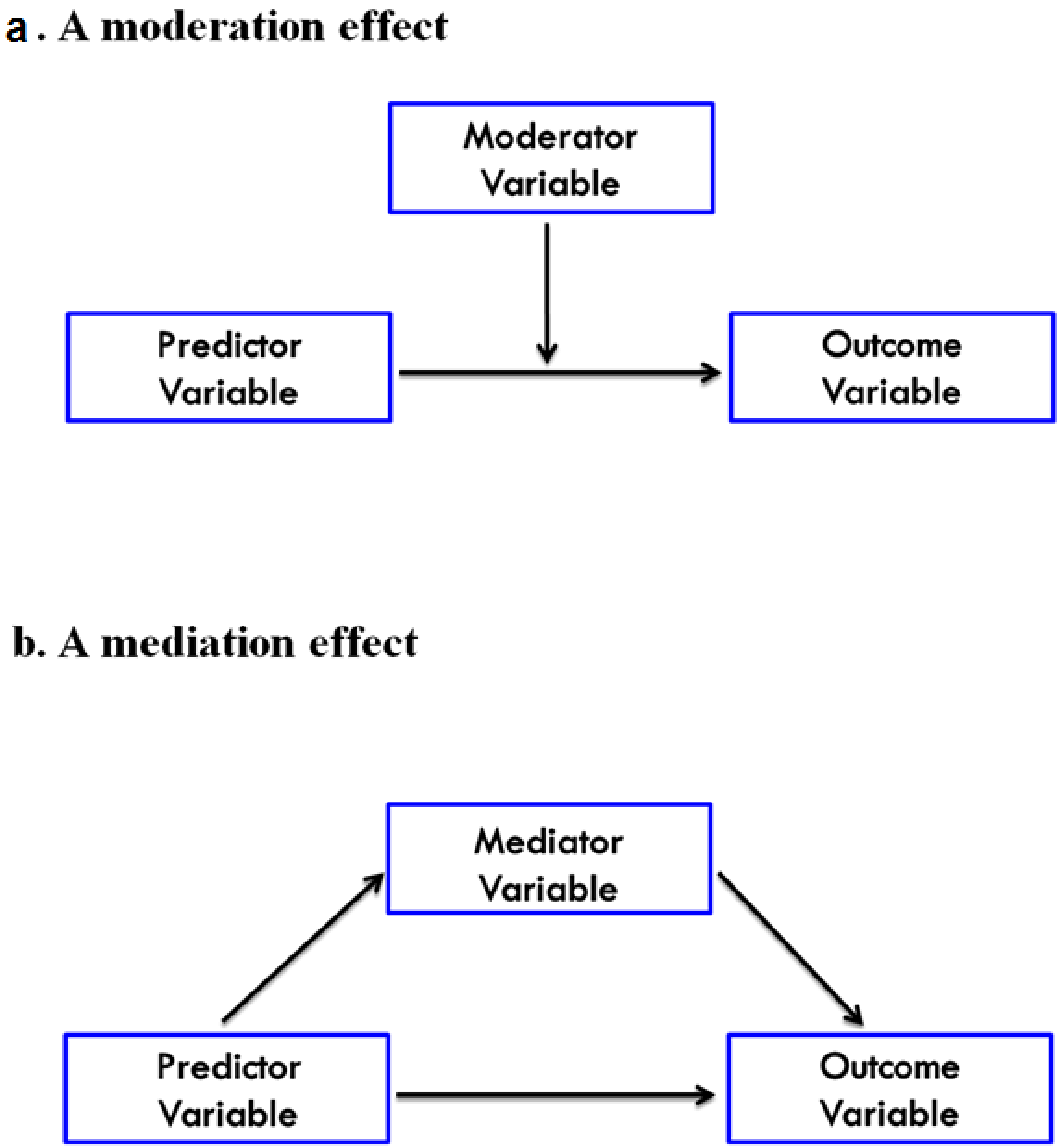
The key question of the current study was whether working memory would exert a moderation effect in the relationship between prosaccade latency and antisaccade error rate. The following specific hypotheses were tested:

Hypothesis 1: Antisaccade error rate was negatively correlated with prosaccade latency.

Hypothesis 2: Prosaccade latency was a reliable predictor of antisaccade error rate.

Hypothesis 3: Taking individual differences in working memory in the regression model increased predictability of antisaccade error rate.

Hypothesis 4: Working memory capacity moderated the relationship between prosaccade latency and antisaccade error.



<u>Figure 1</u> Visualizations of a moderation effect and a mediation effect.

CHAPTER 2

METHOD

Participants

Undergraduate participants (N = 165) were recruited from the UGA Psychology Research Pool (mean age=19.4 years, *SD*=1.3, 70% female). Exclusions included any history of psychiatric illness or severe head trauma (self-report). Twelve subjects were omitted from the analyses due to technical difficulty in recording data or the participants' failure to understand task instructions. As a result, data for 153 participants were analyzed (*M*=19.4 years, *SD*=1.27; 71% female). The study was approved by UGA institutional review board (IRB), and written informed consent was obtained.

