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DUAL MECHANISMS OF COGNITIVE CONTROL:

AN EYE TRACKING STUDY

A Thesis

Presented to the

Faculty of

California State University,

San Bernardino

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

in

Psychological Science

---

by

Kyle Mobly

December 2020

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Approved by:

Jason Reimer, Committee Chair, Psychology

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ABSTRACT

The purpose of the present study was to attempt to provide an ocular signature for the dual mechanisms of cognitive control (proactivity and reactivity) by utilizing an eye tracker to record gaze patterns while participants were administered a modified version of the AX-CPT 40. Additionally, we sought to clarify whether context updating or maintenance was responsible for the higher Total Visit Duration (TVD) on the cue location during the ISI that was found in previous studies by providing both a short (1.5 seconds) and long (3 seconds) ISI length. This allowed us to disentangle context updating from maintenance by removing the demand on maintenance with a 1.5 second condition. Our analyses provided conflicting information with the findings from previous studies where TVD on the cue location during the ISI was positively associated with PBI. In the current study, TVD on the cue location during the ISI was negatively associated with PBI. This association is in the opposite direction of what was found in previous experiments. In conclusion, further replication needs to be performed to ascertain the accuracy of these findings.

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CHAPTER ONE

COGNITIVE CONTROL

One could argue the ability to effectively plan or organize in order to influence future events or behaviors is a defining attribute of humankind. While other species may have comparable memory abilities, none appear to experience the complex interplay between cognitive control and working memory capacity (WMC) that humans do. It is thought that the prefrontal cortex (PFC) region of the brain is central to higher level thought processes like cognitive control (Braver, Gray, & Burgess, 2007), and that it is this evolutionarily augmented portion of our brain that contributes to our humanity. The purpose of the present study is to look at the association between cognitive control and eye movements by utilizing a modified version of the AX-CPT.

Cognitive Control as Context Processing

Cognitive control has been defined as “the ability to regulate thoughts and actions in accordance with internally represented behavioral goals” (Braver, 2012, p. 106). It was also defined by Reimer, Radvansky, Lorsbach, and Armendarez (2015, p. 1374) as “a set of processes that support goal-directed action including the representation of the task goal, its maintenance over time, the inhibition of goal-irrelevant information, and the updating of goal information during changing task conditions.” Essentially, when people are planning an action or goal, they should have control over their own thoughts. People would

not be able to function without the ability to guide their own individual behaviors and implement actions that achieve goals. Unfortunately, people do suffer from cognitive control deficits and therefore research into the mechanisms behind this ability is crucial.

Braver et al. (2001) has posited that many age-related impairments in cognitive control can be attributed to a single deficit; the ability to correctly represent, maintain, and update task-relevant context. According to Braver et al., deficits in context processing impair cognitive control in many different areas like working memory, attention, inhibition, executive function, and episodic memory. Braver et al. define context as any task-relevant information that is represented internally and can bias processing in the pathways utilized for task performance. Examples of context would be information that is manipulated or previous responses that are maintained and monitored (Braver et al., 2001). In the Stroop task, the word name must be inhibited when the correct color response is relatively infrequent, but working memory underlies the inhibition mechanism to the extent that one needs to keep the task instructions of the Stroop task in mind while eliciting a response (Braver et al., 2001). Inhibition and attention are mechanisms of cognitive control, but working memory is what holds it all together. Working memory is crucial to processing contextual information because without it, it would not be possible to inhibit an incorrect response. Contextual information can be used strategically for preparation and it is the processing of this information that allows humans to navigate through their

environment effectively (Richmond, Redick, & Braver, 2015). Without the ability to put the environment into context, humans would be unable to make an intentional response to anything.

According to Braver et al. (2001), functions of cognitive control such as attention and inhibition may be explained by a context-processing mechanism. These cognitive functions utilize context processing which biases decision making (Braver et al., 2001). Braver et al. found that elderly individuals display a reduced sensitivity to context and it was postulated that this is why they suffer from cognitive impairments. Elderly individuals also appear to make more errors on tasks that measure inhibitory function like negative priming and stop-signal paradigms (Braver et al., 2001). According to Braver et al., context representations give top-down support for task-relevant processes. Therefore, context processing makes it possible to ignore irrelevant stimuli and maintain task-relevant information. Another area in which cognition tends to deteriorate with age is attentional control. This has been shown with the Stroop Color and Word Test (Braver et al., 2001). Context representations provide an attentional function by choosing task-relevant information over contending task-irrelevant sources of information (Braver et al., 2001).

Assessing Cognitive Control and the AX-Continuous Performance Test

Cognitive control has frequently been assessed with a version of the continuous performance task known as the AX-CPT (Braver et al., 2007).

Different components of cognitive control are measured by the AX-CPT including working memory, attention, and inhibition (Braver at al., 2007). Within this task, participants are shown a series of letters (presented one at a time) and are asked to respond to every pair of letters in the series (i.e., letter one presented first and letter two presented second) based on a rule given by the researcher (See Figure 1). The rule consists of responding “Yes” to the X probe (i.e., the second letter), but only when it is preceded by an A cue (i.e., the first letter). Participants are asked to make a “No” response to all other cases.

In the typical AX-CPT there are four trial types. One trial type represents a target trial: AX (i.e., target cue and target probe) and three non-target trials: AY (i.e., target cue and non-target probe), BX (i.e., non-target cue and target probe), and BY (i.e., non-target cue and non-target probe). In the standard version of the AX-CPT, target AX trials occur 70% of the time. Non-target trials make up 30% of the AX-CPT with 10% allocated to BX trials, 10% to (AY) trials, and 10 % to BY trials. The reason for this disproportionate amount of targets trials is to generate two types of biases in the participants (Braver et al, 2007). The first bias is to make a “Yes” response whenever an X probe is presented (Braver et al., 2007). On BX trials (where B is any non-A cue), the correct action from the participants is to make a “No” response (Braver et al., 2007). However, the large number of target AX trials biases participants to make either an incorrect “Yes” response to BX trials or to make a correct “No” response but with increased response time (RT). This is because of how often the letter X is preceded by the letter A in other

trials. Thus, BX trials require a person to maintain the “B” context in working memory so that a correct (“No”) response can be given upon the presentation of the probe. In this way, maintaining the cue allows one to inhibit the prepotent “Yes” response upon seeing an X.

As one proceeds through the AX-CPT, the other bias that takes place is when a participant expects the X probe after an A cue is presented (Braver et al., 2007). For this bias, the context given by the A cue is predictive of an X probe on a majority of trials and therefore causes participants to expect that they will have to make a “Yes” response (Braver et al., 2007). This means that in AY trials where an A is not followed by the letter X, participants tend to make an incorrect “Yes” response, despite the fact that the correct response is “No.” The participant may choose the correct response in this instance, but it is often coupled with an increased RT. Therefore, incorrect responses and increased RTs on the AY trials are indicative of someone who is a good context processor. Conversely, faster RTs and correct responses on the BX trials indicate that someone is maintaining the “B” in mind to elicit a non-targeted response and is not forced to inhibit the response to the X because they have already prepared the “No” response. On BY trials, participants tend to make correct responses and have faster RTs than on the other trials. For proficient context processors, this is because they are maintaining the “B” in mind as they respond to the probe. However, even for those less adept at context processing, reacting to the “Y” probe leads to correct responses and faster RTs as well. This essentially allows

the BY trials to serve as a control or baseline. Thus, in sum, a behavioral signature of good context processing is better performance in BX than AY trials (Braver et al., 2001).

Developmental Differences in the AX-Continuous Performance Test

Healthy young adults have been shown to have good context processing ability (Braver et al., 2001). In contrast, research shows that relative to younger adults, older adults display a decreased level of cognitive control. Understanding the mechanisms behind this is critical for potentially reducing this deficit. Age-related reductions in dopamine concentration in the prefrontal cortex have been associated with cognitive impairments. It is thought that this pathway is being utilized when a person is using cognitive control (Braver et al., 2001). During healthy aging, episodic memory deficits are the most pronounced of the impairments in cognitive control and research has suggested that the most severe age-related declines in episodic memory all seem to integrate the outputs of long-term memory with relevant contextual information (Braver et al., 2001).

In a study carried out by Braver et al. (2001), a standard version of the AX-CPT was used with younger and older adults. Braver et al. found that younger adults showed fewer errors on the BX trials, but more AY errors than the older adults (Braver et al., 2001). Since the BX trials are meant to measure the inhibition response tendency by requiring the participants to hold the “B” in working memory and using it to inhibit a “Yes” response, it would seem that the elderly tend to acquire deficits in inhibition as they age. The contextual

information associated with the cue should be used to inhibit the dominant response tendency, which is to press “Yes” when they are presented with the X probe, but this ability falters in the elderly, as the slower RTs imply. They are reacting to the X rather than holding the “B” in WM and using it to inhibit a “Yes” response.

Braver et al. suggest that the older adults make fewer errors on the AY trials because they have context representation and maintenance impairments. They do not encode the A-cue or maintain the goal in mind as well as young adults, so they see the “Y” probe and immediately make a correct non-targeted response. The inverse relationship in error rates on the AY and BX trials between young adults and the elderly is a product of differences in context processing aptitude. Holding the A or “B” cues in working memory (WM) is something at which young adults excel compared to older adults. Therefore, the young adults hold the A-cue in WM on AY trials, expecting to make a targeted response. This causes them to make an incorrect “Yes” response to an AY trial. However, on BX trials, young adults maintain the “B” cue in working memory and are prepared to make the correct non-targeted response throughout the delay. The opposite is true of older adults, who have WM deficits.

Mechanistically, the cognitive changes that take place later in the human lifespan may be due to the diminished ability to process context information (Braver, Satpute, Rush, Racine, & Barch, 2005). In a study conducted by Braver et al. (2005), two components of context processing (activation/updating and

maintenance) were examined in healthy younger and older adults, alongside people inflicted with early stage dementia of the Alzheimer's type (DAT). Braver et al. separated these components of context processing by manipulating the cue-probe delay between two conditions. In the short-delay condition, the cue-probe delay was 1000 ms. However, in the long-delay condition, the cue-probe delay was 5000 ms. Braver et al. theorized that the difference in delay period would separate maintenance from activation/updating in context processing. The reasoning behind this is that a longer cue-probe delay would require more context maintenance because the participant had to keep the cue in mind for a prolonged period of time. With a short cue-probe delay, the participant has to activate/update, but not maintain. Therefore, if the same results are still found with a short cue-probe delay, it would mean maintenance was not a factor. Individuals from both of the older groups displayed impairments in activation/updating, yet only those over 75 years old and those in the DAT group showed impairments in context maintenance; the latter group showing greater impairments (Braver et al., 2005). By isolating context maintenance from other components of context processing, Braver et al. was able to better our understanding of the cognitive impairments in aging adults.

