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Task-switching in oculomotor control: Systematic investigations of the unidirectional prosaccade switch-cost

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TASK-SWITCHING IN OCULOMOTOR CONTROL: SYSTEMATIC INVESTIGATIONS OF THE UNIDIRECTIONAL PROSACCADE SWITCH-COST

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by

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Abstract

An antisaccade requires suppressing a stimulus-driven prosaccade (i.e., response suppression) and remapping a target's spatial location to its mirror-symmetrical position (i.e., vector inversion). Notably, my previous work demonstrated that the successful execution of an antisaccade selectively lengthens the reaction time (RT) of a subsequently completed prosaccade (i.e., the *unidirectional prosaccade switch-cost*; Weiler & Heath, 2012a; Weiler & Heath, 2012b). Thus, the objective of this dissertation was to further investigate, and ultimately provide a mechanistic explanation for the unidirectional prosaccade switch-cost.

In Chapter Two, I demonstrate that the magnitude of the unidirectional prosaccade switch-cost is not dependent of the number of previously executed antisaccades. Such a finding is noteworthy as it demonstrates that antisaccades do not engender additive inhibitory effects within the oculomotor system. In Chapter Three, I demonstrate that no-go catch-trials and antisaccades impart a comparable increase in RT for subsequently completed prosaccades. In accounting for this result, I propose that the top-down process of response suppression engenders a residual inhibition of the oculomotor networks that support prosaccade planning (i.e., the *oculomotor inhibition hypothesis*). Notably, however, the unidirectional prosaccade switch-cost could also be attributed to a persistent activation of non-standard antisaccade task-rules (i.e., a task-set) and therefore produce a prosaccade switch-cost (i.e., *task-set inertia hypothesis*). The goal of the Chapter Four was to test the theoretical predictions of the aforementioned hypotheses. Notably, Chapter Four demonstrates that only antisaccade trial-types – but not prosaccades trials requiring response suppression – lengthen the RT of subsequent prosaccades. As a result I conclude that the oculomotor inhibition hypothesis cannot account for the unidirectional prosaccade switch-cost. Instead I propose that the prosaccade switch-costa is due to a persistently active task-set adopted to complete the previous antisaccade response. In Chapter Five I demonstrate that alternating from an anti- to a prosaccade does not modulate the amplitude of the P3 event related brain potential. This is a notable finding as amplitude modulation of the P3 reflects task-set updating. These electrophysiological results are directly in line with my assertion that a persistently active antisaccade task-set provides the most parsimonious account for the unidirectional prosaccade switch-cost.

Keywords

Antisaccade

Inhibition

Oculomotor

Prosaccade

Reaction time

Switch-cost

Task-set

Task-switching

Top-down control

Co-Authorship Statement

I conducted the work of this dissertation under the supervision of Dr. Matthew Heath. Specially, I conceived and designed all the experiments, collected, analyzed and interpreted all of the data, and prepared the manuscripts. I received support from an undergraduate volunteer research assistant (T. Mitchell) in the collection of data for Chapter Three and that individual has been credited as a co-author in the published version of that work. In addition, I received technical support from Dr. Krigolson and a doctoral candidate (C. Hassell) with the post-processing of the electroencephalography data found in Chapter 5. These individuals will be included as co-authors when this manuscript is submitted for publication. The work within my dissertation contains published manuscripts (Chapters Two, Three and Four) as well as one manuscript that is currently under review (Chapter Five). On all manuscripts, I was the first author and Dr. Matthew Heath was a co-author.

Abbreviations

ANOVA: analysis of variance

CI: confidence interval

EEG: electroencephalography

ERP: event related brain potential

MS: millisecond

RT: reaction time

SD: standard deviation

SR: stimulus-response

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Chapter 1

General Introduction

1.1 Oculomotor control

A saccade is a rapid shift of gaze that brings a peripheral area of interest onto the region of the retina that has maximal visual acuity (i.e., the fovea). The flexible and dynamic nature of a saccade is made possible by six extraocular muscles that move the eye. Specifically, the lateral rectus and medial rectus muscles enable ocular abduction and adduction, respectively, the superior rectus and inferior rectus muscles enable ocular elevation and depression, respectively, and the superior oblique and interior oblique muscles enable ocular intorsion and extorsion, respectively. These extraocular muscles are innervated by cranial nerve III (superior rectus, medial rectus, inferior rectus, and inferior oblique), nerve IV (superior oblique) and nerve VI (lateral rectus) located in the brain stem (Kandel et al., 2000).

The cranial nerves that innervate the eye musculature fire in response to neural activity generated within cortical (e.g., dorsolateral prefrontal cortex, frontal eye field, supplementary eye field) and subcortical (e.g., superior colliculus) saccade structures. A central theme of oculomotor control research is to determine how these neural structures work in concert to produce an efficient and effective goal-directed saccade. Notably, prosaccades and antisaccades are two paradigms – or ‘tasks’ – frequently employed in this area of research and are tasks that I examined throughout this dissertation. For the prosaccade task participants are required to saccade to the location of a single and exogenously presented target. The direct overlap between stimulus and response allow retinotopically organized maps within the superior colliculus to enable efficient (i.e., fast) and effective (i.e., accurate) prosaccades planning with minimal top-down control (Wurtz & Albano, 1980; see also Pierrot-Deseilligny et al., 1995). Indeed, prosaccades can be elicited with reaction times (RT) as low as 70 ms (i.e., the visual grasp reflex; see Pierrot-Deseilligny et al., 1995) and typically display a slight undershooting bias (i.e., ~10% of the total response amplitude; Becker 1989; Deubel et al, 1986) which allows the target to land on the fovea but minimizes the energy requirements of the response (Becker 1989; Gillen et al., 2013; Oliveira et al., 2005). In contrast, the antisaccade is a non-standard (i.e., non-direct) top-down oculomotor response that requires participants to saccade to the mirror-symmetrical location of a single exogenously presented target (Hallett, 1978; Hallet & Adams, 1980). An extensive literature has reported that antisaccades elicit longer RTs (Hallett, 1978; Fischer & Weber, 1996), more directional errors (Hallet, 1978), reduced peak velocities (Edelman et al., 2006), as well as less accurate and more variable endpoints (Dafoe et al., 2007; Krappman et al., 1998; Heath et al., 2010) than their prosaccade counterpoints. The reduction in efficiency and effectiveness of an antisaccade has been attributed to two top-down processes required for the response's successful execution. Specifically, participants must suppress the visual grasp reflexive when presented with an exogenous visual target (i.e., response suppression) and then visually remap the target's spatial position 180° (i.e., vector inversion) to be used as the goal-location for the volitional saccade (Funahashi et al., 1993; Zhang & Barash, 2000). Most notably, neuroimaging studies have linked the top-down requirements of an antisaccade to increased activity within the frontal eye field, supplementary eye field, dorsolateral prefrontal cortex, lateral intraparietal area, and the anterior cingulate cortex (Brown et al., 2007; see also Curtis & D'Esposito, 2003; DeSouza et al., 2003; Ford et al., 2005). Moreover, single-cell recordings in non-human primates have demonstrated that prior to stimulus presentation antisaccades engender a respective increase and decrease in the baseline firing rates of collicular fixation and saccade build-up neurons (Everling et al., 1999) and that this pre-stimulus activity is correlated with the *successful* execution of an antisaccade (Everling, et al., 1998). In summary, an extensive neuroimaging and electrophysiology literature has linked the antisaccade behavioural ‘costs’ to diffuse changes in activity of the cortical and subcortical structures that comprise the oculomotor system (see Figure 1-1 for depiction of the oculomotor system).