Materials and procedure

Each participant was tested in one session with one examiner. This manuscript reported a subset of three tasks that were completed in the overall study: an antisaccade, a prosaccade, and a symmetry span task. And they received a short break after each task. The tests were administered in the same order for all the participants.

Saccadic tasks and eye movement monitoring

Participants were seated 70 cm from a color flat screen monitor in a quiet darkened room. A chin rest was used to minimize head movement during the task. Saccadic eye movement were collected with an EyeLink II eye movement monitor with infrared cameras mounted onto a headband (SR Research Ltd., Ottawa, Ontario, Canada). The infrared camera recorded eye position in real time for further analysis (sampling rate=500 Hz). Eye movement recordings were displayed on a computer monitor, and performance could therefore be monitored continuously by the experimenter. Standard instructions were given before each of the tasks, and subjects were asked to repeat the instructions to demonstrate their understanding. Prior to each task participants were presented with calibration targets at central fixation, ±5º, 10º, and 15º. Stimuli were constructed using Presentation software (Neurobehavioral Systems, Inc., Albany, CA) and presented using a flat screen monitor.

Saccade tasks were analyzed for percentage correct and reaction time using MATLAB (The Mathworks Inc., Natick, MA). Trials were eliminated from analyses if the latency was faster than 80 ms, if there was a blink during stimuli onset, if there was no response, or if the data were too noisy to be scored (the total number of trial eliminated was less than 5%). Individual trials were scored as a correct or an error response based on eye direction relative to target direction, with percentage error rate quantified as the number of correct trial divided by the total number of usable trials. Latency was defined as the time interval between the presentation of a visual stimulus and the initialization of an eye movement. Latencies for the correct trials were generated using procedures that have been previously described (Dyckman, Camchong et al. 2007).

Prosaccade task

The Prosaccade task required a rapid eye movement to a peripheral visual cue. In the current study, a prosaccade trial started with a 2.5° yellow dot presented at central fixation which remained there for 1500 msec. Then the fixation dot was extinguished, and after a gap of 200 msec, a 2.5° yellow dot was presented plane in the periphery at a $\pm5^{o}$ or $\pm10^{o}$ visual angle on the horizontal for 750 msec (half of trials in each visual field; see Figure 2). Participants were instructed to move their eyes to the dot as quickly and accurately as possible. The prosaccade task consisted of 200 trials.

Antisaccade task

The antisaccade task required inhibition of a glance toward a newly appearing cue and redirection of gaze to its mirror image location (Hallett 1978; McDowell, Brown et al. 2002; Luna, Velanova et al. 2008). In the current study, an antisaccade trial began with a 2.5° blue dot presented at central fixation for 2000 ms. Then the fixation dot was extinguished, and after a gap of 200 msec, a 2.5° blue dot was presented plane in the periphery at $\pm 5^o$ or $\pm 10^o$ visual angle on the horizontal for 1400 ms (half of trials in each visual field; see Figure 3). Participants were instructed to look at the cue when it was in the middle of the screen, but to look to the mirror image (opposite side of the screen, the same distance from the center) when it appeared at a peripheral location. The antisaccade task consisted of 60 trials.

Symmetry Span task (SSPAN)

SSPAN requires subjects to remember an arrangement of shapes in a matrix while judging symmetry (Unsworth & Spillers, 2010). In the symmetry-judgment part, participants were shown an 8 X 8 matrix with some squares filled in black and participants were instructed to decide whether the design was symmetrical about its vertical axis (the pattern was symmetrical half of the time). Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 X 4 matrix with one of the cells filled in red for 650 ms, after which, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix (see Figure 4). There were three trials of each list-length with list-length ranging from 2 to 5 for a total possible of 42 ((2+3+4+5)*3=42). For all of the span measures, items were scored if the item was correct and in the correct position. The variable of interest was the number of correct items in the correct position. The total number of items tested per subject was 42. So the full score was 42, and a higher score suggested a better performance in the task.

Data preparation

Variables of interest were prosaccade latency, antisaccade error rate, and SSPAN score. The predictor variable prosaccade latency and the moderator variable SSPAN score were centered to reduce multicollinearity incurred with the interaction term and to facilitate interpretation (Aiken & West, 1991; Cohen et al. 2003). The interaction term was created as the centered prosaccade latency multiplied by the centered SSPAN score.

Statistical Analysis

Descriptive statistics were calculated. Correlation analysis was conducted to study the relationship among the variables. In order to further explore the relationship, hierarchical multiple regression analyses were conducted (SPSS Version 21, IBM, Armonk, NY), and the following models were generated and compared.

Model 1: a baseline regression model was generated to test whether prosaccade latency was a significant predictor of antisaccade error, and to calculate how much variance in antisaccade error was attributable to variation in prosaccade latency. In this model, the predictor variable was prosaccade latency and the outcome variable was antisaccade error rate.

Model 2: in order to test whether working memory increased the variance of antisaccade error rate explained beyond that of prosaccade latency, working memory SSPAN score was added to regression Model 2. In this model, the predictor variables were prosaccade latency and SSPAN; and the outcome variable was antisaccade error rate.