Similar to Braver et al. (2001), Lorsbach and Reimer (2008) examined developmental differences in context processing. However, Lorsbach and Reimer looked at differences between children and adults, whereas Braver et al. compared young adults to older adults. Lorsbach and Reimer found that relative

to BY trials, young adults performed more poorly on AY than BX trials. Essentially, the young adults were focusing on the context cue (A) on nontarget trials. In addition to this, Lorsbach and Reimer found that sixth graders had a larger difference between BX and BY errors than young adults. Therefore, when the cue (B) was held constant, it was more difficult for children to inhibit the dominant, but incorrect response, to the target probe. Furthermore, the difference between RTs for young adults on AY and BY trials was significantly larger than the difference between AY and BY trials for sixth graders. Lorsbach and Reimer postulate that this is due to the young adults experiencing interference from the target cue (A). In summation, young adults were more adept at maintaining previous context information than children, which was similar to elderly individuals in Braver et al. (2001). The findings of this study align with the hypothesis that young adults and children have different capacities for using context information, which indicates that age-related changes in a context processing mechanism may help explain the cognitive control functions of working memory, inhibition, and attention (Lorsbach & Reimer, 2008).

In a related study, Lorsbach and Reimer (2010) investigated developmental differences in cognitive control between third and sixth graders. In Experiment 1, Lorsbach and Reimer found that on AY trials, third graders had faster RTs than sixth graders. Lorsbach and Reimer suggested this was likely because sixth graders required more time to overcome the expectancy bias created by the cue (A). They expected an X probe to follow the cue (A) and took

more time to inhibit their response. In contrast, sixth graders had faster RTs on BX trials than third graders because they held the context information of the cue (B) more effectively and had a nontarget response prepared after the cue appeared (Lorsbach & Reimer, 2010). Experiment 1 led Lorsbach and Reimer to attempt to discern whether these results were due to developmental differences in cue maintenance or cue representation.

In Experiment 2, Lorsbach and Reimer (2010) adjusted the cue-probe delay from 5500 ms to 1000 ms to reduce how long context representations must be held in working memory. The reasoning behind this was that if Lorsbach and Reimer found no differences between third and sixth graders on the AY and BX trials with a shorter cue-probe delay, then it would imply that there is a dissimilarity in the proficiency in maintaining (as opposed to simply representing) context information between the two groups. They did indeed find age-related differences in the ability to maintain context information. Another adjustment Lorsbach and Reimer made in Experiment 2 was alternating the color of the cue and probe (green or red). If the cue was both an A and the color red, the children were to choose a “Yes” response. If the cue was green or if an X was not preceded by an A, they were to give a “No” response. This manipulation was done to assess whether the differences between the two groups were due to the capacity for representing goal information when presented with the cue (Lorsbach & Reimer, 2010). If the condition where the representational demands were high resulted in differences between the groups, independent of delay, this

would suggest that the ability to effectively represent goal information is responsible for the developmental differences. Lorsbach and Reimer found that when representational demands were high, there were developmental differences. This means that the ability to both represent and maintain goal information improves as children age.

Dual Mechanisms of Control Framework

More recently, a number of studies have demonstrated that there is both intra-individual and inter-individual variation in performance on the AX-CPT (Braver et al., 2001). The dual mechanisms of control framework (DMC) attempts to explain why there is variation within and between individuals in cognitive control abilities (Braver et al., 2007). According to the DMC, the two major strategies or approaches to cognitive control are proactive and reactive control (Braver, 2012). Reactive control requires a stimulus from the environment to reactivate a goal that is not being held in working memory in order to achieve realization of the desired result (Braver, 2012). In reactive control, cognitive control is dependent on bottom-up input. Reactive control is used after, as opposed to before, a certain event happens (Braver et al., 2007). According to Braver et al. (2007), reactive control tends to be used as needed and is more like an “on-the-fly” cognitive control mechanism. Thus, Braver et al. describe reactive control as a “just-in-time” strategy. By contrast, proactive control involves maintaining goal-relevant information in working memory so that the goal may be achieved in the future. It is used before an event happens and involves keeping a

goal in mind up until the event. As a result, the difference between proactive and reactive control has been likened to the difference between early selection and late correction, respectively (Braver et al., 2007).

Proactive and reactive control each have advantages and disadvantages, so utilizing each mechanism at appropriate times allows people to be cognitively efficient in different environments. For example, a disadvantage of proactive control is that it uses up a great deal of cognitive resources since it requires continued attention while utilizing working memory (Braver et al., 2012). Therefore, it is not always the best strategy, so people spend the majority of their time utilizing reactive control. If people were to use proactivity all the time, they would not be able to allocate their mental resources to other things that may require their attention. In reactive control, goal representations are retrieved only when they are needed, and it has the advantage of freeing up resources during the time between when the intention is formed and when it is completed (Braver, 2012). This is similar to how many computer systems operate because they use a top-down flow of control (proactive control) but use a bottom-up flow of control for interrupts (reactive control) (Braver et al., 2007).

The degree to which one is utilizing a proactive vs. reactive strategy has been assessed using the Proactivity Behavioral Index (PBI). The PBI is calculated by entering RTs or error rates associated with AY and BX trials in the following formula: (AY – BX) / (AY + BX) (Gonthier, Macnamara, Chow, Conway, & Braver, 2016). The higher that the PBI is, the more proactive the participant is,

while an increase in the use of a reactive strategy is associated with lower PBI scores. In the study done by Richmond, Redick, and Braver (2015), they found that using proactive control results in a higher error rate on AY trials and using reactive control leads to a higher error rate on BX trials.

The DMC accounts for humans being able to alternate between proactivity and reactivity in order to attain an objective in an ever-changing environment. A disadvantage of reactive control is that “it requires repeated reactivation of the goal rather than continuous maintenance” (Braver, 2012, p. 3). During a short time, employing proactive control makes more sense and is more efficient (Braver, 2012). However, longer periods of time may be best suited for reactive control (Braver, 2012). This is because using proactive control all day long to keep a goal in mind may draw upon more resources than would be necessary (Braver, 2012).

An everyday example of proactive vs. reactive control can be found in going to a laundromat after work. With a proactive strategy, a person would maintain this goal in working memory throughout the day, whereas a reactive strategy would entail not holding the goal of going to the laundromat in working memory throughout the day, but instead depending on a stimulus or a trigger event that would bring the event (going to the laundromat) to mind (Braver et al., 2007). For example, seeing a laundromat ticket on the car seat might serve as a trigger that reminds the person that he or she needs to pick up laundry after work.

Lorsbach and Reimer (2010) found that cognitive control develops from ages 8 to 13 years and in a similar study learned that it continues to develop from when children are in sixth grade to when they are young adults (Lorsbach & Reimer, 2008). This gives us evidence supporting the idea that proactivity use increases as one ages. However, according to Braver et al. (2005), this increase in proactivity utilization declines at around the age of 60. It appears that children and the elderly use a more reactive control strategy than those in adulthood. Developmental differences in cognitive control suggest that there is not a single or uniform strategy being employed when storing and maintaining goal-relevant information, and that this process is dynamic. The DMC account serves to shed light upon this by offering a theory that incorporates proactive and reactive control strategies.

Employing a proactive control strategy is associated with having a strong tendency to relate prior contextual information to an objective. By using prior contextual information to analyze events, one typically is exhibiting good decision-making skills (van Wouwe, Band, & Ridderinkhof, 2009). The AX-CPT is adept at emulating context processing situations and “yields errors when a target probe appears in a non-target context or when a non-target probe appears in a target context” (van Wouwe et al., 2009). In an article by van Wouwe et al., they posit that events bound to episodic memory bias future actions and allow the participants who initially use primarily reactive control to improve performance by switching to proactive control to a degree. There is a tradeoff between proactive

and reactive control and there are advantages to each. Therefore, the brain switches back and forth between the two modes of cognitive control depending on the environment and/or goal in mind.

Brain Activity

Pisapia and Braver (2006) found that during proactive control, participants showed sustained activity in the anterior and lateral pre-frontal cortex (PFC) and during reactive control, they had transient activity in the lateral PFC. This is likely because keeping a goal in mind requires sustained activity and responding to a stimulus from the environment would require transient activation once the stimulus is shown (Carlos, 2018). Proactivity also appears to be associated with dopamine in the PFC (Braver et al, 2012) and when utilizing proactivity, one needs to continuously maintain the goal in memory, therefore, sustained activity in the PFC means a person is using proactive control. With short, intermittent activity in the lateral PFC, it can be concluded that a stimulus-driven strategy would only appear activated immediately after the stimulus is presented in the environment. The dual mechanisms of cognitive control framework support these findings because it verifies that there are two types of activity during cognitive control. The length of activity for each of the two strategies employed solidifies the idea of proactivity and reactivity. Braver et al. (2007) also found that there is activity in the medial temporal lobe of the hippocampus, while storing goal information to memory. This coincides with the many studies surrounding the importance of the hippocampus in memory.

The PFC plays a major role in the active maintenance of context information processing in other parts of the brain to keep this maintained information (Braver et al., 2007). By doing this, the PFC interacts with the hippocampus (central to memory) during proactivity and the premotor cortex during reactivity (Braver et al., 2007). Understanding how the PFC interacts with other neural networks is crucial to understanding the DMC account. Proactive and reactive cognitive control is governed by different portions of the brain; however, the PFC seems to be the core of these strategies.

Individual Differences in Modes of Control

Using measure of reactive control, Chevalier (2015) found that young children and aging adults tend to utilize a reactive mode of control more than a proactive model (Chevalier, 2015). However, Chevalier found that young children may be capable of proactive control, but make different metacognitive decisions than older children do. When reactive control becomes more difficult to implement than proactive control in a scenario, children use proactive control. This contrasts with older children, who use proactive control more frequently.

Van Gerven, Hurks, Bovend'Eerdt, and Adam (2016) recently examined how differences in age result in dissimilar prevalence of proactivity and reactivity in cognitive control. The participants ranged from ages 5-97 years and it was found that people generally utilize reactive cognitive control early in life (under 12 years of age) before they switch to proactivity for most of their life, then switch back to reactivity around the age of 60. Cognitive control quality improves

throughout childhood, remains relatively stable from adolescence and on, at least up until the age of 60, where it begins to decline again. Their results were also consistent with the idea that inhibitory function has a high potential to deteriorate (Van Gerven et al, 2016).

Morales, Yudes, Gomez-Ariza, and Bajo (2015) administered the AX-CPT to groups of monolinguals and bilinguals while measuring Event Related Potentials (ERP). The AX-CPT predicts efficient performance by requiring participants to adjust monitoring (proactive) and inhibition (reactive) control (Morales, Gomez-Ariza, and Bajo, 2013). They found that bilinguals used the proactive cognitive control strategy more often than monolinguals. Morales et al. hypothesize that fluently speaking two languages allows the bilinguals to switch effectively between the two modes of cognitive control.

Unlike other psychotic disorders, schizophrenia spectrum illnesses seem to be linked to working memory impairments (McClure, Flory, Barch, Harvey, & Siever, 2008) and these deficits affect context processing tasks substantially. In the study by McClure et al., 63 people with schizotypal personality disorder (SPD), 23 with other personality disorders, and 42 healthy individuals that served as controls were given 3 versions of the modified AX Continuous Performance Test and an N-back working memory test (McClure et al., 2008). They found that those with schizotypal personality disorder (SPD) appear to make several context processing errors on these tests, providing support for context processing impairments in schizophrenia spectrum illnesses (McClure et al., 2008).