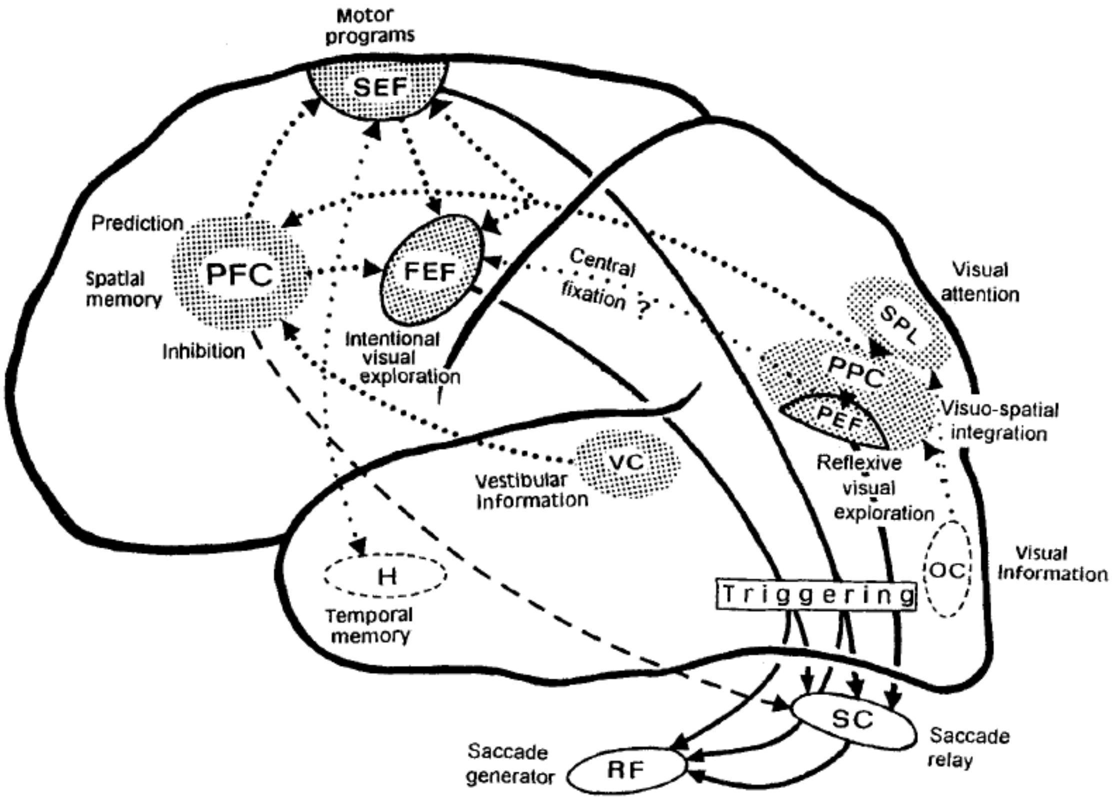

Figure 1-1: Organization and cortical and subcortical regions that comprise the oculomotor system (Pierrot-Deseilligny et al, 1995).

1.2 Task-switching

Human behaviour can flexibly adapt to appropriately respond in an ever changing environment. For example, a waiter in Montreal who greets patrons with a customary "Bonjour" will usually speak English after hearing a customer's Anglophone accent. This example highlights a central topic in cognitive psychology research: What are the cognitive (i.e., top-down) processes associated with flexible, adaptive behaviour and how are these processes implemented to meet the demands of the current situation?

One experimental methodology to address these questions is to have participants occasionally alternate – or 'switch' – between discrete tasks that are completed on individual trials (i.e., task-switching experiments). Although some have argued that it is difficult to precisely define what constitutes a 'task' (Rogers & Monsell, 1995), a task can be broadly thought of as a stimulus-response (SR) conditional statement; that is "if presented with stimulus X, do response Y". Thus, the basis of task-switching experiments is to occasionally manipulate the required response (i.e., do 'Z' instead of 'Y') associated with a common stimulus (i.e., 'X'). Notably, the utility of task-switching experiments is that they enable an assessment of how individuals flexibly adapt their behaviour to meet the goals of the current situation. To make this assessment, responses in such experiments are dichotomized into two specific trial-types: a trial wherein the task is the same relative to the previous trial (i.e., task-repetition trial) or a trial wherein the task is different relative to the previous trial (i.e., task-switch trial). The typical results of these experiments are that task-switch trial-types have longer RTs and display an increased number of errors relative to task-repetition trial-types – a finding referred to as a *switch-cost* (for extensive task-switching review see Kiesel et al., 2010).

Importantly, the overall goal of task-switching experiments is to explain the nature of switch-costs as it provides insight to the top-down processes associated with flexible and adaptive behaviour.

A number of experimental paradigms have been developed to explain the nature of switch-costs. The *cued task-switching* paradigm represents one classic methodology within this field because it systematically controls several parameters that have been shown to modulate the effects observed when alternating between two tasks. In a cued task-switching experiment, participants are provided with task-instructions in advance of a stimulus that initiates the response (e.g., Meiran, 1996; Sudevan & Taylor, 1987). This paradigm allows researchers to manipulate two experimental parameters. First, the cued task-switching paradigm enables direct control over the frequency and/or predictability when participants alternate between the two (or more) tasks (Koch, 2005; Wylie & Allport, 2000). Second, this paradigm enables the time between the task-instructions and the response-cue to be controlled; that is, the cued task-switching paradigm enables the amount of time participants have to prepared for an upcoming response to be manipulated (Altmann, 2004).

It is also important to realize that a plethora of tasks have been used within this literature depending on the specific research question. For example, participants have been required to state the magnitude (i.e., large or small) or the parity (i.e., odd or even) of a to-be-presented numerical digit (e.g., Gajewski & Falkenstein, 2011) or to depress a button with the left or the right index finger in response to the presentation of a particular stimulus (e.g., Meiran, 1996). Notably, there are little asymmetric difficulties between these types of task-pairings; that is, one task is not fundamentally more difficult to complete compared to the other. Recall, however, the Montreal waiter who must be able to flexibly switch between speaking his/her native language and a less practiced secondary language. This example highlights that pairs of tasks may have difficulty asymmetries; that is, one task may be highly learned and pre-potent (e.g., the native language), whereas the alternate response may require increased cognitive control for its successful execution because the task is relatively novel (e.g., second language). Evidence has shown that alternating between tasks with asymmetric difficulties yields a specific switch-cost pattern. For example, using the Stroop task Allport and colleagues (1994) demonstrated that alternating from the non-standard colour-naming response to the pre-potent word-naming response results in reliable RT switch-cost. Notably, however, RT switch-costs were not observed when alternating in the reverse direction. To explain this unidirectional 'difficult-to-easy' switch-cost, Allport suggested that the task-rules (i.e., a task-set) engendered to complete the cognitively demanding non-standard colour-naming response persist inertially and delays the planning of its pre-potent and well-learned counterpart (i.e., the *task-set inertia hypothesis*). Although this is only one of several proposed theories to explain the nature of switch-costs, the task-set inertia hypothesis has been influential in accounting for unidirectional switch-costs observed when alternating between tasks with difficulty asymmetries (e.g., Meuter & Allport, 1999; Wylie & Allport, 2000).