Model 3: Given the hypothesis that working memory moderated the relationship between prosaccade latency and antisaccade error rate, the prosaccade latency by SSPAN interaction was added to the regression Model 3. In this model, the predictor variables were prosaccade latency, SSPAN and the prosaccade latency by SSPAN product term; and the outcome variable was antisaccade error rate.

Prosaccade Task

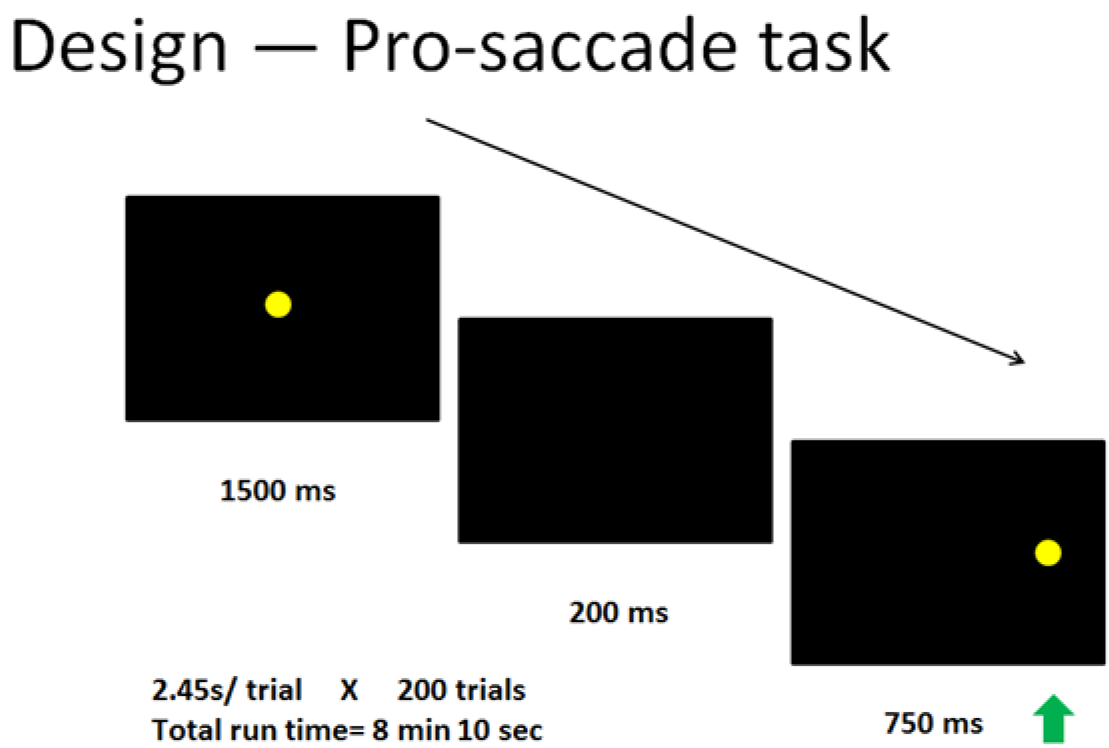


Figure 2 Stimuli Presented During the Prosaccade Task

When the yellow dot moves to the side, participants are instructed to follow it with their eyes as quickly and accurately as possible. The green arrow shows the correct eye position. Participants performed 200 trials of prosaccades in the study.