Lesh et al. (2013) conducted an experiment with both healthy controls and patients with schizophrenia and found that the healthy individuals showed activity in the parietal cortex, anterior cingulate cortex, and prefrontal cortex during proactivity and reactivity. However, patients with schizophrenia showed activation during reactivity, but little activation during proactivity (Lesh et al., 2013). The results imply that schizophrenic patients utilize reactive cognitive control more often than proactivity when compared to healthy individuals. Therefore, patients with schizophrenia mostly use reactivity, much like children under 12 years of age and elderly individuals over the age of 60.

Eye Movements in Cognitive Control

Many studies have been conducted that track eye movements while participants perform various cognitive tasks (Hutton, 2008; Michell et al., 2008). By doing so, researchers are able to discern where people's attention is during these tasks. While the association between eye movements and various aspects of cognition have been explored extensively, few studies have been done that measure a participant's gaze while using proactive versus reactive control.

Saccades

Experiments carried out in non-human primates have found that it takes a total of 60 ms for a signal to trigger a saccadic eye movement to a specific location once it reaches the retina (Hutton, 2008). However, a saccade made toward a target takes approximately 200 ms in humans and it is hypothesized that this extra amount of time to make a saccade is caused by people deciding

where to look and or where not to look (Hutton, 2008). This implies that cognition plays a role in the latency of saccades directed toward an unexpected target. Therefore, the latency of a saccade is indicative of the time it takes to decide whether to look at a particular location (Hutton, 2008). According to Hutton, goal directed behavior hinges on the capacity to properly maintain and manipulate context information while also ignoring irrelevant information and inhibiting an inclination toward an undesired response. These abilities are components of working memory and reflect one's level of proactivity. An antisaccade task requires a person to look in the opposite direction of a flashed cue shown in their periphery. It is a reflex for one to look at the flashed cue when it is positioned within peripheral vision. Therefore, an antisaccade involves inhibiting a predisposed response. Roberts, Hager, and Heron (1994) carried out a study which found that performing antisaccade tasks and solving mental arithmetic problems simultaneously resulted in more errors and longer latency times on the antisaccade tasks. It appears that allocating cognitive resources to solving the arithmetic problems reduces the resources available to make accurate and fast controlled saccadic eye movements. Therefore, deficits in antisaccade performance vary according to working memory load (Mitchell, Macrae, & Gilchrist, 2002).

Intentional Oculomotor Behavior

The ability to deliberately look at a visual stimulus can be examined by fixation tasks, which reflects cognitive control (Luna, Velanova, & Geier, 2008).

The gaze is intentional, therefore, there is a goal in mind that influences one's oculomotor response. Suppressing automatic responses to inhibit an undesired behavior, maintaining information to premeditate a response (working memory), and altering the focus of attention are all components of cognitive control that can be measured by eye movements (Luna et al., 2008). According to Luna et al., these components work together, but can be identified separately. Examining eye movements while someone is utilizing each distinctive element of cognitive control (inhibition, working memory, and attention) gives us direct neurophysiological measures of cognitive control.

There is considerable variability in the age-related maturation of eye movements governed by cognitive control (Luna et al., 2008). Luna et al. found that the processes reflective of cognitive control all are present early on but differ in their flexibility of use. The capacity for inhibiting saccades improves greatly from childhood to adulthood (Luna et al, 2008). However, according to Luna et al., the elderly display a more subtle reduction in the ability to inhibit saccades, which coincides with the studies related to declines in cognitive control. Luna et al. also established that those with schizophrenia, autism, and depression show similar deficits in saccades governed by cognitive control, despite these disorders being related to impairments in different brain functions.

Pupillary Changes and Blink Rates in Adults

In a study by Mäki-Marttunen et al. (2018), pupillary changes and blink rate were measured while administering the AX-CPT to young healthy adults.

Enlarged pupils and increased blink rate were indicative of greater cognitive effort allocation (Mäki-Marttunen et al., 2018). They used these two psychophysical measurements during the cue maintenance and response intervals (Mäki-Marttunen et al., 2018). Participants were divided into proactive, reactive, and intermediate groups based on their PBI, which is a measure of how proactive or reactive someone is (Mäki-Marttunen et al., 2018). The study reported that during the cue period, the less frequent non-target B cues significantly increased pupil size and blink rate in all participants. During the presentation of the probe, AY trials caused pupil dilation in all participants, but larger pupil dilation in participants classified as proactive (Mäki-Marttunen et al., 2018). Although Mäki-Marttunen et al. (2018) expected otherwise, the groups did not differ in blink rate or pupillary changes while the cue was presented. In all groups, the blink rates were significantly higher during the delay period after a non-target cue than when the cue was an “A” (Mäki-Marttunen et al, 2018). The amount of time before the first blink after the cue was presented was shorter when the cue was an “A” than when it was a non-target cue (Mäki-Marttunen et al., 2018). After the probe was presented, there was a longer amount of time before the first blink after AY trials than in the other trials (Mäki-Marttunen et al., 2018).

Taken together, these data suggest that proactive participants showed increased cognitive effort allocation after the probe appeared in AY trials and those from the reactive group utilized more cognitive effort after the probe in BX

trials. This was shown by increased pupillary size during these periods (Mäki-Marttunen et al., 2018). For the more proactive group, this was potentially due to participants inhibiting an incorrect targeted response after having encoded and maintained the A cue. The authors theorized that in reactive participants, the “X” probe was associated with an “A” cue, therefore, it required more cognitive effort to inhibit the dominant targeted response tendency when the probe was an “X” on BX trials (Mäki-Marttunen et al., 2018). Mäki-Marttunen et al. suggest that mostly reactive participants are more susceptible to interference from familiarity.

Developmental Differences in Pupil Dilation

In a study by Chatham, Frank, & Munakata (2009), the AX-CPT was given to a group of 3.5-year-olds and a group of 8-year-olds while measuring pupil dilation. The 8-year-olds were found to be more proactive than the 3.5-year-olds (Chatham et al., 2009). Averaged across all trials, the 8-year-olds exhibited larger pupils than the 3.5-year-olds during the delay period (Chatham et al., 2009). This points to increased cognitive effort allocation for context maintenance in proactive participants (Chatham et al., 2009). 3.5-year-olds had larger pupils throughout the probe period which alludes to increased mental effort for context retrieval (Chatham et al., 2009). The idea that reactive participants allocate increased cognitive effort for context retrieval is consistent with previous literature on cognitive control.

CHAPTER TWO

PRESENT STUDY

The purpose of the present study is to assess whether eye gaze data can be used to predict modes of cognitive control and provide information regarding the nature of cognitive control in young adults (i.e., the role of context updating vs. maintenance). Previous research has examined the ocular signature of cognitive control, specifically related to strategies that people utilize. Recall that Mäki-Marttunen et al. (2018) demonstrated that people using a proactive mode of control during the AX-CPT showed larger pupil size during probe presentation on AY trials than reactive participants. This suggests that proactive participants expended increased mental effort to inhibit the prepotent response (i.e., a target response) that was prepared based on the A cue. In contrast, on BX trials, reactive participants displayed greater pupil size than proactive participants during probe presentation. In this case, the reactive group allocated greater cognitive effort to inhibit an incorrect target response to the X probe. In order to do so, they had to reactivate the cue's identity, which was not proactively kept active in WM. These findings demonstrate that there are ocular differences between participants who adopted a more proactive, compared to a more reactive, mode of control in terms of the amount of cognitive effort allocated during *probe* processing.

One unexpected result in Mäki-Marttunen et al.'s (2018) study was that they failed to find differences in pupillary changes between reactive and proactive participants during *cue* presentation, or, more importantly, during the cue-probe delay. In order to address this shortcoming, Reimer, Sierra, Mobly, Perez-Martinez, and Rivera (2020) conducted a study designed to measure eye movements during a 3 s cue-probe delay within the AX-CPT. In an attempt to identify possible differences in eye movements and fixations during the cue-probe delay of the AX-CPT, a modified version of the task known as the AX-CPT 40 (Richmond et al., 2015) was used. In Reimer et al.'s study, cues were centered on the left-hand side of the computer screen (see Figure 2), while probes were presented either at the top or the bottom right-hand side of the screen (see Figures 3, 4, and 5). In this case, probe location was determined by the cue's identity (i.e., A or B). For AX and AY trials, cues were always paired with a probe located at the top-right corner of the screen, while with BX and BY trials, probes were presented at the bottom-right corner of the screen. As a result, participants could perfectly predict the location of the probe based on the identity of the cue, and therefore, create an expectation as to where the probe would be located on any given trial. Reimer et al. were interested in determining where participants fixed their eye gaze during the cue-probe delay period as a way to potentially differentiate between participants who utilized a proactive vs. reactive mode of control. Specifically, Reimer et al., were interested in measuring the amount of time participants spent looking at three locations during the cue-

probe delay: the cue location and the two probe locations (top and bottom) (see Figure 6).

Recall that PBI has been used as a measure of the use of proactive control during the AX-CPT (higher PBI values are associated with an increased use of proactive control). Reimer et al. found that the amount of time participants spent looking at the cue AOI (Area of Interest) during the delay predicted the degree to which individuals utilized a proactive vs. reactive mode of control as measured by PBI. Specifically, for AY trials (see Figures 7 and 8), cue TVD (Total Visit Duration) predicted PBI in participants who spent more time looking at the cue AOI than the top probe AOI, but not for participants who spent more time looking at the top AOI than the cue AOI. For BX trials (see Figure 9), increased TVD in the cue region was associated with higher PBI. Reimer et al. interpreted these results as indicating that increases in the use of a proactive mode of control are associated with an increased amount of time spent on context updating during the ISI.

Taken together, the results of the Mäki-Marttunen et al. (2018) and Reimer et al. (2019) studies indicate that specific ocular signatures may be associated with proactive and reactive control strategy use during the AX-CPT. What is still not clear, however, is whether the greater cue-region TVD that is associated with proactive control in Reimer et al.'s study stems from increased context updating, or from increased cue maintenance, during the delay period. Our current hypothesis is that this relationship is caused by the increased time required to

fully integrate the cue's identity and the AX-CPT rule under a proactive control strategy. According to this account, proactive control on the AX-CPT relies on the intentional engagement of cue encoding that involves three critical components: 1) an initial encoding of the cue's perceptual features in order to build a representation of the cue's identity (A or B), 2) integrate the cue's identity and the AX-CPT rule in order to prepare a response (e.g., "press 'target' key if probe is an X" for an A cue; or "press 'nontarget' key" for a B cue), and 3) activate a motor-based response set. If this is the case, the association between increased TVD in the cue region and PBI with both AY and BX trials found by Reimer et al., may result from the presence of individual differences in the control of the context updating process. Engagement in this form of controlled updating takes time, resulting in increased eye fixation on the cue region that may last even into the delay period after the cue disappeared. Previous research has demonstrated that people tend to maintain a local eye gaze pattern in one area during the encoding of information (e.g. Patt et al., 2014). Given that there are individual differences in working memory and attentional control (Unsworth & Robinson, 2015), small cue-region TVD may reflect a shift to a less demanding (at least initially) reactive strategy on the part of some participants. In this account, therefore, cue-region TVD during the cue-probe delay in the AX-CPT may represent a new ocular signature of proactive cognitive control.