1.3 Task-switching in oculomotor control

Although oculomotor control and task-switching comprise a vast literature, only a paucity of work has combined the two fields to determine whether task-switching effects are present in oculomotor control; that is, relatively little work has sought to determine whether the completion of a prosaccade influences the planning of a subsequent antisaccade, or vice versa. One group, however, attempted to address this question using a novel saccade paradigm (i.e., cued-saccade paradigm: Barton et al., 2002; Barton, Greenzang, et al., 2006; Barton, Raoof et al., 2006). For this work, participants would fixate a central cross that was surrounded by an annulus and were concurrently presented with two equidistant targets left and right of fixation prior to response cuing. The annulus would then 'jump' and surround (i.e., cue) one of the two targets. Notably, prior to each trial participants were informed whether they were required to saccade to the target that was cued (i.e., 'prosaccade') or to the target that was not cued (i.e., 'antisaccade') (see Figure 1 of Manoach et al., 2002). Their results demonstrated that prosaccades completed after antisaccades were associated with an increase in RT. In other words, alternating from an anti- to a prosaccade resulted in a prosaccade RT switch-cost. Notably, antisaccades completed after prosaccades were associated with shorter RTs compared to the second of two consecutively completed antisaccades; that is, alternating from a pro- to an antisaccade was associated with an antisaccade RT switch-benefit. In order to explain this 'paradoxical' finding, the authors concluded that the completion of an antisaccade engendered residual inhibitory effects within the oculomotor system. Thus, it was proposed that *any* response completed after an antisaccade was associated with a lengthened RT.

It is important to realize that the cued-saccade paradigm does not reflect the pro- and antisaccade tasks commonly found within the oculomotor literature. More specifically, the concurrent presentation of two equidistant targets prior to response cuing engenders an environment that fundamentally changes the top-down requirements of the antisaccade task. Indeed, because a target is never exogenously presented in the cued-saccade paradigm, participants are not required to suppress the visual grasp reflex; that is, there is no response suppression requirement for antisaccades elicited within the cued-saccade paradigm. Moreover, vector inversion is not required as the un-cued target serves as the goal-location for antisaccades in the cued-saccade paradigm. In other words, antisaccades elicited within the cued-saccade paradigm are associated with direct SR relations. Due to this atypical methodology, I sought to determine whether the completion of an antisaccade influences the planning of a subsequent prosaccade – or vice versa – and employed the experimental paradigm most commonly used in oculomotor control research (i.e., a single exogenously presented target) in combination with the cued task-switching paradigm (see above). For this experiment, participants were informed – via the colour of a fixation cross – whether to execute a pro- or antisaccade in advance of target presentation and alternated between pro- and antisaccades after every second trial (i.e., AABB task-order). Results demonstrated that prosaccades completed after antisaccades (i.e., task-switch prosaccades) had longer RTs compared to the second of two consecutively completed prosaccades (i.e., task-repetition prosaccades). Notably, however, the RTs of antisaccades completed after prosaccades (i.e., task-switch antisaccades) or other antisaccades (i.e., task-repetition antisaccades) did not reliably differ (Weiler & Heath, 2012a). To determine whether this pattern of results was specifically attributed to the predetermined ‘AABB’ task-order, a subsequent study had participants alternate between the two saccade tasks in two separate blocks. In one block, participants alternated between pro- and antisaccades after every second trial (i.e., AABB), whereas in another block participants alternated between the two tasks in a randomized task-order. Results again demonstrated that task-switch prosaccades had longer RTs compared to their task-repetition counterparts, whereas the RTs of task-switch and task-repetition antisaccades did not reliably differ. Notably, this finding was independent of the predictability in which participant alternated between the two saccade tasks (Weiler & Heath, 2012b). Thus, my previous work demonstrated that switch-costs in oculomotor control are selectively elicited when alternating from an anti- to a prosaccade: a behavioural phenomenon that I have termed the *unidirectional prosaccade switch-cost*.

1.4 Dissertation objectives

The objective of my doctoral research program was to further investigate the unidirectional prosaccade switch-cost. In Chapter 2, I sought to determine whether the magnitude of the unidirectional prosaccade switch-cost was influenced by the number of previously completed antisaccade trials. Such a question was motivated by previous work which showed that the magnitude of the switch-cost imparted on a well learned dominant response increases as the number of previously executed non-standard responses increases (Wylie & Allport, 2000). In addition, a secondary goal of this chapter was to determine the locus of the switch-cost. As described previously, switch-costs are computed by comparing task-switch against task-repetition trials. A fundamental assumption of this computation is that task-repetition trials represent a stable baseline value in which to make this assessment. Indeed, the *relative* difference between task-switch and task-repetition trials may not be a result of a slowing of the former trial-type; rather, the difference may be due to a speeding up of a latter trial-type (so-called task-repetition benefit). In Chapters 3, I sought to determine what aspect of the antisaccade was responsible for lengthening the RT of a subsequent prosaccade. Specifically, I tested the hypothesis that response suppression – a top-down requirement of the antisaccade task – accounts for the unidirectional prosaccade switch-cost. Results from this chapter suggested that suppressing a stimulus-driven prosaccade (i.e., response suppression) engenders a residual inhibition of the oculomotor networks involved in prosaccade planning (i.e., the *oculomotor inhibition hypothesis*). However, a shortcoming of Chapter 3 was that the results may have been attributed to a mutually exclusively hypothesis that is well documented in the task-switching literature (i.e., the task-set inertia hypothesis). Therefore, in Chapter 4 I sought to determine whether the oculomotor inhibition or task-set inertia hypothesis provides the most parsimonious account for the unidirectional prosaccade switch-cost. Notably, results of this chapter indicated that my proposal asserting that response suppression engenders a residual inhibition of the oculomotor networks that support prosaccade planning was incorrect. In Chapter 5, I concurrently measured the behavioural and electroencephalography (EEG) data associated with an oculomotor task-switching experiment. More specifically, I assessed the amplitude of the P3 event related brain potential (ERP) because modulation of this waveform reflects updating the task-set required for upcoming response (Barceló et al, 2008; Barceló et al, 2002; Nicholson et al, 2005). The results of this chapter support the position that the unidirectional prosaccade switch-cost is best explained by the task-set inertia hypothesis.

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Chapter 2

Repetitive antisaccade execution does not increase the unidirectional prosaccade switch-cost

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Weiler, J., & Heath, M. (2014). Repetitive antisaccade execution does not increase the unidirectional prosaccade switch-cost. *Acta Psychologica, 146,* 67-72.