Antisaccade Task

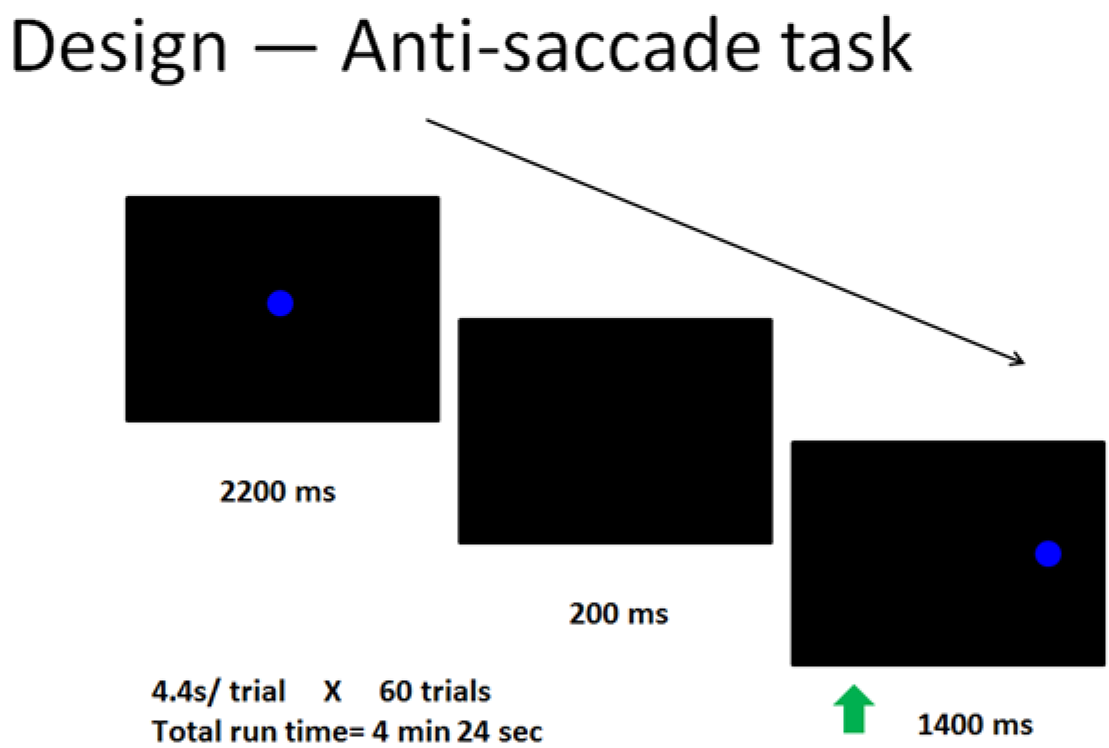


Figure 3 Stimuli Presented During the Antisaccade Task

When the blue dot moves to the side, participants are instructed to look at the opposite side (the same distance from the center) as quickly and accurately as possible. The green arrow shows the correct eye position. Participants performed 60 trials of antisaccades in the study.

Symmetry Span task

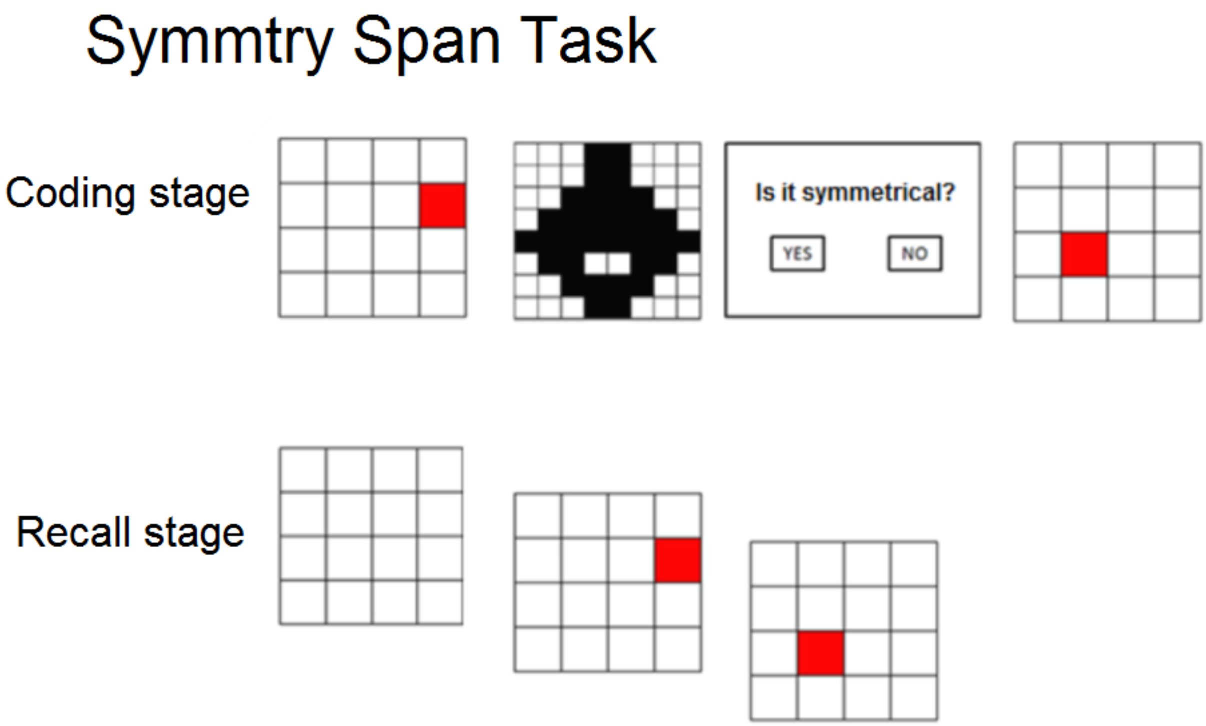


Figure 4 **Stimuli Presented During the Symmetry Span Task**

Participants are instructed to decide whether the design of a 8 X 8 matrix is symmetrical about its vertical axis. Immediately after determining whether the pattern is symmetrical, participants are presented with a 4 X 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recall the sequence of red-square locations in the preceding displays, in the order they appear by clicking on the cells of an empty matrix.

CHAPTER 3

RESULTS

Correlation Analysis

Descriptive statistics and correlations analyses of prosaccade latency, antisaccade error rate and SSPAN were shown in Table 1. Prosaccade latency was negatively correlation with antisaccade error rate, r=-0.35, p<0.05; prosaccade latency was also negatively correlated with SSPAN, r=-0.21, p<0.05. These results suggested that individuals with shorter prosaccade reaction time tended to have a higher antisaccade error rate; and individuals with shorter prosaccade reaction time tended to have a higher working memory score.