What is still unclear, however, is the role that the relatively long cue-probe delay (3 s) used by Reimer et al.'s (2020) played in their results. It is possible

that the relationship between cue-region TVD and PBI found by Reimer et al. was largely a function of the relatively long cue-probe delay that was used. That is, it is possible that the increased TVD in the cue region associated with high PBI individuals may have not reflected only increased cue processing, but also the use of an additional maintenance process, or at least the preparation of a maintenance process, that was engaged to proactively keep cue-related representations active in WM over the relatively long delay. The present study is designed to test this possibility. Specifically, the present experiment is designed to determine whether the relationship between cue-region TVD and PBI found by Reimer et al. is present only when a relatively long delay is used, or whether this relationship can also be found when a shorter cue-probe delay is used, where demand associated with cue maintenance is significantly reduced.

According to the present account, the relationship between cue-region TVD and PBI is the result of individual differences in the engagement of proactive context updating after cue presentation, and not the result of increased maintenance demands associated with a long delay. If this is the case, a relationship between cue-region TVD and PBI should be found even when a relatively shorter cue-probe delay is used, as long as participants are given enough time to fully integrate the cue identity with the rule provided. Thus, the present study extends Reimer et al.'s (2020) study by examining eye movements during the cue-probe delay of the AX-CPT under two cue-probe delay conditions: a short (1500 ms) and long (3000 ms) cue-probe delay condition. A 1500 ms

cue-probe delay was chosen for the short delay condition for two reasons. First, a similar (1000 ms) delay has been used in previous studies to reduce the demands of cue maintenance (see e.g., Braver et al., 2001; Lorsbach & Reimer, 2010). Second, this delay will still allow ample time for participants to fully encode the cue and incorporate the AX-CPT rule. In Reimer et al.'s study, the average amount of time that proactive people fixated on the cue was approximately 900 ms. As in Reimer et al.'s study, the present study will use an adapted version of the AX-CPT 40. This version of the AX-CPT has 40% BY and 40% AX trials. BX and AY each comprise 10% of the total trials. The probes in the AY and AX trials will always appear at the top-right of the screen and BX and BY will always appear at the bottom-right.

We expect to find a similar pattern of response times (RTs) and error rates on BX and AY trials to that which has been found previously in the literature. Specifically, we expect to find that most participants will use proactive control and thus will have higher accuracy and faster RTs on BX trials relative to AY trials (resulting in a relatively high PBI). Regarding results from the eye tracking data, there are at least two different possible outcomes of interest. First, it is possible that the context updating account presented above is correct. If this is the case, similar to Reimer et al. (2020), we should find that increased TVD in the cue region is positively correlated with PBI in both AY and BX trials. If, however, the relationship between cue-region TVD and PBI found by Reimer et al. were

largely a function of the relatively long cue-probe delay that they used, we expect to find that such a relationship will not be found in the short-delay condition.

CHAPTER THREE

METHODS

Participants

In this study, there were 87 participants and all had normal or corrected-to-normal vision. Eighteen participants were excluded from the analysis (2 due to computer error and 16 because the eye tracker captured less than 50% of the potential gaze data), leaving 69 participants (*M* age: 23.3 years; *SD*: 3.9; age range: 18-37 years; 59 females, 10 males). The study was conducted according to the Institutional Review Board guidelines at California State University, San Bernardino. All participants were provided with informed consent.

Design

This study used a 4 (Trial Type: AX vs AY vs BX vs BY) x 3 (AOI Location: cue, top probe, bottom probe) x 2 (Cue-Probe Delay: 1.5 s vs. 3 s) mixed-design. Trial type varied within participants while Cue-Probe Delay varied between participants. Dependent variables included error rates and RTs, as well as Total Visit Duration (TVD) at each AOI. The two cue-probe delay conditions were counterbalanced across participants.

Apparatus

Eye tracking was implemented utilizing a Tobii T60XL eye tracker on a Dell OptiPlex 9020 desktop computer running Windows 7. The system specifications of this computer include an Intel Core i7 processor, 16 gigabytes of RAM, and a 24-inch LCD monitor with 1920 x 1080 pixels resolution. The sampling rate of the eye tracker was 60Hz with a processing latency of less than 17 ms and a RT of 4 ms. This computer was linked via an ethernet cable to a computer that ran the AX-CPT 40 using E-Prime 3.0 software. The computer with the AX-CPT was a Dell OptiPlex 7050 running Windows 10 with an Intel Core i5 processor, 8 gigabytes of RAM, and a 20-inch monitor with 1920 x 1080 pixels resolution.

Materials

The sensors on the eye tracker pinpoint and register eye-fixations and gaze duration to particular areas of the monitor screen. The AX-CPT 40 was presented on the eye tracker monitor and the participants were positioned approximately 65 cm from the monitor by use of a chin rest mounted to a table. Gaze data was processed in Tobii Studio and the AX-CPT-40 was programmed in E-Prime 3.0. The letters were in uppercase red 18pt Consolas font on a black background. E-Prime 3.0 recorded RTs and error rates for the participants completing the AX-CPT 40.

The AX-CPT included four types of trials (see Figure 10; Braver et al., 2001): AX target trials (“A” cue followed by “X” probe), AY trials (“A” cue followed

by a letter other than “X”), BX trials (”B” cue followed by an “X”), and BY trials (the cue is a “B” and the probe is not an “X”). On the typical AX-CPT, the proportion of AX, AY, BX, and BY trials is (AX = .70), (AY = .10), (BX = .10), and (BY = .10), respectively. The reason for the disproportionate amount of AX trials is to create a bias toward targeted responses. Participants expect A and X to be paired together because this is true 70% of the time when there is an A cue. In the AX-CPT 40 (the version to be employed in this study), there is a different ratio of each type of trial (AX = .40), (AY = .10), (BY = .40), and (BX = .01).

Letters were presented to the participants in pairs, one at a time. In the long cue-probe delay condition participants were required to look at the cue for 1000 ms (indicated by a box around the letter). The cue-probe delay (delay period with black screen) lasted for 3000 ms and the probe appeared for 500 ms. In the short cue-probe delay condition, participants were also required to look at the cue for 1000 ms but the cue-probe delay lasted for only 1500 ms. A response box with buttons labeled “Yes” (target) and “No” (nontarget) was used for recording responses from the participants. Participants used their right index finger to press the “Yes” button and their right middle finger to press the “No” button.

All participants were given identical instructions for the experiment. In the AX condition, the probe was always presented at the top-right of the screen (see Figure 2). In the BY condition, the probe was always presented at the bottom-right of the screen (see Figure 3). The AY condition displayed the probe at top-

right of the screen (see Figure 4) and the BX condition presented the probe at the bottom-right (see Figure 5). Feedback was provided by a sound from the speakers of the computer immediately after participants responded to the probe. A chime sounded for correct responses and the participants heard a buzzer if they chose an incorrect response. If the participant took longer than 1500 ms to respond to the probe, a message would display on the screen requesting that they respond faster.

A practice version of the task consisting of 10 trials was given to participants in order to allow them ample time to ask questions. The AX-CPT was programmed with 4 blocks of 40 trials with 3 optional breaks in between blocks to give the participants an opportunity to rest. Statistical analyses of behavioral data were performed in IBM SPSS statistical software. The proactive behavioral index (PBI) was calculated for each participant by using AY and BX error rates and RTs (Braver et al., 2009) with the formula: (AY - BX) / (AY + BX). Number of errors was computed using: (number of errors + 0.5) / (number of trials + 1). The PBI falls between -1 and +1. Scores closer to +1 indicate a more proactive strategy and scores closer to -1 indicate a more reactive strategy being employed. A score of 0.0 means there were equal numbers of errors made on AY and BX trials. Participants were categorized into two groups: proactive (PBI > 0) and reactive (PBI < 0). If Tobii Studio captured less than 50% of eye gaze data, then that participant was excluded from the analysis.

Procedure

Participants were tested individually in a well-lighted room and administered either version of the AX-CPT (short vs. long cue-probe delay) in a single session that lasted approximately 30 minutes. After signing a consent form and filling out their demographic information (date of birth, gender, and indicating whether they wear glasses), participants were randomly assigned to either the short or long cue-probe delay condition and seated in front of the eye tracking sensor. Participants were seated opposite the center of the monitor and instructed to adjust the seating position to a height that they deemed comfortable. They were then be told to place their chin on the chin rest and were informed of the calibration process. The calibration involved a visual target that moved around the screen. The participants were told to follow the target with their gaze until calibration ended. The target stopped at 5 positions: four at each corner and the fifth at the center of the screen. If calibration was not completed successfully, it was repeated until all 5 bullet points displayed a green dot in them (indicative of a successful calibration).

Participants were instructed to make a targeted response (press “Yes” button) when they saw the letter “X”, but only when it was preceded by the letter “A”. For all other pairs of letters, the participants were instructed to make a non-targeted response (press the “No” button). Each letter was presented on the screen one at a time. The participants were also informed that the location of the letters should have no bearing on whether they press the “Yes” or “No” button. It

was made known on two separate occasions throughout the instructions that the participants are to respond as quickly and accurately as possible. In addition to this, they were given the opportunity to ask any questions they may have.

Before beginning the task, participants were given a practice session consisting of ten trials. If they had no questions and seemed to understand the task, the participants began the AX-CPT. The AX-CPT was divided into 4 blocks with 40 trials each. Within each block there were 16 AX, 4 AY, 4 BX, and 16 BY trials. The participants were given the opportunity to take a short break in between each block of trials. The researcher was seated behind the participant and remained in the room throughout the task in order to answer any questions the participant may have had as they completed the task. Upon completing the AX-CPT 40, participants were assigned 3 points of extra credit through SONA.

CHAPTER FOUR

RESULTS

A total of eighteen participants were removed from the analyses. Two participants were removed due to computer error. Another sixteen participants were excluded because the eye tracker captured less than fifty percent of the potential gaze data. This may have been caused by several factors such as interference from eye make-up or the participant being too fatigued to look at the screen for an adequate amount of time. On average, eye gaze samples were recorded to a data file 71.5% (*SD* = 9.5%) of the time across conditions and participants in the study. The final sample included 69 participants. RT and error rate means were computed for both conditions, however, only data for trials where a correct response was given and had a RT greater than 200 ms were analyzed. TVD reported below was calculated by dividing the total number of eye gaze samples in which a fixation was recorded within a particular AOI by the total number of all eye gaze samples recorded during the cue-probe delay. This was done separately for each participant within each trial type. These TVD scores, therefore, reflect the proportion of total eye gaze samples recorded during the cue-probe delay that included a fixation within a specific AOI. It should be clarified that “cue-probe delay” within the context of this study refers to the ISI and not the stimulus onset interval (SOA) traditionally examined in the literature.