2.1 Introduction

A salient feature of human oculomotor control is the rapid and reflexive manner in which a saccade can be generated to an exogenously presented peripheral stimulus (i.e., prosaccade). Notably, the direct retinotopic mappings afforded between stimulus and response (i.e., standard response: e.g., Bruce et al., 1985; Wurtz and Albano, 1980) during a prosaccade allows for maximally efficient and effective motor output (Fitts & Seeger 1953; for review see Kornblum et al., 1990). It is, however, important to recognize that the direction of an oculomotor response is not ineluctably coupled to the spatial location of a presented stimulus; rather, the oculomotor system can flexibly "look" in a direction other than the stimulus (i.e., non-standard response). The properties of this non-standard response are highlighted in the antisaccade task wherein participants are instructed to look mirror-symmetrical to the location of an exogenously presented target (e.g., Hallett, 1978). Extensive evidence has shown that antisaccades produce longer reaction times (RT), as well as increased directional errors compared to their prosaccade counterparts (e.g., Hallett, 1978; Fischer & Weber, 1996). Moreover, convergent neuroimaging and electrophysiological studies involving human and non-human primates have linked the behavioural costs of antisaccades to a two-component process requiring: 1. The top-down suppression of a stimulus-driven prosaccade (i.e., response suppression; Everling et al., 1998; Everling et al., 1999) and 2. The visual remapping of target properties to mirror-symmetrical space (i.e., vector inversion: Funahashi, et al., 1993; Zhang & Barash, 2000). Furthermore, neuroimaging work has shown that antisaccades are associated with greater activation of classic cortical saccade networks (e.g., frontal eye field, supplementary eye field, and intraparietal sulcus) than their prosaccade counterparts (Brown et al., 2007; Curtis & D'Esposito, 2003; DeSouza et al., 2003; Ford et al., 2005). Thus, evidence indicates that the completion of a successful antisaccade is associated with diffuse changes within the oculomotor system (for review see Munoz & Everling, 2004).

The modulation of oculomotor networks during an antisaccade task is thought to result, in part, from a task-specific response mode that pre-sets the network to withhold a reflexive prosaccade (DeSouza et al., 2003; Ford et al., 2005). As such, a corollary to the *pre-setting theory* is that antisaccades engender a persistent response-set that delays the planning of a subsequent pro- or antisaccade. To address this issue, our previous work investigated the planning costs associated with alternating from a prosaccade to an antisaccade and vice versa (i.e., task-switching paradigm). In particular, participants alternated between pro- and antisaccades using a block of trials involving the classic task-switching paradigm (i.e., AABB paradigm; Weiler & Heath, 2012a; Weiler & Heath, 2012b) and a block wherein pro- and antisaccades were presented in pseudo-randomized task-switching order (Weiler & Heath, 2012b). Our results have consistently shown that a prosaccade completed after an antisaccade (i.e., task-switch prosaccade) elicits longer RTs in comparison to the second of two consecutively completed prosaccades (i.e., task-repetition prosaccade). In contrast, RTs for antisaccades were refractory to the nature of the previously completed response (i.e., task-switch and task-repetition antisaccades). In other words, our results demonstrate a unidirectional prosaccade switch-cost and our results have recently been replicated by an independent group (Chan & DeSouza, 2013). Notably, such findings are in-line with the cognitive task-switching literature reporting a unidirectional switch-cost when alternating from a non-standard to a standard task. For example, Allport and colleagues (1994) showed that alternating from the unfamiliar colour-naming (i.e., non-standard task) to the familiar word-naming (i.e., standard task) Stroop task resulted in a reliable switch-cost, whereas the converse switch did not.

It is, however, important to bear in mind that most cognitive task-switching studies require a simple button press or oral response (for review see Kiesel et al., 2010), whereas task-switching in oculomotor control requires the evocation of a spatially constrained action. As such, task-switching in oculomotor control adds importantly to the literature insomuch as it demonstrates that such an effect manifests in the context of an action constrained by speed/accuracy relations. Indeed, due to the symmetry between oculomotor (Chan & DeSouza, 2013; Weiler & Heath, 2012a; Weiler & Heath, 2012b) and cognitive task-switching results (Allport et al., 1994) as well as oculomotor neuroimaging (Brown et al., 2007; Curtis, & D'Esposito, 2003; DeSouza et al., 2003; Ford et al., 2005) and electrophysiology (Everling & DeSouza, 2005; Everling et al., 1998; Everling et al., 1999) evidence, we have proposed that the top-down processes required to implement an antisaccade results in a residual inhibition of the dedicated oculomotor networks that support the planning of subsequent prosaccades.

An interesting question arising from our previous work is whether the residual inhibition of oculomotor networks accumulates over successive antisaccade trials. This question stems from evidence demonstrating that a switch-cost can increase as a function of the number of non-standard trials preceding a standard switch-trial. For example, Wylie and Allport (2000) demonstrated that increasing the ratio of the non-standard trials preceding a standard trial reliably increased the magnitude of the switch-cost (see Figure 8 of Wylie & Allport, 2000). Thus, it is possible that the unidirectional prosaccade switch-cost noted in our previous work may be influenced by the number of previously completed antisaccade trials. Such a finding would suggest that antisaccades not only delay the planning of subsequent prosaccades, but also engenders residual inhibition that accumulates (or strengthens) over successive trials.

The first goal of the present investigation was to determine if the number of antisaccades preceding a to-be-completed prosaccade influences the documented unidirectional prosaccade switch-cost (Weiler & Heath, 2012a; Weiler & Heath, 2012b). To accomplish that objective, switch-costs were compared in separate blocks wherein tasks (i.e., pro-, antisaccades) alternated after every second (i.e., double block) and fourth (i.e., quadruple block) trial. In terms of research predictions, if antisaccades provide additive inhibition to oculomotor networks then the magnitude of the unidirectional prosaccade switch-cost is predicted to increase as a function of the number of previously completed antisaccades. In contrast, if the inhibition of oculomotor networks does not engender an additive level of oculomotor inhibition, then it is predicted that the magnitude of the unidirectional prosaccade switch-cost will be refractory to the number of previously completed antisaccades.

The second goal of the current investigation was to evaluate the specific locus of the unidirectional prosaccade switch-cost. Indeed, Wylie and Allport (2000) have cautioned against the fundamental task-switching assumption that task-repetition trials represent a proxy for a baseline measure of standard or non-standard trials because "…the comparison of Repeat trial RTs and RTs in a baseline condition is [usually] not possible" (pp. 213). In other words, task-repetition trials-types may differ from their counterparts performed in a separate block of trials (Goffaux et al., 2006). Given this consideration, a critique of our past work is that we did not demonstrate that the relative increase in RTs for task-switch compared to task-repetition prosaccades was selectively related to a previously completed antisaccade (Weiler & Heath, 2012a; Weiler & Heath, 2012b); rather, it is possible that the difference between prosaccade task-switch and task-repetition trials may be linked to a shortening of RTs in the latter condition. To illustrate this issue, Figure 2-1 presents theoretical data for prosaccade task-switch and task-repetition trials as well as prosaccades performed in separate blocks of trials. The top panel of the figure shows that prosaccade task-switch trials produce longer RTs than their task-repetition and blocked trial counterparts (which do not differ): a pattern of results that would support our contention of a unidirectional prosaccade switch-cost. In turn, the bottom panel shows that prosaccade task-repetition trials produce shorter RTs than task-switch *and* blocked trial counterparts. In this scenario, the relative difference between the RTs for task-switch and task-repetition prosaccades is not the result of a previously completed antisaccade; rather, the hypothetical difference is a result of a “speeding-up” of the second of two consecutively completed prosaccades. To directly address this issue, the present study compared pro- and antisaccade task-switch and task-repetition trials with pro- and antisaccades completed in their own block of trials.