Hierarchical Multiple Regression

To test the hypothesis that working memory would moderate the relationship between prosaccade latency and antisaccade error rate, hierarchical multiple regression analyses were conducted. The results of the regression results were summarized in Table 2. The procedures followed recommendation by Cohen et al. (2003) in testing moderation effects.

Model 1 was conducted to test the hypothesis that prosaccade latency was a reliable predictor of antisaccade error rate. The results showed that the model was significant, $R^2 = .12$, F (1, 151) = 21.35, $p < .05$. Prosaccade latency was a significant predictor of antisaccade error rate, $b = -.352$, t (151) = -4.62, $p < .05$. Prosaccade latency accounted for 12% of variance in antisaccade error rate. Model 2 was conducted to test the hypothesis that including SSPAN to the regression analysis would increase the predictability of antisaccade error rate. The results showed that Model 2 was also significant, $R^2 = .16$, F (2, 150) = 14.29, p <.05; Δ $R^2 = 0.04$, p <.05. The results demonstrated that prosaccade latency and SSPAN were significant predictors of antisaccade error rate. The two accounted for 16% of variance in antisaccade error rate;

SSPAN accounted for 4% in addition to the 12% explained by prosaccade latency in Model 1. Model 3 was conducted to test the hypothesis that, in addition to the prosaccade latency and SSPAN, the product of the two was also a significant variable in predicting antisaccade error rate in the new regression model. A significant interaction would support a moderation effect among the three variables. The results showed that Model 3 was significant, $R^2 = .191$, $F(3, 149) = 11.74$, $p < .05$; $\Delta R^2 = 0.03$, $p < .05$. The results demonstrated that prosaccade latency and SSPAN, and the prosaccade by SSPAN interaction were significant predictors of antisaccade error rate. The three accounted for 19 % of the variance in antisaccade error rate; the prosaccade by SSPAN interaction accounted for an additional 3% of the variance beyond what has been explained by the two separately in Model 2. The results showed that there was a significant moderation effect among the three variables.

The regressions of antisaccade error rate on prosaccade latency at three levels of SSPAN, the mean, one standard deviation below the mean, and one standard deviation above the mean, were plotted to facilitate visualization and interpretation of the interaction between working memory and prosaccade latency (for further details, see Figure 5). Number and percentage of subjects in each part was summarized in Table 3.

Table 1

Summary of Means, Standard Deviation, and Correlations

	M	SD	1. AS error rate	2. PS latency	3. SSPAN
1. AS percentage error	39.7	20.8	1		
2. PS latency (ms)	125.5	19.3	-.35**	1	
3. SSPAN	28.8	7.3	-.11	-.21*	1

Note. AS=antisaccade; PS=prosaccade. Correlation coefficients were reported with * p<.05, ** p<.01.

Table 2

Summary of the Three Regression Models

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					Δ R Square	Δ F Change	df1	df2	Δ Sig. F
1	.35	0.12	0.12	19.51	0.12	21.35	1.00	151.00	0.00
2	.40	0.16	0.15	19.17	0.04	6.46	1.00	150.00	0.01
3	.44	0.19	0.18	18.87	0.03	5.73	1.00	149.00	0.02

Note. Dependent variable was antisaccade error rate. Model 1 predictor was prosaccade latency. Model 2 predictors were prosaccade latency and SSPAN. Model 3 predictors were prosaccade latency, SSPAN and (prosaccade latency)xSSPAN

Table 3

Summary of the Number and Percentage of Subjects in Figure 5

	Sspan					
ProRT	> +2 SD	between +1 SD and +2 SD	Between -1 SD and +1 SD	between -2 SD and -1 SD	< -2 SD	sum
> +2 SD	0 (0%)	0 (0%)	2 (1.3%)	5 (3.3%)	0 (0%)	7 (4.6%)
+1 SD and +2 SD	0 (0%)	2 (1.3%)	14 (9.2%)	1 (0.7%)	1 (0.7%)	18 (11.8%)
-1 SD and +1 SD	0 (0%)	17 (11.1%)	76 (49.7%)	11 (7.2%)	3 (2.0%)	107 (70.0%)
-2 SD and -1 SD	0 (0%)	5 (3.3%)	15 (9.8%)	1 (0.6%)	0 (0%)	21 (13.7%)
< -2 SD	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0(0%)
sum	0 (0%)	24 (15.7%)	107 (69.9%)	18 (11.8%)	4 (2.6%)	153 (100%)