Response Time and Accuracy for Target and Non-Target Trials

Mean RTs and error rates were computed for each participant in each trial type (AX, AY, BX, and BY) and cue-probe delay (see Table 1 for means). An independent samples *t*-test was performed to compare RT and error rates for the AX trials in each ISI condition. There was no significant difference in RTs between the 1.5 second ISI (*M* = 477 ms, *SD* = 78.4) and 3 second ISI (*M* = 484 ms, *SD* = 99) conditions. There was also no significant difference in error rates between the 1.5 second ISI (*M* = .01%, SD = 1.2%) and 3 second ISI (*M* = 1.6%, SD = 1.8%) conditions. This was as expected and indicates PBI should have been distributed evenly across conditions.

A 2 (ISI: 1.5 s vs. 3 s) x 3 (Trial Type: AY vs. BX vs. BY) repeated measures ANOVA was conducted on the RT data from non-target trial types. There was a significant main effect of Trial Type, $F(2, 67) = 191.3$, $MSE = 2674.9$, $p < .001$. Post hoc comparisons revealed that all three means were significantly different from each other. Participants had significantly slower RTs on AY trials (*M* = 601 ms, *SE* = 12.6 ms) than BX trials (*M* = 468 ms, *SE* = 15.1 ms). Participants also had significantly slower RTs for BY trials (*M* = 439 ms, *SE* = 12.8) than BX trials. No other significant effects were found. These results indicate that certain trial types may require more inhibition.

A 2 (ISI: 1.5 s vs. 3 s) x 3 (Trial Type: AY vs. BX vs. BY) repeated measures ANOVA was also conducted on the error rate data for non-target trials (AY, BX, and BY). There was a significant main effect of Trial Type for error rate,

$F(2, 67) = 26.9$, $MSE = .001$, $p < .001$. Post hoc comparisons revealed that all three means were significantly different from each other. Participants had a significantly lower error rate on BX trials ($M = 1.3\%$, $SE = .5\%$) than AY trials ($M = 4.2\%$, $SE = .6\%$). Participants also had a significantly higher error rate on BX trials than BY trials ($M = 1.2\%$, $SE = .1\%$). No other significant effects were found. Taken together with the results from the previous ANOVA evaluating RT for the different trial types, we can infer that AY trials may require the most inhibition.

Total Visit Duration at Each Area of Interest for Target Trials

We examined differences in TVD at each AOI for AX trials with the intention of later comparing them to AY and BX trials. This was done to assess whether the participants were adhering to the observed rule by allowing us to confirm that the bias generated by an A cue was being adapted. A 2 (ISI: 1.5 s vs. 3 s) x 3 (Location AOI: Cue vs. Top Probe vs. Bottom Probe) repeated measures ANOVA was performed for the mean proportion of TVD in a particular AOI to total eye gaze data points captured by the eye tracker during the ISI for the target trial type (AX). There was a significant main effect of Location**,** $F(2, 134) = 145.9$, $MSE = .243$, $p < .001$. Participants had significantly higher mean TVD for the 1.5 s ISI condition ($M = .221$, $SE = .009$) than the 3 s ISI condition ($M = .193$, $SE = .012$). They also had significantly higher mean TVD on the Top Probe ($M = .378$, $SE = .02$) than both the Cue ($M = .237$, $SE = .013$) and Bottom Probe ($M = .006$, $SE = .001$), as well as a significantly higher mean TVD on the

Cue than the Bottom Probe. These findings suggest the bias we attempted to elicit for AX trials was successfully generated.

There was a significant interaction between Location and Delay, $F(2, 134) = 17.4$, $MSE = .29$, $p < .001$ (see Table 2 for means). For the 1.5 s ISI condition, simple main effects test showed that there was a significant effect of Location for AX trials, $F(2, 68) = 24.9$, $MSE = .16$, $p < .001$, where proportion of the TVD spent on the Top Probe ($M = .123$, $SE = .023$) was greater than the Bottom Probe ($M = .006$, $SE = .002$) and the Cue ($M = .007$, $SE = .003$). For the 3 s ISI condition, simple main effects test revealed that there was also a significant effect of Location for AX trials, $F(2, 66) = 14.8$, $MSE = .096$, $p < .001$. The proportion of the TVD spent on the Top Probe ($M = .153$, $SE = .009$) was greater than the Bottom Probe ($M = .006$, $SE = .002$) and the Cue ($M = .005$, $SE = .002$). This further reinforces the evidence surrounding the effectiveness of the bias we created for the participants. The probe always appears at the top after an A cue, therefore, the participants immediately look to the top probe location after observing the cue's identity.

Location by Trial Type

We were then compelled to learn whether an interaction between Location and Trial Type existed in each condition. There was a significant interaction between Location and Trial Type for the 1.5 s ISI condition, $F(6, 204) = 368.5$, $MSE = 2.58$, $p < .001$ (see Table 3 for means). A simple main effects test revealed that there was a significant effect of Trial Type in this condition, $F(3,$

102) = 648.4, *MSE* = 1.43, $p < .001$. Proportion of the TVD spent on the AOIs was greater in AX trials (*M* = .384, *SE* = .009) than in both BX (*M* = .184, *SE* = .009) and BY trials (*M* = .006, *SE* = .002). AY trials (*M* = .388, *SE* = .009) had a greater proportion of TVD spent on AOIs than BX and BY trials as well. In the 3 s ISI condition, there was a significant interaction between Location and Trial Type, $F(6, 198) = 300.4$, *MSE* = 2.16, $p < .001$. A simple main effects test showed that there was a significant effect of Trial Type in the 3 s ISI condition as well, $F(3, 99) = 327$, *MSE* = 1.25, $p < .001$. Proportion of the TVD spent on the AOIs was greater in AX trials (*M* = .32, *SE* = .01) than in both BX (*M* = .127, *SE* = .009) and BY trials (*M* = .136, *SE* = .008). AY trials (*M* = .326, *SE* = .01) had a greater proportion of TVD spent on AOIs than BX and BY trials as well. This interaction indicates that participants looked at the AOI locations more often when an A cue was presented. A potential explanation for this is that the presentation of a B cue always requires a non-target response and does not force the participant to update or maintain the cue once it has been identified and processed. Thus, the participants are able to look anywhere.

Total Visit Duration at Each Area of Interest (AY and BX Trials)

In order to address the questions we posed in this study, we found it pertinent to examine differences in TVD at each AOI by the two trial types used to calculate PBI. A 2 (ISI: 1.5 s vs. 3 s) x 2 (Trial Type: AY vs. BX) x 3 (Location AOI: Cue vs. Top Probe vs. Bottom Probe) repeated measures ANOVA was

conducted for the mean proportion of TVD in a particular AOI to total eye gaze data points captured by the eye tracker during the ISI separately for each non-target trial type (AY and BX). There was a significant main effect of Trial Type, $F(1, 67) = 104.3$, $MSE = .002$, $p < .001$. Participants had significantly higher mean TVD for AY trials ($M = .211$, $SE = .01$) than BX trials ($M = .162$, $SE = .01$). There was also a significant main effect of Location, $F(2, 67) = 64.4$, $MSE = .027$, $p < .001$. There was a significantly higher mean TVD on the cue ($M = .244$, $SE = .01$) than the bottom probe ($M = .058$, $SE = .02$). There was a significantly higher mean TVD on the cue than the top probe as well ($M = .257$, $SE = .02$). Finally, there was a significant main effect of Delay, $F(1, 67) = 8.67$, $MSE = .014$, $p < .01$. Participants had significantly higher mean TVD for the 1.5 second ISI condition ($M = .20$, $SE = .01$) than the 3 second ISI condition ($M = .169$, $SE = .01$).

These main effects, however, were qualified by two significant interactions. The interaction between Location and Delay was significant, $F(2, 134) = 22.5$, $MSE = .597$, $p < .001$ (see Figure 11). In the 1.5 s ISI condition, participants had significantly higher mean TVD on the cue ($M = .332$, $SE = .025$) than the top ($M = .214$, $SE = .017$) or bottom ($M = .065$, $SE = .012$) locations, as well as more TVD on the top than bottom. In the 3 s ISI condition, participants had significantly higher mean TVD on the top ($M = .30$, $SE = .025$) than either the cue ($M = .156$, $SE = .01$) or bottom ($M = .051$, $SE = .01$) location. Additionally, the proportions were higher for the cue than the bottom location.

Furthermore, there was a significant interaction between Trial Type and Location, $F(2, 134) = 110.35$, $MSE = .012$, $p < .001$ (see Figure 12). Simple main effects test revealed that there was a significant effect of location for AY trials, $F(2, 136) = 113.76$, $MSE = .023$, $p < .001$, where proportions were greater in the cue location ($M = .237$, $SE = .02$) than the bottom ($M = .006$, $SE = .002$), however, the proportions were greater in the top ($M = .389$, $SE = .02$) than the cue. A significant effect of location was also found for BX trials, $F(2, 136) = 17.99$, $MSE = .024$, $p < .001$. However, in this case, proportions were greater in the cue ($M = .253$, $SE = .017$) than both the top ($M = .124$, $SE = .016$) and bottom ($M = .111$, $SE = .017$) locations. Therefore, during AY trials, participants had greater TVD on the top probe than the cue location, but we find the opposite for BX trials. This may potentially represent an ocular signature for these two types of trials.

Regression Analyses for Total Visit Duration on Cue in AX, AY, and BX Trials

A series of simple linear regressions were calculated to predict PBI scores based on the proportion of all fixations on a given AOI during the ISI to total eye gaze data points recorded by the eye tracker during the ISI. In the first regression analysis, the proportion of fixations on the cue during AX trials in the 1.5 second ISI condition significantly predicted PBI based on RT, $\beta = -.496$, $t(33) = -3.28$, $p < .01$. Additionally, it also explained a significant proportion of variance in PBI RT, $R^2 = .246$, $F(1, 33) = 10.74$, $p < .01$. Another regression analysis was conducted

to look at whether the proportion of all fixations on the cue during the ISI to total eye gaze data points recorded by the eye tracker during the ISI predicted PBI scores. This analysis revealed that this proportion of TVD on the cue in AY trials in the 1.5 second ISI condition significantly predicted PBI RT, β = -.413, $t(33)$ = -2.61, $p < .05$. Furthermore, it explained a significant proportion of variance in PBI RT, R^2 = .145, $F(1, 33)$ = 6.79, $p < .05$. A third set of regression analyses were performed to examine whether the proportion of all fixations on the cue during the ISI to total eye gaze data points recorded by the eye tracker during the ISI in BX trials predicted PBI scores. It was found that the TVD proportion used for the cue in BX trials in the 1.5 second ISI condition predicted PBI RT, β = -.351, $t(33)$ = -2.15, $p < .05$. This same TVD measurement explained a significant proportion of variance in PBI RT in the 1.5 second ISI condition, R^2 = .096, $F(1, 33)$ = 4.63, $p < .05$. For all 3 trial types, the PBI calculated using RT was negatively correlated with the proportion of TVD on the cue.