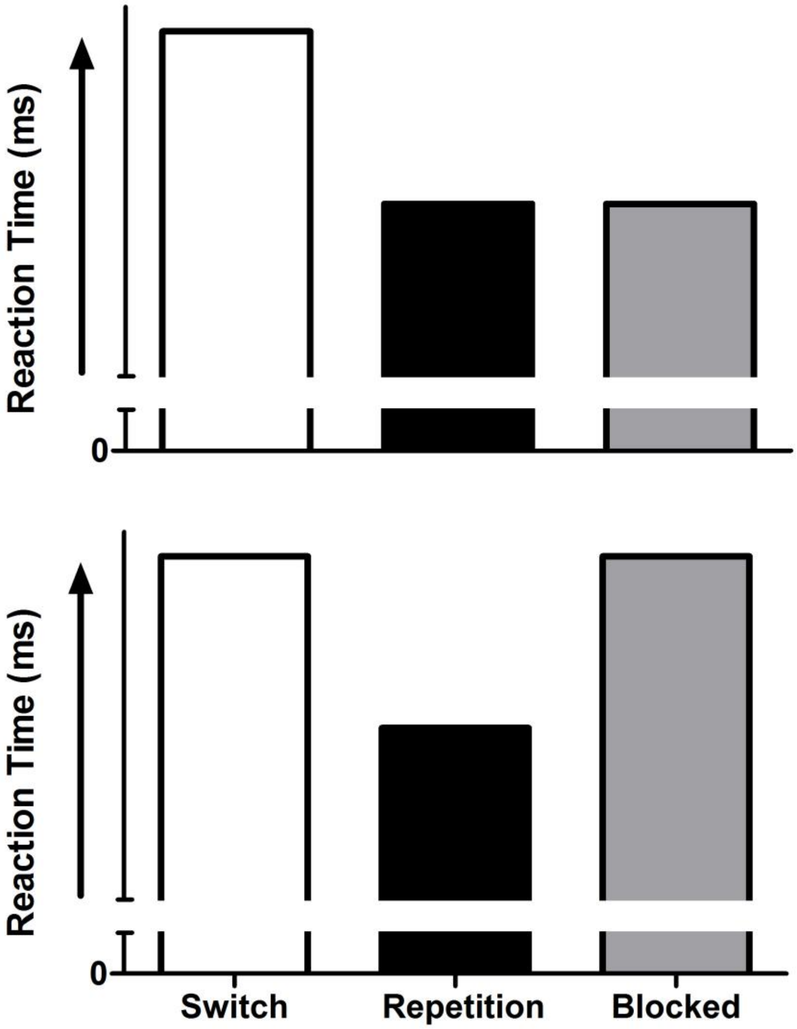

Figure 2-1: Hypothetical data highlighting potential differences between blocked, task-switch and task-repetition prosaccades. The top panel shows longer RTs for task-switch prosaccades compared to their task-repetition and blocked counterparts (which do not differ): a result consistent with our assertion of a unidirectional prosaccade switch-cost. In contrast, the bottom panel depicts shorter RTs for task-repetition prosaccades than their task-switch or blocked conditions counterparts (which do not differ). Indeed, results conforming to the lower panel would suggest that differences between task-switch and task-repetition prosaccades relates to a “speeding up” of oculomotor planning mechanisms.

2.2 Methods

2.2.1 Participants

Twenty participants (12 females, 8 males; age range 19 – 30 years old) from the University of Western Ontario community volunteered for the current investigation. All participants declared being right-hand dominant and had normal or correct-to-normal vision. Prior to data collection, each participant provided informed written consent. This study was approved by the Office of Research Ethics, The University of Western Ontario, and was conducted according to the guidelines of the Declaration of Helsinki.

2.2.2 Apparatus and Procedures

Participants sat at a table with their head placed in a head-chin rest during data collection. Visual stimuli were presented on a 30-inch LCD monitor (60 Hz, 8 ms response rate, 1280 by 960 pixels, Dell 3007WFP, Round Rock, TX, USA) centered on the participant's midline at a viewing distance of 550 mm. The gaze location of the participant's left eye was obtained via a video-based chin-mounted eye tracking system (Eye-Trac 6: Applied Sciences Laboratories, Bedford, MA, USA) sampling at 360 Hz. Prior to data collection a nine-point calibration of the participant's viewing space was performed. Two additional monitors, that were only visible to the experimenter, provided: (1) real-time point of gaze information, (2) a visual depiction of trial-to-trial saccade trajectories (e.g., displacement, velocity), and (3) information about the accuracy of the eye tracking system. All computer events and visual stimuli were controlled via MATLAB (7.6: The Math Works, Natick, MA, USA) and the Psychophysics Toolbox extensions (ver 3.0; Brainard, 1997). The lights in the experimental suite were extinguished during data collection.

Visual stimuli were presented against a high contrast black background. Stimuli included a green (53 cd/m^2) and a red (27 cd/m^2) fixation cross (1.0°) that were centered horizontally on the monitor and at the eye level of the participant. In addition, yellow (75 cd/m^2) crosses (1.0°) served as targets and were located 11.9° (proximal) or 14.4° (distal) left and right of the fixation cross. Each trial began with the presentation of either the green or the red fixation cross which alerted the participant to direct their gaze to its location. The colour of the fixation cross indicated the task to be performed in an upcoming trial. A green fixation cross indicated a saccade to the veridical location of the to-be-presented target (i.e., prosaccade), whereas a red fixation cross denoted a saccade to the mirror-symmetrical location of the to-be-presented target (i.e., antisaccade). After a stable gaze was maintained on the fixation cross (±1.5° for 420 ms), a randomized foreperiod (1,000 – 2,000 ms) was introduced during which time the fixation cross remained visible (so-called no-gap paradigm). Following the randomized foreperiod, a target was briefly presented (i.e., 50 ms) and the fixation cross was concurrently extinguished. The presentation of the target and removal of the fixation cross served as the cue to pro- or antisaccade "as quickly and accurately as possible".

Pro- and antisaccades were completed in their own blocks of trials, and in two additional blocks wherein the task (i.e., pro- and antisaccade) alternated after every second (i.e., AABB: henceforth termed 'double block') or after every fourth (i.e., AAAABBBB: henceforth termed 'quadruple block') trial. In the separate pro- and antisaccade blocks, the ordering of target eccentricity (proximal, distal) and visual space (left, right) was randomized and participants completed 12 trials to each target eccentricity and visual space combination to produce 48 trials for each task type. The double and quadruple blocks consisted of 96 and 192 trials, respectively. For these blocks the trial-by-trial target location (i.e., left and right visual field at proximal and distal eccentricities) was randomly selected. Trials in the double block were equally divided between 48 task-switch trials (i.e., a prosaccade preceded by an antisaccade or vice versa) and 48 task-repetition trials (i.e., pro- or antisaccade preceded by the same saccade task). The quadruple block also contained 48 task-switch trials, and additionally involved 144 task-repetition trials. Notably, the threefold different between task-switch and task-repetition trials in the quadruple block was due to the completion of four consecutive prosaccades (or antisaccades) prior to alternating to the other task. Our initial pilot testing demonstrated that participants may experience mild eye or mental fatigue after approximately 200 trials. Thus, experimental testing took place over two sessions separated by 24 hours. To equate for between-day trial numbers, on one day of testing participants completed the separate pro- and antisaccades blocks as well as the double block, and on a second day of testing completed the quadruple block (or vice versa). The specific trial blocks completed on the first and second days of testing were counterbalanced across participants. In addition, the order of blocks on the day that participants completed the separate pro- and antisaccade blocks as well as the double block was randomized. In both the double and quadruple task-switching blocks, the task associated with the first trial of a block was randomized. As the first trial in the double and quadruple block was neither a task-switch nor a task-repetition trial, it was not used in any subsequent analysis.