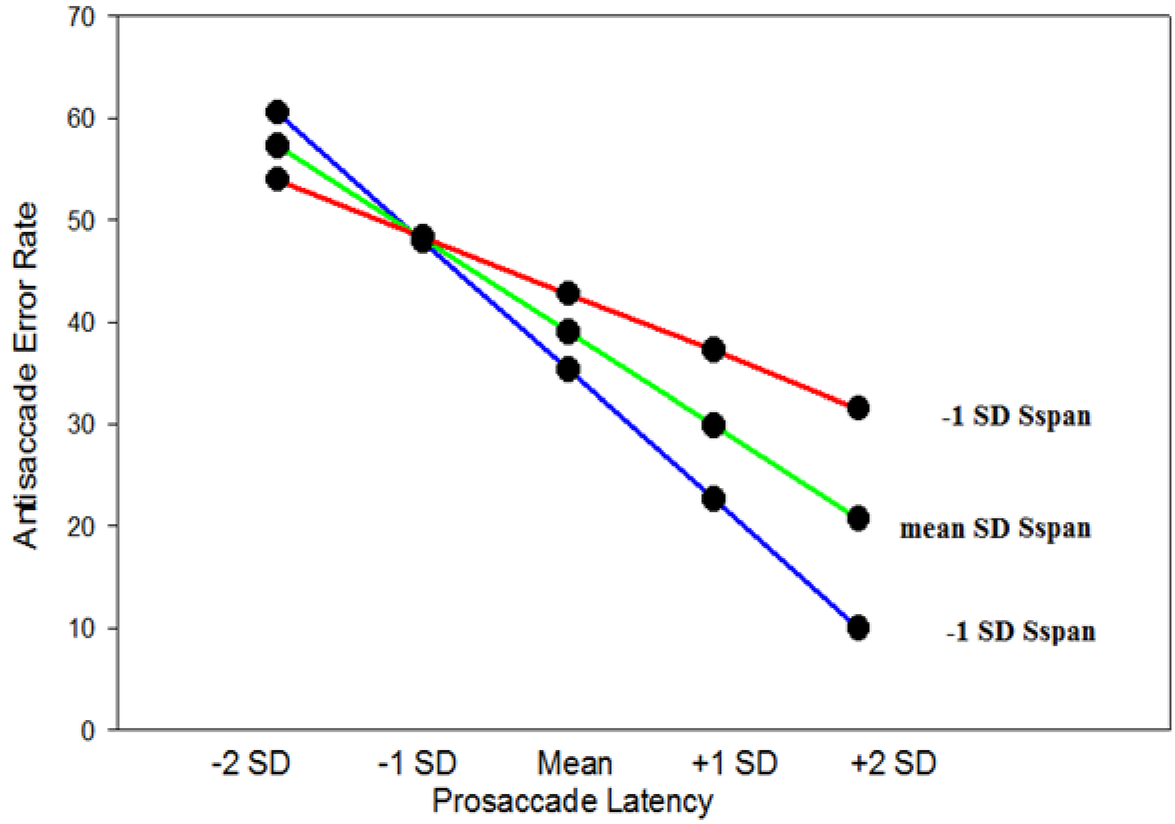


Figure 5 Moderation effect: simple regression lines.

The regression of antisaccade error rate on prosaccade latency at three levels of SSPAN, the mean, one standard deviation below the mean, and one standard deviation above the mean, were plotted to facilitate visualization and interpretation of the interaction between working memory and prosaccade latency.

CHAPTER 4

DISCUSSION

This study investigated whether individual differences in working memory were associated with different relationships between prosaccade latency and antisaccade performance in a large sample of healthy participants. The following empirical findings emerged from this study: (1) correlation analyses replicated previous studies demonstrating that antisaccade error rate was significantly correlated with prosaccade latency. Individuals with shorter prosaccade latency tended to have higher antisaccade error rate. This result provided evidence that the probability of a successful antisaccade was related to the speed of visual orienting as measured by prosaccade latency. (2) Prosaccade latency was a significant predictor of antisaccade error rate. The result replicated previous studies (Roberts et al., 1994; Taylor & Hutton, 2004) showing that prosaccade latency was a reliable predictor of antisaccade error rate. Individuals with longer prosaccade latency can be predicted to have a lower error rate. (3) Working memory capacity as measured by SSPAN significantly increased predictability of antisaccade error rate in addition to what has been explained by prosaccade latency. The result demonstrated that including both prosaccade latency and working memory led to a significantly more accurate prediction of antisaccade error rate in a regression model. Individuals with longer prosaccade latency and higher working memory span tended to have a lower antisaccade error rate. (4) The prosaccade latency and working memory span interaction was significant in predicting antisaccade error rate in a regression model, which illustrated that there was a moderation effect. Specifically, working memory moderated the relationship between and prosaccade latency and antisaccade error rate.

The goal of hypothesis 1 was to replicate previous finding on prosaccade latency and antisaccade error rate relationship. A correlation analysis verified the hypothesis and showed similar results with previous studies that prosaccade latency and antisaccade error were negatively correlation, shorter prosaccade latency associated with more antisaccade error (Ethridge et al., 2009). The significant correlation between prosaccade latency and antisaccade error rate suggested that cognitive control of saccadic eye movement and visual processing speed were not independent. A negative direction of the correlation was compatible with the idea that antisaccade errors may occur as a result of a rapid completion of competing reflexive saccade in a competition between a reflexive saccade toward a cue and a volitional saccade toward the mirror image location. According to the parallel processing model, the activations in neural systems supporting these two pathways competed with each other (Massen, 2004). If the activation of one pathway reached a certain threshold first, then the activation of the other pathway would be canceled. Therefore the shorter prosaccade latency may result in a higher antisaccade error rate.