Regression analyses were also performed for the 3 second ISI condition. The proportion of fixations on the cue during AX trials in the 3 second ISI condition significantly predicted PBI based on error rates as well, β = -.372, $t(32)$ = -2.27, $p < .05$. It also explained a significant proportion of variance in PBI RT, R^2 = .11, $F(1, 32)$ = 5.14, $p < .05$. The regression analyses conducted for the AY and BX trials during the 3 second ISI condition did not significantly predict PBI from the proportion of fixations on the cue. The proportion of fixations on the cue during AY trials in the 3 second ISI condition did not significantly predict PBI

based on error rates, β = -.300, $t(32)$ = -1.78, p = .085. It also did not explain a significant proportion of variance in PBI error rates, R^2 = .09, $F(1, 32)$ = 3.15, p = .085. Additionally, the proportion of fixations on the cue during BX trials in the 3 second ISI condition did not significantly predict PBI based on error rates, β = -.256, $t(32)$ = -1.496, p = .145. It did not explain a significant proportion of variance in PBI error rates, R^2 = .07, $F(1, 32)$ = 2.24, p = .145.

Further regression analyses performed sought to determine the time to first fixation (TFF) to the top and bottom probe for AY and BX trials in both conditions. During the 1.5 second ISI condition, TFF to the bottom probe in BX trials predicted PBI composite z scores, β = -.468, $t(28)$ = -2.75, $p < .05$. It explained a significant proportion of variance in PBI composite z scores as well, R^2 = .219, $F(1, 27)$ = 7.58, $p < .05$. Additionally, TFF to the bottom probe in BX trials predicted PBI error rates in the 1.5 second ISI condition, β = -.378, $t(28)$ = -2.12, $p < .05$. A significant proportion of variance in PBI error rates was explained by TFF to the bottom probe in BX trials, R^2 = .111, $F(1, 27)$ = 4.49, $p < .05$. TFF to the bottom probe on BX trials also predicted PBI RT in the 1.5 second ISI condition, β = -.367, $t(28)$ = -2.05, p = .05. A significant proportion of variance in PBI RT was explained by TFF to the bottom probe in BX trials, R^2 = .102, $F(1, 27)$ = 4.19, p = .05. In the 3 second ISI condition, TFF to the bottom probe during BX trials predicted none of these. Furthermore, TFF to the top and bottom probe locations during AY trials did not predict PBI.

CHAPTER FIVE

DISCUSSION

In the present study, we attempted to disentangle context updating from maintenance in cognitive control. Our theory was that the positive association between PBI and TVD on cue location in Reimer et al. (2020) would remain with a 1.5 s ISI condition. By providing two conditions with different ISI lengths, we were able to decrease the demand from maintenance in the shorter ISI when comparing it alongside the 3 s ISI condition. Therefore, context updating would have potentially been responsible for the increased TVD on the cue location during the ISI. We also attempted to provide an ocular signature of the proactive vs. reactive modes of cognitive control based on eye movements. Previous research (Chatham et al., 2009; Mäki-Marttunen et al., 2018) illustrated that proactive participants displayed an increased pupil size during AY trials when presented with the probe, which indicated they were expending increased cognitive effort to inhibit a target response. In contrast, reactive participants showed larger pupil size while the probe was presented on BX trials. This suggests the reactive participants were allocating more cognitive effort than proactive ones in order to inhibit a target response because they needed to spend time reactivating the cue's identity.

A major difference between our study and Mäki-Marttunen et al. (2018) was the length of the ISI. Their study used a 2500 ms delay, whereas our conditions used either a 1.5 s or 3 s delay. For this reason, the present study was capable of decoupling context updating from maintenance by accounting for a limitation of Mäki-Marttunen et al. (2018) and their pupillometry approach. With pupillometry, the size of the pupil is measured, but what was lacking in order to disentangle context updating and maintenance was a duration metric. Pupillometry is unable to discern the length of maintenance during the ISI because it only indicates that increased cognitive effort is being utilized. This does not provide a metric that can distinguish between the context updating and maintenance components of cognitive control.

During the ISI on the AX-CPT 40, Reimer et al. (2020) found a positive association between increased TVD on the cue and PBI for BX trials. The amount of time spent on the cue location after it disappears may be indicative of the level of control one has during the context updating process. It may be that proactive individuals simply take longer to update. Alternatively, the longer TVD on the cue during ISI for proactive participants may indicate a greater degree of context maintenance being used. To address this ambiguity, we adjusted the study conducted by Reimer et al. and added a 1.5 s ISI condition to compare alongside the 3 s ISI condition. This was done to decrease the demand required by context maintenance and served to isolate the context updating phase. It was hypothesized that the association between cue TVD and PBI would persist in the

1.5 s condition, suggesting there is a context updating mechanism responsible for longer TVD on the cue in proactive participants.

In the present study, for AX trials, participants spent more time on the top probe than the bottom probe or cue in both the 1.5 s and 3 s ISI conditions. For AY trials, participants spent more time on the top than the cue or bottom probe. For BX trials, participants spent more time on the cue than the two probe locations. Therefore, for A-cue trials, participants spent more time looking at the top probe than the bottom probe or cue, yet on BX trials participants spent more time looking at the cue than either the top or bottom probe. This was as expected for the A-cue trials because the consistently top-right located probe was meant to create a bias toward looking to that location. However, it seems somewhat unexpected that we do not find the corresponding results for BX trials. In other words, why did the bias generated for looking to the bottom probe location not occur in these trials and instead the highest TVD was spent on the cue? It should be noted that the 2nd longest TVD was on the bottom probe and not the top probe location, indicating the participants did adhere to the observed rule to an extent.

It is possible the highest TVD was on the cue throughout the ISI during BX trials because participants were properly integrating the identity of the B cue with the observed rule to give a non-target response, which requires inhibition to respond. Allocating more cognitive effort to inhibiting a target response may have resulted in this higher TVD on the cue location because it either requires more context updating to prepare an inhibitory response or the participants are

returning to the cue in order to reactivate the cue from memory. In order to provide an explanation for this difference in eye gaze patterns for AY and BX trials, a series of regression analyses were performed in an effort to predict PBI based on the eye gaze data.

In the 1.5 s ISI condition, there was a negative correlation between TVD on the cue and PBI scores during AX, AY, and BX trials. Therefore, a more reactive participant spent more time on the cue than the top or bottom probes. This may be due to primarily reactive participants requiring more time on context updating to prepare their response. We can infer from this that proactive participants are actively incorporating the rule for giving a target response while observing the cue, therefore, they look away from the cue toward the probe during the ISI faster. These findings may prove to provide an ocular signature for modes of cognitive control. While superior updating abilities may be responsible for the decreased TVD spent on the cue, an alternative hypothesis would be that the reason there is an increased amount of TVD on the cue for reactive participants is they allocated their attention back to the cue location after looking to the probe location in order to reactivate the goal in memory. This would mean returning to the cue location after glancing at the probe location may be indicative of a lower PBI because of reactivation and not due to an increased amount of time required for context updating.

For the 3 s ISI condition, longer TVD on the cue was associated with lower PBI for AX trials, but did not predict PBI for AY or BX trials. These findings differ

from Reimer et al. where only a 3 s ISI condition was used. In the Reimer et al. study, AOI location gaze patterns predicted PBI, including for AY and BX trials. However, for the 3 s ISI condition in this study, this was only partially replicated. This may have been due to different potential limitations of the study, which will be discussed further.

It is possible that proactive participants look almost immediately to the top probe location in AY trials because switching to maintaining the goal, rather than updating, is where they expend the most cognitive effort. Reactive participants may spend more time on the cue location during the ISI because they are updating longer than proactive ones. If less effort is spent context updating, the cue's identity may not be held in working memory as well, regardless of how well the goal itself is being maintained in memory. This may be why proactive participants make more errors during AY trials. Usually a target response is supposed to follow an A-cue due to the disproportionate amount of AX and AY trials, so they are focusing on their prepared response after seeing an A-cue and not allocating as much time to fully integrating the cue's identity with the observed rule to the extent that a more reactive participant would.

For BX trials, participants classified as primarily reactive also spent more time on the cue than the probe locations during the ISI as well. Slower RT on BX trials is typically associated with reactivity and it may be that extra time spent updating comes with a cost of spending more time to inhibit a target response. Their reactivity is triggered by the X probe and are forced to recall whether the

first letter was an A or B, which takes time. On AY trials, proactive participants are the ones who take longer to inhibit a target response. The association between less context updating and slower PBI RT on AY trials may indicate that proactive participants take longer to inhibit a target response on this trial type because they did not integrate the observed rule with the cue's identity as well.

Limitations

There are some limitations of the study that should be considered. For example, the study was conducted during an almost 3-week time period, but it was at the end of the academic quarter. Preparing for exams at the end of a course generally leaves students more fatigued than usual and perhaps this affected the participants' ability to allocate their attention to the screen or move their gaze as quickly as they would have otherwise. Another potential limitation to consider is the cross-cultural applicability of these findings. The participants all spoke English, a language read from left to right and top to bottom. It is possible using letters of the alphabet as stimuli provides an inclination toward looking to the top-right of the screen next for those who speak a certain language. However, there are many written languages throughout the world where letters or characters are read from right to left. It would be interesting to see if the direction one typically reads would affect participants' eye movements if we switched the location of probes on A-cue and B-cue trials.

The sample size may be a limitation of this study as well. 87 participants went through the experiment, but 18 were excluded from analysis. Most of those

excluded were done so because the eye tracker captured less than 50% of the potential eye gaze data. Therefore, the eye tracker itself was somewhat of a limitation in the study. Additionally, almost all participants in the study were young adults and the applicability of these findings to other age groups may be hasty because the external validity has not yet been determined. Most participants were also female, albeit the current research has not found inter-individual differences in performance on the AX-CPT based on gender.

Conclusion

For the 3 s ISI condition, we were only able to partially replicate Reimer et al. (2020) for the AY and BX trials. Cue TVD did not predict PBI in this condition. However, while it did predict PBI for the 1.5 s condition, cue TVD was negatively associated with PBI. This conflicts with the Reimer et al. (2020) study where cue TVD was positively associated with PBI. As previously mentioned, a limitation of the study was that it took place within the last 3 weeks of the academic quarter. Students may not have had the attentional endurance to concentrate for the longer, 3 s ISI. Further studies need to be conducted for replication of the results for either the 3 s ISI condition in this study or the 3 s ISI used in Reimer et al.

This study sought to test whether the findings of Reimer et al. (2020) persisted when a shorter ISI was used, which greatly decreased the demand on context maintenance. We found that reactive participants spent more time on the cue during the ISI than proactive ones in the 1.5 s condition, which taken with the results of Reimer et al. (2020), cannot confirm or disconfirm the hypothesis that

part of the increased cue TVD in proactive participants in the previous study was due to cue maintenance. With further replication of these studies, we may yet ascertain the salience of context updating when employing the two modes of cognitive control.

This study attempted to unsnarl context updating from maintenance in cognitive control and may have done so if the 3 s ISI condition in Reimer et al. had been completely replicated. However, the results of the 1.5 s ISI condition implicate a different eye movement pattern to that which was discerned by Reimer et al. in order to predict PBI. More studies should be conducted to confirm this pattern in the 3 s ISI condition. The results of our 1.5 s ISI condition may yet answer the question as to whether maintenance is responsible for the longer TVD spent on the cue in proactive participants from Reimer et al. (2020). If this eye gaze paradigm exists for both the 1.5 s and 3 s ISI conditions, then it is unlikely that increased context maintenance in proactive participants is the reason they spend less time on the cue during the ISI. Context updating may be a more central component of cognitive control than maintenance, therefore, requiring larger attentional allocation or cognitive effort. However, it should be emphasized that the results of this study are inconclusive without further replication of the 3 s ISI condition eye gaze pattern, regardless of whether the replication shows a positive or negative association between cue TVD and PBI. The analyses performed for this study showed a negative association between cue TVD and PBI, which contrasts with the positive association found in Reimer

et al. (2020). Therefore, further research should attempt to replicate either of these studies' findings. In summation, context updating plays a significant role in cognitive control and how much context updating a person does may be a predictor of PBI.