2.2.3 Data reduction and dependent variables

Displacement data were filtered offline using a dual-pass Butterworth filter employing a low-pass cut-off frequency of 15 Hz. Filtered displacement data were used to compute instantaneous velocities via a five-point central finite difference algorithm. Acceleration data were computed similarly via the velocity data. Saccade onset was determined on the basis of velocity and acceleration values that exceeded 30°/s and 8,000°/s^2, respectively.

We recorded the percentage of saccade directional errors (i.e., a saccade directed at the incorrect goal location), as well as saccade reaction time (RT: time from stimulus presentation to saccade onset). Trials involving a directional error were not used in our computation of RT. In addition, trials were excluded if RTs were less than 80 ms (i.e., anticipation saccades; Everling & Munoz, 2000) or were greater than two standard deviations above the participant's mean RT value. Responses involving a loss of signal (e.g., blinks) comprised 1.4% of the trials.

2.3 Results

2.3.1 Effects of task-switching schedule on saccade switch-costs

Here we evaluated our first research objective and examined whether the previously reported unidirectional prosaccade switch-cost elicits an additive or non-additive inhibition of oculomotor networks. Thus, we submitted the percentage of saccade directional errors and mean RT values to a 2 (task-switching block: double, quadruple) by 2 (task: pro-, antisaccade) by 2 (task transition: task-repetition, task-switch) repeated measures ANOVA[1.] It is important to note that the double task-switch block included one task-repetition trial prior to a task-switch trial, whereas the quadruple task-switch block included three task-repetition trials prior to a task-switch trial (see Methods). In order to determine if there was an effect of repetitive task execution in the quadruple block, we contrasted of RT for the first and third task-repetition trial separately for prosaccades and antisaccades. Notably, these values did not differ (prosaccade: t(19) = 0.76, p = n.s.; antisaccades: t(19) = 2.07, p = n.s.). Thus, in order to equate for between-block differences in the number of task-repetition trials, only the last repetition trial in the quadruple block (i.e., … aaa‘A’bbb‘B’aaa’A’…) was used in the above-mentioned ANOVA model.

Results yielded main effects of task, Fs(1,19) = 18.41 and 36.09, respectively for the percentage of directional errors and RT, ps<0.001, task transition, Fs(1,19) = 8.48 and 4.50, respectively for the percentage of directional errors and RT, ps<0.05, and their interaction, Fs(1,19) = 6.92 and 4.98, respectively for the percentage of directional errors and RT, ps<0.05. Task-switch prosaccades produced more directional errors (4.0%, SD = 3.4) and elicited longer RTs (227 ms, SD = 53) than their task-repetition counterparts (0.3%, SD = 0.5; 211 ms, SD = 39), (ts(19) = 4.90 and 2.38, respectively for percentage of directional errors and RT, ps < 0.05). In contrast, the percentage of directional errors and RT values for antisaccades did not vary across task-switch (6.6%, SD = 5.9; 273 ms, SD = 50) and task-repetition (5.6%, SD = 5.3; 272 ms, SD = 45) trials (ts(19) < 1, ps = n.s.) (see Figure 2-2). Further, results for the percentage of directional errors and RT did not elicit any main effects or higher-order interactions involving task-switching blocks (F < 2). As such, the double and quadruple task-switching blocks were included as a collapsed factor in the analyses presented below.

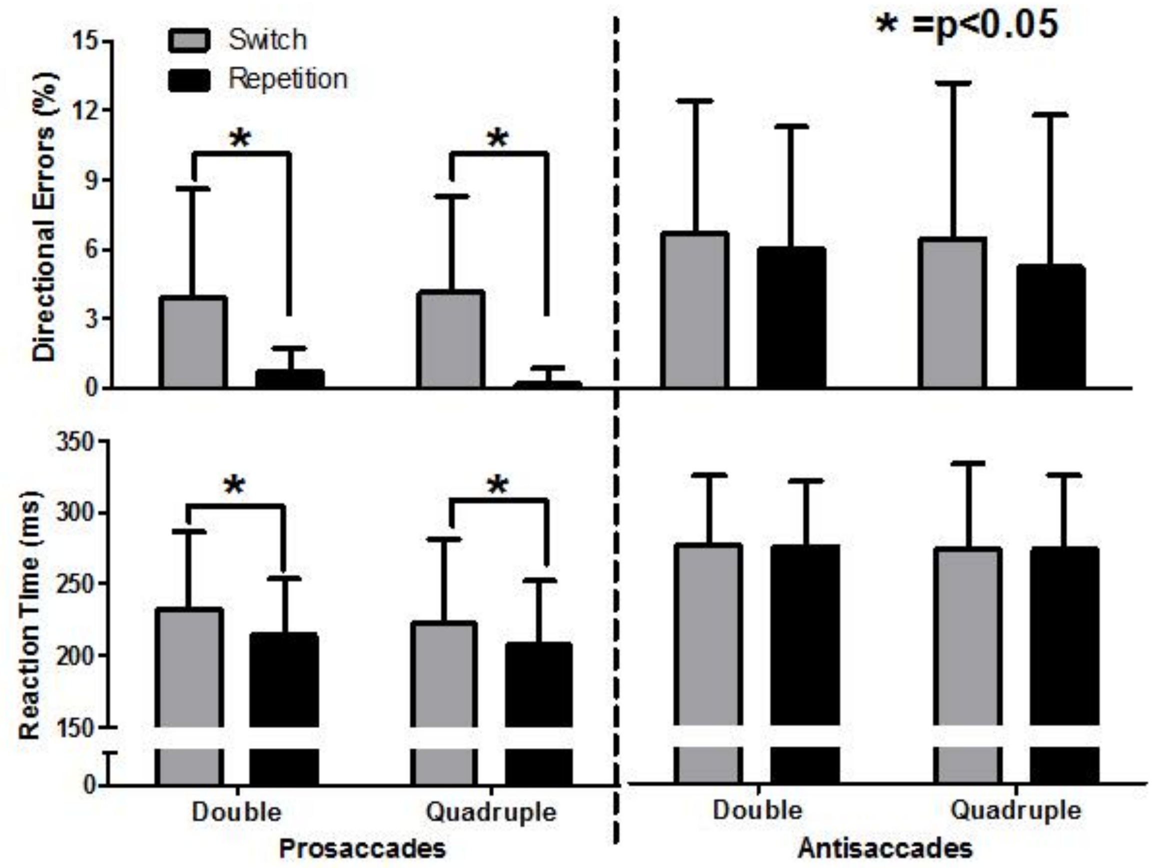

Figure 2-2: Group mean directional errors (top panels) and reaction times (bottom panels) for pro- and antisaccades as a function of the double and quadruple task-switching blocks. Error bars represent the between-participant standard deviation. Note: we elected to show results separately for the double and quadruple blocks to specifically demonstrate that such conditions did not modulate the documented unidirectional prosaccade switch-cost.