The goal of hypothesis 2 was to further explore the relationship between prosaccade latency and antisaccade error rate by predicting the later from the former in a regression model. Therefore a regression with prosaccade latency as predictor variable and antisaccade error rate as outcome variable was conducted. First of all, the result showed predicting antisaccade error rate from prosaccade latency was a valid model. This result was consistent with previous study that prosaccade latency was a reliable and strong predictor of antisaccade error rate (Crawford et al., 2011; Taylor & Hutton, 2004). Second, the beta coefficients of prosaccade latency was negative, suggesting that a unit increase in prosaccade latency predicted a unit decreased in antisaccade error rate. This negative beta coefficient was compatible with the idea that antisaccade error may be due to a fast reflexive prosaccade (Massen, 2004). An alternative explanation was that this might suggested a speed-accuracy tradeoff in cognitive control of behavior (Ethridge et al., 2009; Forster, 2003). Some task may require individuals to trade between speed and accuracy in movement, especially when there was a limited time to respond. Some individuals might favor accuracy over speed and some might sacrifice accuracy to emphasize speed. For example, a previous study conducted a cluster analysis on saccadic variables and reported two subgroups of subjects: one subgroup showed increased errors clustered with faster latency, while the other showed decreased errors clustered with slower latency (Li et al., 2012) suggesting participants might utilize two different strategies in performing antisaccade tasks, either to emphasize speed or to maximize accuracy.

The goal of hypothesis 3 was to test whether whether individual differences in working memory significantly contribute to the prediction of antisaccade error beyond what has been explained by prosaccade latency. In other word, this analysis examined whether including another predictor variable SSPAN in regression made it a better model in predicting antisaccade error rate. The following results were found: first of all, this model was significant and the two predictor variables were both significant, which indicated prosaccade latency and SSPAN were reliable predictors of antisaccade error rate. This result suggested that working memory shared some common variance with antisaccade error rate in this study, which was compatible with previous research suggesting that working memory was required when there was a strong conflict or internal interference in behavior execution (Mitchell et al., 2002; Roberts et al., 1994). Working memory was proposed to be involved not only in maintaining task instruction and goal but also in resolving the conflict between the prepotent visually guided saccade and volitional saccade. Secondly, the beta coefficient of SSPAN was negative, which demonstrated that individuals with higher working memory capacity were predicted to have a lower antisaccade error rate. This result was consistent with previous studies of individual difference reporting that high working memory span subjects often showed less antisaccade error rate than those with low span (Kane et al., 2001; Unsworth et al., 2004). In sum, hypothesis 3 verified that it was a valid regression model to predict antisaccade error rate from prosacade latency and SSPAN.

The goal of hypothesis 4 was to test whether working memory moderated the relationship between prosaccade latency and antisaccade error rate. The key of this model was to test whether there was a significant interaction effect. An interaction effect represented the combined effects of multiple predictor variables on the outcome variable. When an interaction effect was present, the impact of one variable depended on the level of the other variable. By testing whether R-square change was significantly different from zero, it tested whether including the prosaccade latency and SSPAN interaction as an additional predictor variable in the regression made it a better model in predicting antisaccade error rate.

The following results were found: first, the regression model was significant. This result demonstrated that it was valid to predict antisaccade error from prosaccade latency, SSPAN and the product of the previous two variables. The R-square change was significant which indicated that this model was significantly better than the previous one in predicting antisaccade error rate. Second, the predictor variable prosaccade latency by the SSPAN product term was significant, which indicated the existence of an interaction effect. The interaction effect represented that the effect of prosaccade latency on antisaccade error rate differed at different levels of working memory. In other words, working memory span moderated the relationship between prosaccade latency and antisccade error rate. In order to interpret a moderation effect, the convention was to examine the effect of one predictor variable while the other factor was confined at certain level.

The regressions of the outcome variable on one predictor variable at specific values of the other predictor variable were called simple slopes. When the moderator variable was a continuous variable, the convention was to plot the simple slopes with the mean of the moderator variable, one standard deviation below and above the mean the moderator variable. Consequently, the regressions of antisaccade error rate on prosaccade latency were plotted in blue, green and red as at high, average and low working memory span scores in Figure 5.