APPENDIX A

TABLES AND FIGURES

Table 1. Mean Correct Response Times and Error Rates (in Proportions) by Trial Type and Delay

ISI Delay	AX	AY	BX	BY
1.5 s				
RT	477 (78)	603 (18)	468 (21)	444 (18)
Error Rate	1.1% (1.0%)	5% (1%)	1% (1%)	2% (0.1%)
3 s				
RT	484 (99)	597 (18)	467 (22)	433 (18)
Error Rate	2% (2%)	0.3% (0.1%)	2% (0.1%)	0.1% (0.1%)

Table 2. Delay by Location (in Total Visit Duration Proportions)

	Delay	
Location	1.5 s	3 s
Bottom	.01 (.002)	.006 (.002)
Cue	.007 (.003)	.005 (.002)
Top	.123 (.02)	.153 (.009)

Note: Standard errors are in parentheses.

Table 3. Trial Type by Location (in Total Visit Duration Proportions)

	Trial Type			
TVD	AX	AY	BX	BY
1.5 s	.384 (.009)	.388 (.009)	.184 (.009)	.006 (.002)
3 s	.32 (.01)	.326 (.01)	.127 (.009)	.136 (.008)

Note: Standard errors are in parentheses.

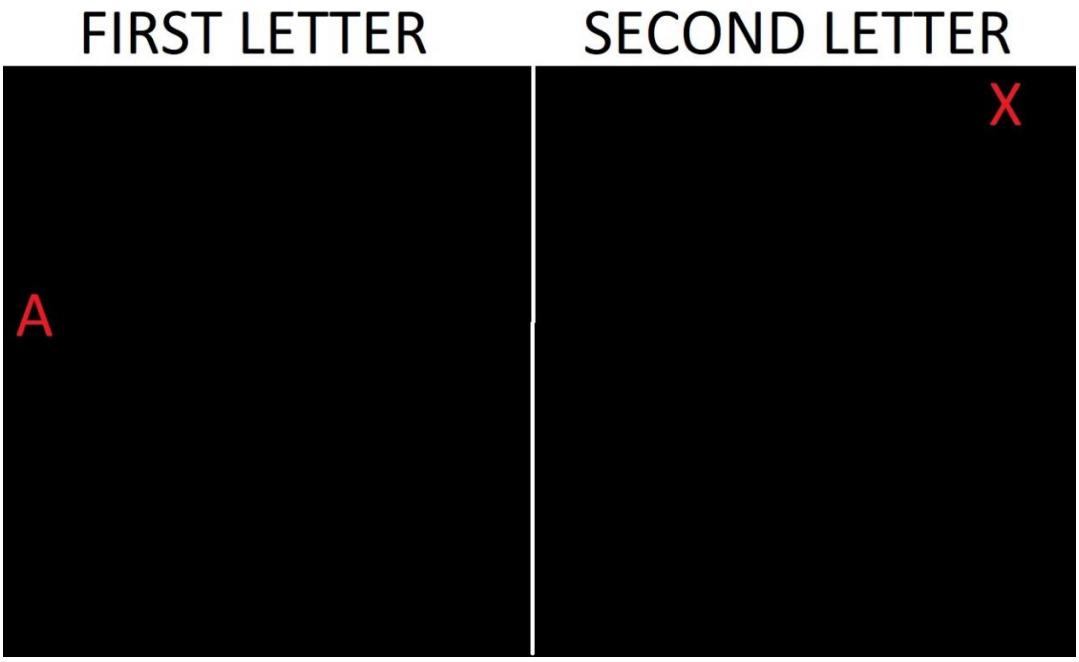

Figure 1. A Pair of Letters Shown Sequentially in the AX-Continuous Performance Test.

Figure 2. A Modified Version of the AX-Continuous Performance Test 40 with the Cue (A) Appearing in the Left-center of the Monitor Screen and the Probe (X) Appearing at the Top-right.

Figure 3. A Modified Version of the AX-Continuous Performance Test 40 with the Cue (B) Appearing in the Left-center of the Monitor Screen and the Probe (Y) Appearing at the Bottom-right.

Figure 4. A Modified Version of the AX-Continuous Performance Test 40 with the Cue (A) Appearing in the Left-center of the Monitor Screen and the Probe (Y) Appearing at the Top-right.

Figure 5. A Modified Version of the AX-Continuous Performance Test 40 with the Cue (B) Appearing in the Left-center of the Monitor Screen and the Probe (X) Appearing at the Bottom-right.

Figure 6. Areas of Interest for Eye Tracker. The Cue is the Area of Interest on the Left with the Two Areas of Interest on the Right Representing the Two Possible Probe Locations.

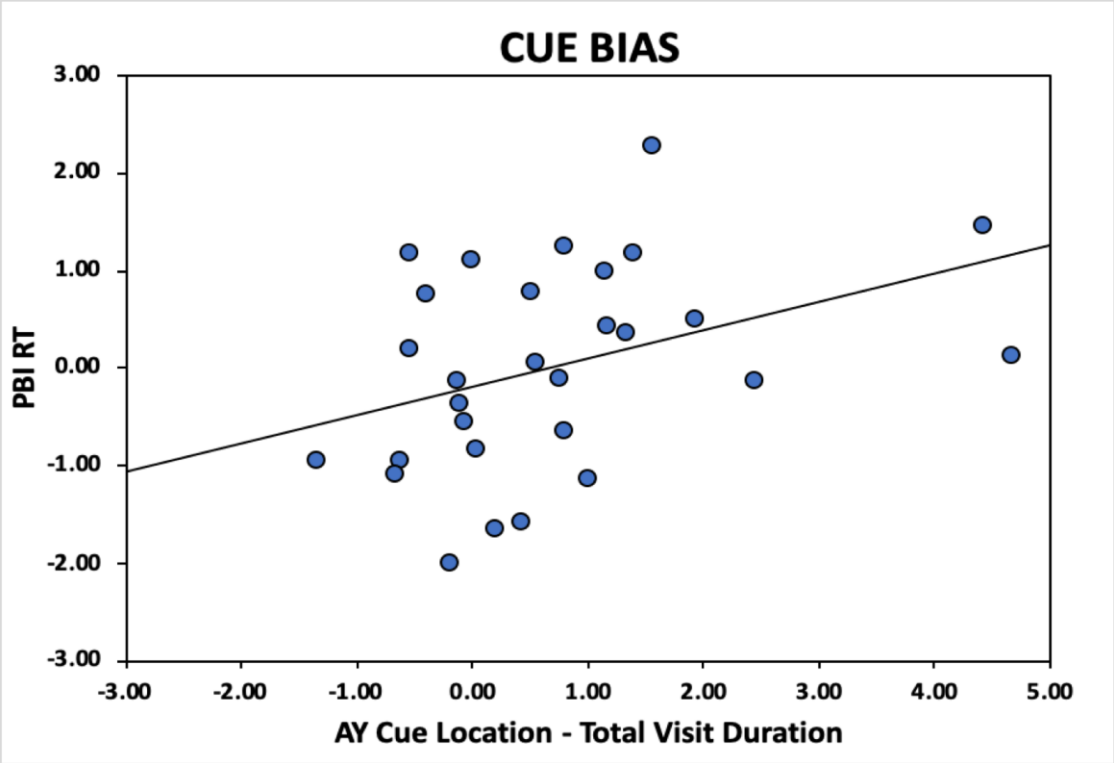

Figure 7. AY Trials: Cue Total Visit Duration Predicted Proactive Behavioral Index in Participants Who Spent More Time Looking at the Cue Area of Interest than the Top Probe Area of Interest.

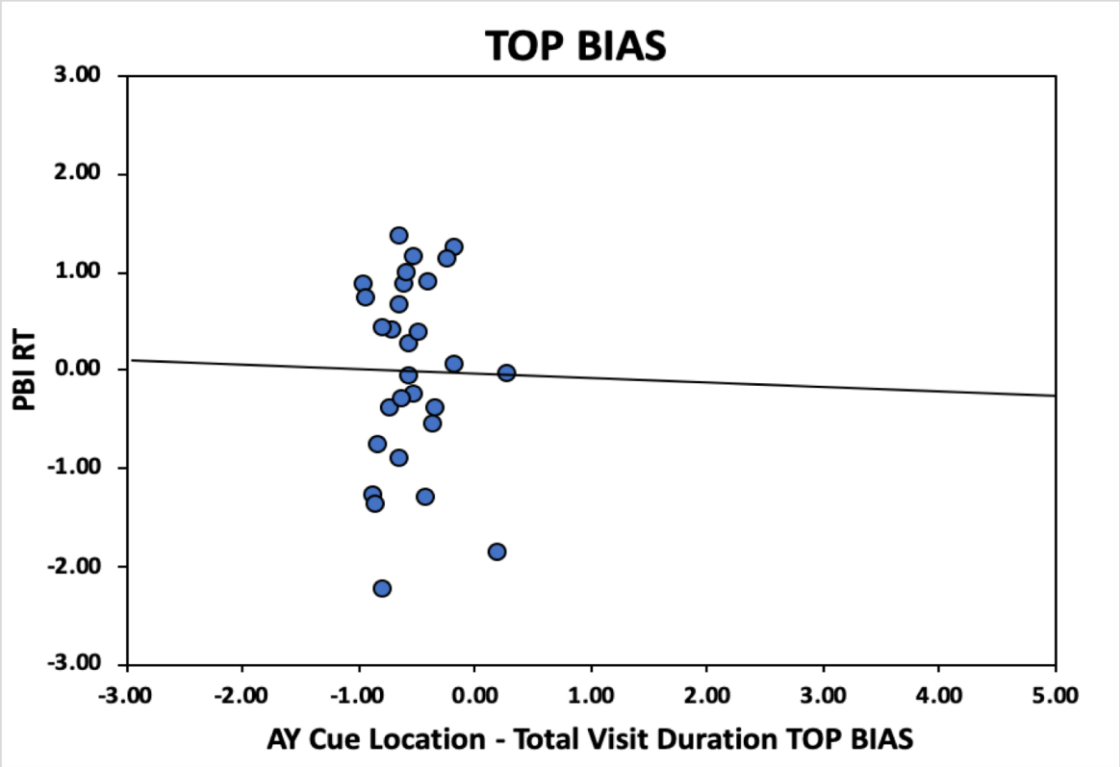

Figure 8. AY Trials: Cue Total Visit Duration Did Not Predict Proactive Behavioral Index for Participants Who Spent More Time Looking at the Top Area of Interest than the Cue.