2.3.2 Switch-cost or repetition benefit for pro- and antisaccades

The analysis presented in the above provides indirect evidence of a non-additive unidirectional switch-cost. Indeed, and although a *relative* difference between task-switch and task-repetition prosaccades is present for RT and directional errors, it is not clear whether the differences results from a cost associated with switching from an antisaccade to a prosaccade or due to a benefit attributed to consecutively completed prosaccades. Thus, and in order to address our second research goal, we compared the percentage of directional errors and RTs of blocked pro- and antisaccades with their task-switch and task-repetition trial counterparts.

Blocked prosaccades produced fewer directional errors (0.1%, SD = 0.5) and shorter RTs (208 ms, SD = 39) than their task-switch counterparts (4.0%, SD = 3.3; 227 ms, SD = 53), ts(19) = 5.12 and 2.71, respectively for directional errors and RTs, ps < 0.05. However, the directional errors and RT values of blocked prosaccades did not differ from their task-repetition counterparts (0.4%, SD = 0.5; 211ms, SD = 39), ts(19) = 2.0 and 0.49, respectively for directional errors and RTs, p = n.s. In terms of antisaccades, the percentage of directional errors and RTs for blocked (7.0%, SD = 8.5; 274 ms, SD = 44), task-switch (6.6%, SD = 6.0; 273 ms, SD = 50) and task-repetition (5.6%, SD = 5.3; 272 ms, SD = 45) trials did not differ (ts(19) < 1, ps = n.s.) (see Figure 2-3). Notably, the percentage of antisaccade directional errors reported here is lower than that observed in our previous work (Weiler & Heath, 2012a); however, it is important to note that such a rate is within the range established in the extant antisaccade literature (i.e., ~5 – 40%: Everling, et al., 1999; Milea et al., 2003; Reuter et al., 2006)**.** As such, our combined analyses evince that a previously completed antisaccade restrictively modulates the accuracy and planning of a to-be-completed prosaccade; that is, results demonstrate a unidirectional prosaccade switch-cost.

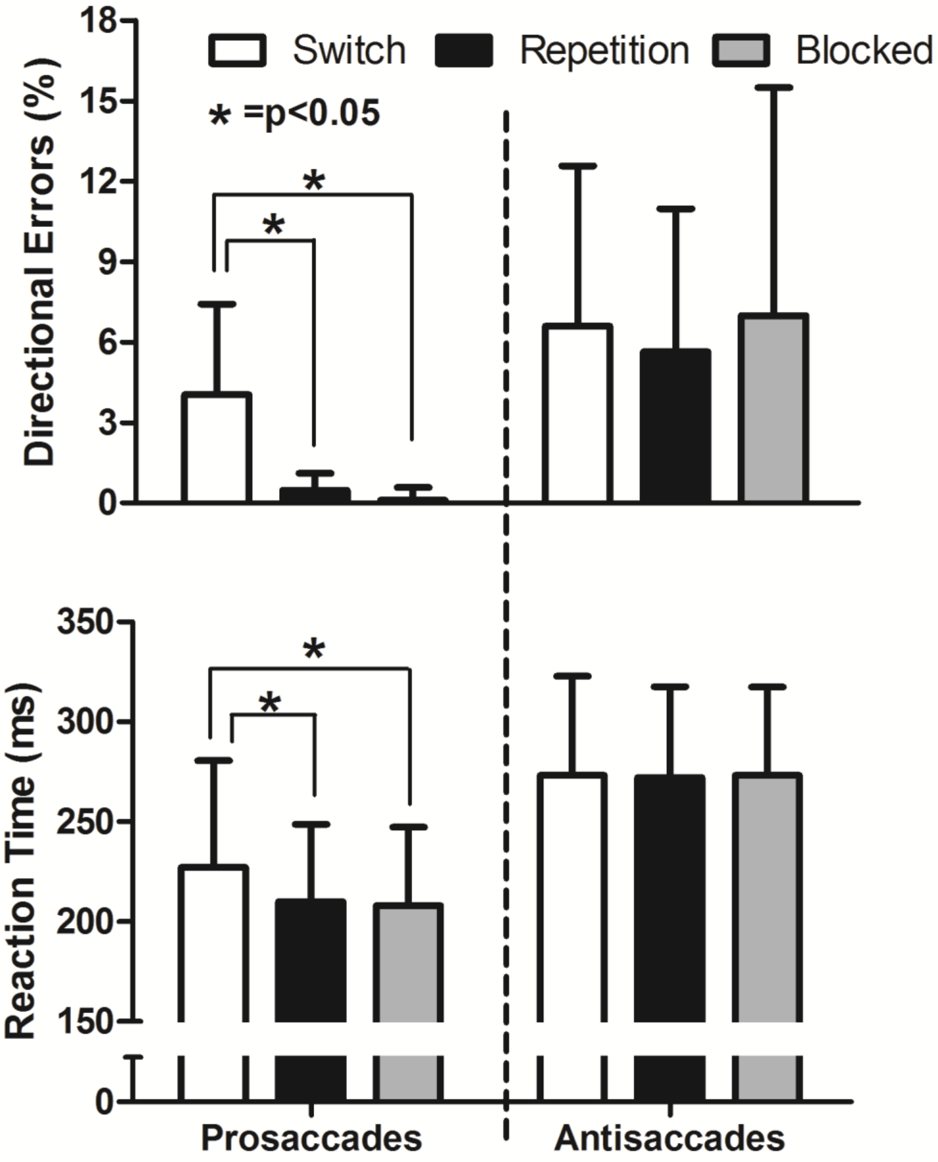

Figure 2-3: Group mean directional errors (top panel) and reaction time (bottom panel) contrasting pro- and antisaccade task-switch and task-repetition trials with their blocked counterparts. Error bars represent the between-participant standard deviation.

2.4 Discussion

2.4.1 Task-switch and task-repetition pro- and antisaccade trials versus their blocked condition counterparts

Before addressing our results related to the double and quadruple task-switching blocks we first discuss results comparing pro- and antisaccade task-switch and task-repetition trials with their blocked condition counterparts. As can be seen in Figure 2-3, antisaccades were not modulated across the different trial types; that is, blocked, task-switch and task-repetition antisaccades produced a comparable percentage of directional errors and RTs. In contrast, task-switch prosaccades elicited longer RTs and produced more directional errors than their task-repetition and blocked condition counterparts (which did not differ). Thus, the difference between task-switch and task-repetition prosaccades cannot be attributed to an increase in the efficiency (i.e., speed) in which the latter response is planned. Indeed, this direct comparison between task-switch, task-repetition and blocked prosaccades is noteworthy as task-switching experiments have seldom contrasted task-switch and task-repetition trials to a baseline or exemplar task (see Wylie & Allport, 2000).