Third, the beta coefficient of the prosaccade latency and SSPAN interaction was negative. It can be observed from Figure 5 that the directions of the simple slopes were all negative – longer prosaccade latency was associated with lower antisaccade error. Moreover, considering the changes of prosaccade latency along x axis, the slope was steeper when the working memory span was higher. In other words, the steepness of the simple slopes depended on the level of working memory, that prosaccade latency was more strongly correlated with antisaccade error in individuals with higher working memory compared to ones with lower working memory. This result suggested that individual differences in working memory impacted the predictability of antisaccade error rate. This might help explain why significant differences in antisaccade performance but not in prosaccade performance were observed between individuals with high- and low- working memory span in previous study (Engle & Kane, 2004; Kane et al., 2001). Next, the effect was examined along y-axis. When prosaccade latency was controlled at one standard deviation below the mean, the antisaccade error rate was high in all subjects regardless of their working memory capacity. This suggested that rapid completion of reflexive saccades had a strong effect on antisaccade error generation. However, the pattern was different when prosaccade latency was controlled at one standard deviation above the mean. The three antisaccade error rates were all lower than those at one standard deviation below the mean prosaccade latency. Moreover, individuals with the highest working memory span tend to have the lowest antisaccade error rate. Antisaccade performance and the visual processing speed was a function of working memory capacity. Among individuals with similar prosaccade latency, a high working memory capacity might facilitate maintenance of task instructions or deal with interference, which resulted in better inhibition to a prepotent tendency to a visual stimulus. Altogether, the results suggested that the fate of an antisaccade trial depended on prosaccade latency, but the extent of the relationship was a function of working memory capacity.

In sum, the results of the present study replicated previous findings that saccade performance was heterogeneous in healthy participants, and antisaccade performance was related to visual orienting speed (Ethridge et al., 2009; Hutton & Ettinger, 2006). Higher error rate was correlated with shorter saccade response time and vice versa. These results also demonstrated that cognitive control and working memory were not independent in a large sample of healthy young adults. Specifically, the current study illuminated the role of working memory as a facilitator of cognitive control. This finding provides a potential explanation for the differences in saccade performance observed within the same group under high and low memory load. In addition, the effects of individual differences in working memory may illuminated the differences in the relationship between prosaccade latency and antisaccade error rate observed in heterogeneous groups, such as children compared to adults, or individuals with psychiatric disorders compared with healthy subjects. A high working memory capacity may enhance goal-oriented behavior; while deficient in working memory may increase the difficulty in inhibition of a prepotent response.

The findings of this study have potential implications for researchers interested in individual differences in working memory and cognitive control. The relationship between the speed of visual orienting and inhibitory ability is found to be dependent on the level of working memory. Neglecting to consider the role of working memory as a moderator might lead to observation of inconsistent relationships between the prosaccade and antisaccade performance in two samples, thus allowing for misinterpretation of the relationship between the two variables. This research presented here also suggests that it is important to sample a wide distribution of working memory capacities in a population; otherwise, the data might be biased.

One strength of the current study is that the samples size is relatively large. Moreover, all three variables were analyzed as continuous variables instead of categorizing or dichotomizing. Although converting continuous variables into categorical variables, which is sometimes called data-driven optimal cut-points, is a common practice in data analysis, it is inadvisable (Naggara et al., 2011; Royston, Altman, & Sauerbrei, 2006). The categorization of continuous variables may lead to a loss of power and a loss of precision of estimation. Categorizing continuous variables might also bias the relationship between the predictor variable and the outcome variables. To avoid such spurious statistical significance, all the variables were analyzed as continuous variable in the current study. Furthermore, the predictor variables were also centered in regression to reduce potential multicollinearity. As a result, these practices guarantee fairly large power of the regression models (Model 1: effect size .14, power.995; Model 2: effect size .19, power.995; Model 3: effect size .23, power.997).

These results, however, should be considered in the context of the following caveats. This moderation effect of working memory capacity on the relationship between antisaccade error rate and prosaccade latency was examined only in a sample of healthy college students. Furthermore, the findings of this study were restricted to the specific tasks. Given that both cognitive control and working memory are broad concepts that can be measured by various tasks, it was possible that the specific tasks used here were particularly sensitive. Future studies are needed to test whether such an effect is presented in: a different subject sample, other working memory measures and other cognitive control measures.

Future studies are needed to test whether this moderation effect is presented in: 1) a more heterogeneous subject sample, such as individuals with certain spectrum mental disorder; 2) additional working memory tasks, such as n-back task and digit span task.; 3) separated corrected antisaccade errors and uncorrected antisaccade errors, as awareness of a antisaccade error or not, suggesting different mechanisms in error generation (Ethridge et al., 2009).

The results from this study replicate previous study that visual orienting speed is a reliable predictor of inhibition error, and these results complement previous study on working memory and cognitive control by highlighting that working memory moderates the visual orienting speed and inhibition error relationship. The prosaccade latency to antisaccade error relationship is strongest in individuals with high working memory and weakest in those with low working memory. Results from this study illustrated relationship between working memory and cognitive control, and may help to elucidate mechanisms for response variability within and between different participant populations. The current study also provides framework for future studies to further explore the role of working memory in cognitive control. This study provides additional evidence of saccade paradigms as valuable and useful research tool in psychology.

CHAPTER 5

CONCLUSION

In conclusion, we find that working memory moderates the relationship between visual orienting speed and inhibition error. This finding not only replicates previous studies that visual orienting speed is a reliable predictor of inhibition error, but also complements them by highlighting the role of working memory in cognitive control performance. Here, the relationship of prosaccade latency andantisaccade error was strongest in individuals with high working memory and weakest in those with low working memory. Data from this study facilitates understanding of cognitive correlates between working memory and cognitive control. These results suggest that working memory may contribute strongly to the individual differences observed with respect to various cognitive control among healthy participants.

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