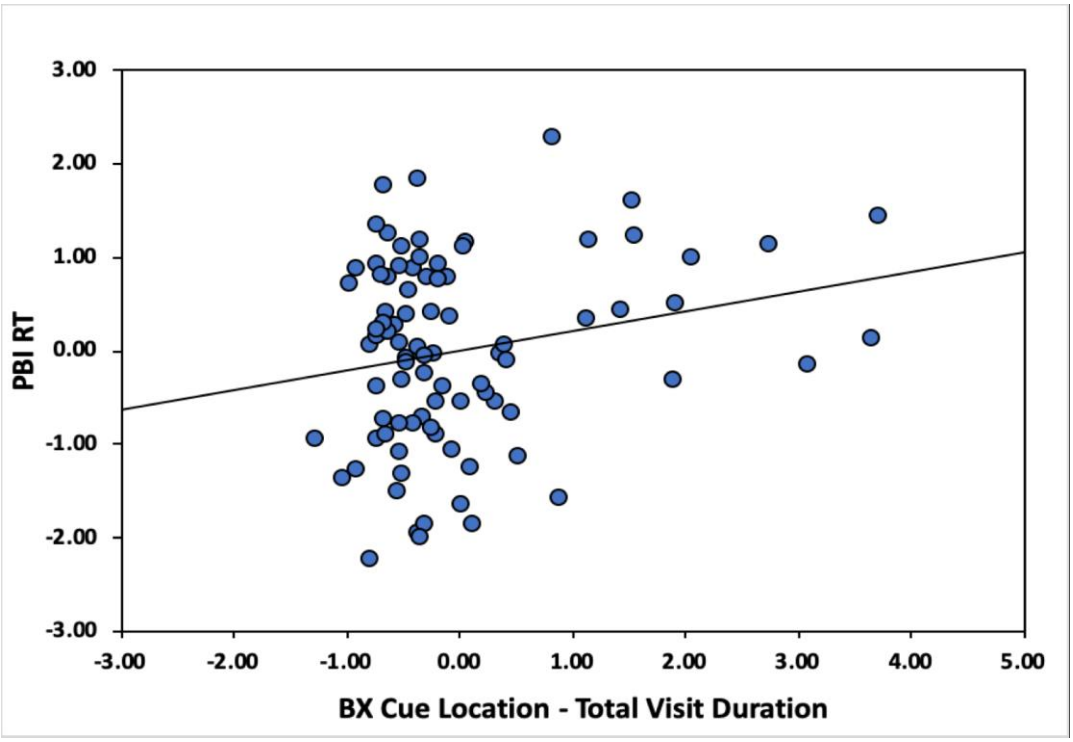

Figure 9. BX Trials: Increased Total Visit Duration in the Cue Region was Associated with Higher Proactive Behavioral Index.

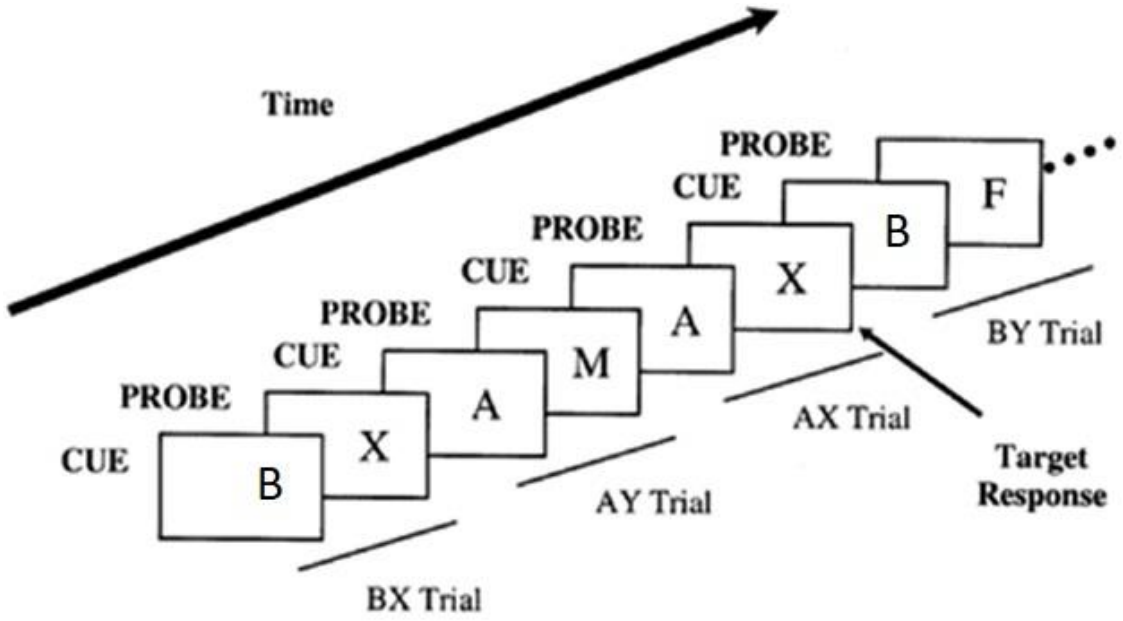

Figure 10. Schematic Overview of the AX-Continuous Performance Test.

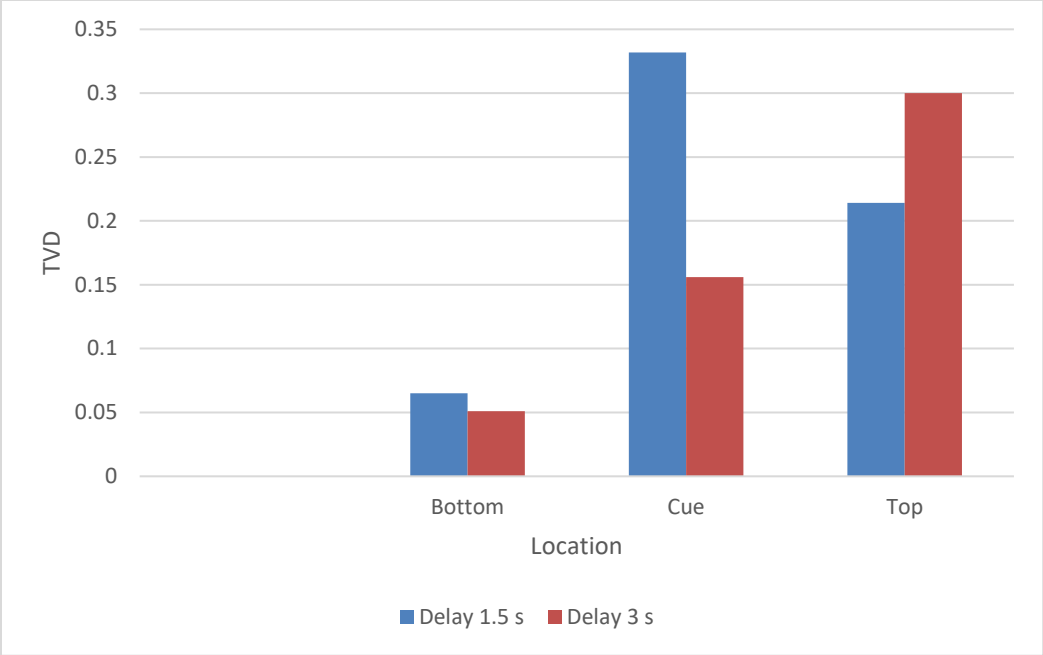

Figure 11. Location by Delay Total Visit Duration.

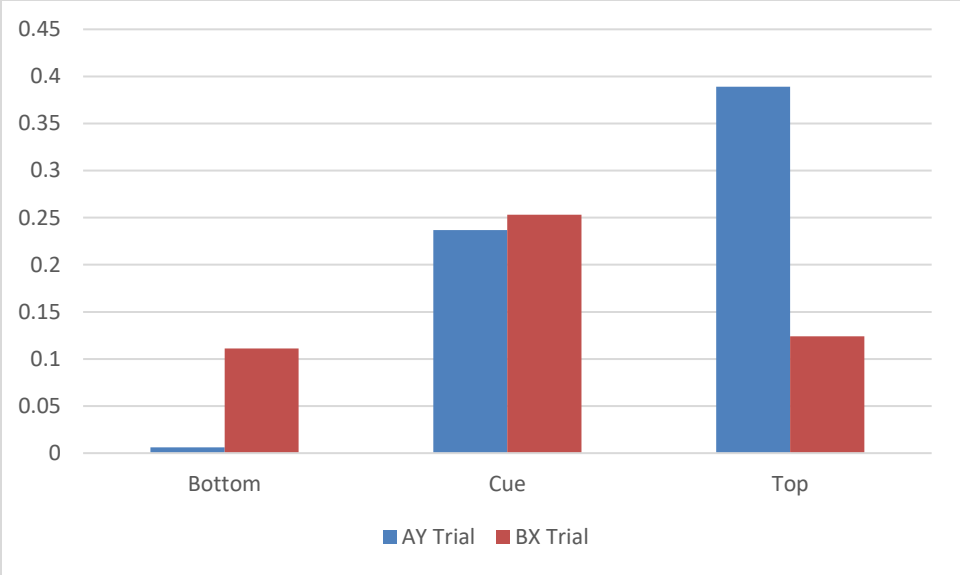

Figure 12. Location by Trial Type.

APPENDIX B

INSTITUTIONAL REVIEW BOARD APPROVAL

CALIFORNIA STATE UNIVERSITY
SAN BERNARDINO

February 18, 2020

CSUSB INSTITUTIONAL REVIEW BOARD
Protocol Renewal
IRB-FY2019-152
Status: Approved

Jason Reimer
CSBS - Psychology
California State University, San Bernardino
5500 University Parkway
San Bernardino, California 92407

Dear Jason Reimer :

Your protocol renewal to use human subjects, titled "Modes of Cognitive Control and Directed Attention" has been reviewed and approved by the Chair of the Institutional Review Board (IRB).

Your renewal is approved from February 18, 2020 through --. Please note the Cayuse IRB system will notify you when your protocol comes up for renewal at 90, 60, and 30 days before the protocol expires. If you are no longer conducting the study you can submit a study closure through the Cayuse IRB system.

The modification of recruiting an additional 100 participants from SONA/CSUSB was approved.

You are required to notify the IRB of the following by submitting the appropriate form (modification, unanticipated/adverse event, renewal, study closure) through the online Cayuse IRB Submission System.

1. If you need to make any changes/modifications to your protocol submit a modification form as the IRB must review all changes before implementing in your study to ensure the degree of risk has not changed.
2. If any unanticipated adverse events are experienced by subjects during your research study or project.
3. If your study has not been completed submit a renewal to the IRB.
4. If you are no longer conducting the study or project submit a study closure.

You are required to keep copies of the informed consent forms and data for at least three years.

If you have any questions regarding the IRB decision, please contact Michael Gillespie, Research Compliance Officer. Mr. Gillespie can be reached by phone at (909) 537-7588, by fax at (909) 537-7028, or by email at mgillesp@csusb.edu. Please include your application identification number (above) in all correspondence.

Best of luck with your research.

Sincerely,

Donna Garcia

Donna Garcia, Ph.D., IRB Chair
CSUSB Institutional Review Board

DG/MG

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