2.4.2 Antisaccades inhibit stimulus-driven saccade networks

A general finding from our experiment was that prosaccades had shorter RTs and yielded fewer directional errors compared to their antisaccade counterparts. Of course, such findings are in-line with an extensive literature and have been attributed to the top-down requirements associated with response suppression and vector inversion (Hallett, 1978; Fischer & Weber, 1996; for review see Munoz & Everling, 2004). Additionally, our results show that task-switch prosaccades produced longer RTs and more directional errors compared to task-repetition prosaccades. In contrast, antisaccades were refractory to the nature of the previously completed task. In other words, the present findings provide evidence of a unidirectional prosaccade switch-cost (Weiler & Heath, 2012a; Weiler & Heath, 2012b).

We have previously proposed that the top-down requirements of the antisaccade task engender a level of oculomotor inhibition that alters the normal planning of stimulus-driven saccade networks (Weiler & Heath, 2012a; Weiler & Heath, 2012b). This proposal is supported by work from the behavioural task-switching literature (Allport et al., 1994), as well as a number of neuro- and electrophysiological studies demonstrating that antisaccades produce marked changes to oculomotor planning networks. For example, during the preparatory period of an antisaccade, single cell recordings in the superior colliculus of non-human primates show increased activity in the neurons that “lock” the eye to the original point of gaze (i.e., fixation neurons; Everling et al., 1999). In addition, directionally correct antisaccades are associated with reduced activation of saccade buildup neurons prior to target presentation: a finding linked to the increased response latencies of antisaccades (Everling et al., 1998; Everling et al., 1999). Furthermore, fronto-parietal regions common to the planning of both pro and antisaccades display increased activity for the latter task during the preparatory period of the response (Brown et al., 2007; Ford et al., 2005; Schlag-Rey et al., 1997). Thus, the activity of subcortical and cortical saccade structures during an antisaccade task has been linked to an oculomotor “pre-setting” that is thought to inhibit the production of a stimulus-driven prosaccade. Moreover, the unidirectional prosaccade switch-cost observed here and in our previous work (Weiler & Heath, 2012a; Weiler & Heath, 2012b) suggests that antisaccade pre-setting engenders a persistent response-set that impedes the planning of stimulus-driven prosaccades.

Most notably, the present findings show that the unidirectional prosaccade switch-cost was not modulated across the double and quadruple task-switching blocks (see Figure 2-2). In other words, prosaccade RTs and directional errors are dependent on the nature, but not the frequency, of the previously completed non-standard antisaccade response. Although such a finding differs from the cognitive task-switching literature presented in the Introduction (Wylie & Allport, 2000), it is important to recognize that such a result is consistent with the inhibition of return literature. For example, Maylor and Hockey (1987) reported the RTs of participants who made four successive stimulus-driven saccades to the same spatial location. Their results demonstrated that although the RT of the second saccade was longer relative to the previous response (i.e., the classic inhibition of return (IOR) effect), the RTs of the third and fourth saccade did not monotonically increase. In other words, the inhibition that delayed the planning time of the second saccade did not progressively accumulate over successive responses. Of course, in presenting Maylor and Hockey' findings we recognize that IOR is a phenomenon that is expressed when a participant is required to return to the same spatial location. Notably, in the current study only 5.2% of task-switch prosaccades were executed to the same spatial location as the previous antisaccade trial. Thus, the increase in RT of task-switch prosaccades cannot be attributed to a planning delay in returning to a specific target location on consecutive trials. Regardless of this difference, Maylor and Hockey's results, in combination with the present findings, suggests that stimulus-driven saccade networks may be susceptible to an asymptotic (or ceiling) level of oculomotor inhibition**.**

2.4.3 Task-switching and Oculomotor Control

The current results and our previous work (Weiler & Heath, 2012a; Weiler & Heath, 2012b) as well as those reported by Chan and DeSouza (2013) indicate a unidirectional prosaccade switch-cost that is consistent with cognitive task-switching literature (see Allport et al., 1994). However, work by Barton and Manoach and their colleagues (Barton et al., 2002; Barton, Greenzang, et al., 2006; Barton, Raoof et al., 2006; Cherkasova et al., 2002; Greenzang et al., 2007; Manoach et al., 2002; Manoach et al., 2007) have demonstrated a prosaccade switch-cost as well as a paradoxical antisaccade switch-benefit (i.e., so-called prior-antisaccade effect). In other words, their results suggest that the completion of an antisaccade inhibits the planning of *any* subsequent saccade (i.e., pro- or antisaccade). Notably, however, Barton and Manoach's group employed a cued-saccade paradigm wherein two concurrently visible targets were presented left and right of central fixation for the duration of a trial (i.e., visible during movement planning and response execution). Participants were then required to saccade directly towards (i.e., their prosaccade task) or away (i.e., their antisaccade task) from the target that was cued via a surrounding annulus. As such, the cued-saccade paradigm employed by Barton and Manoach's group does not represent a standard antisaccade task (e.g., Hallett, 1978). Indeed, in their studies the concurrent presentation of two visible targets provided a visual environment wherein vector inversion was not required for their antisaccade task; rather, participants are required to covertly reorient attention from a cued to an un-cued target and then employ a saccade with direct stimulus-response compatibility (i.e., standard prosaccade). In contrast, the stimulus paradigm used in the current investigation requires that participants withhold a reflexive prosaccade and remap target properties into mirror-symmetrical space. Indeed, this methodological difference is an important one to identify, as it demonstrates that the standard antisaccade task selectively elicits a unidirectional prosaccade switch-cost.

2.5 Conclusion

The absolute comparison of task-switch and task-repetition pro- and antisaccade trials to their blocked condition counterparts demonstrates that antisaccades selectively inhibit the efficiency and effectiveness of stimulus-driven saccade networks. In other words, results provide direct support for a unidirectional prosaccade switch-cost. Furthermore, our results show that such a switch-cost is dependent on the nature, but not the frequency, of the previously completed non-standard antisaccade task.

2.6 Footnotes

1. We did not include visual space (left, right) or target eccentricity (proximal, distal) as factors in our repeated measures ANOVA because our previous work has shown that such factors do not modulate saccade planning characteristics (Heath, Dunham, Binsted, & Godbolt, 2012).

2.7 References

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Chapter 3

Response suppression delays the planning of a subsequent stimulus-driven prosaccade

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3.1 Introduction

The most frequent motor actions that humans make are saccades with direct stimulus-response compatibility (i.e., prosaccades). Importantly, the dimensional overlap between stimulus and response allows for the mediation of a prosaccade via stimulus-driven and retinotopically organized motor maps in the superior colliculus (Wurtz & Albano, 1980). In contrast, antisaccades entail the intentional process of decoupling the spatial relations between stimulus and response and require the evocation of a saccade to a target's mirror-symmetrical location (i.e., 180° spatial transformation). As such, contrasting pro- and antisaccades provides a basis for understanding how top-down and cognitive control influences the oculomotor system. Indeed, an extensive literature has shown that antisaccades produce longer reaction times (RT) (Hallett, 1978; Fischer & Weber, 1996), increased directional errors (Hallet, 1978), and less accurate and more variable endpoints (Heath et al., 2010) than their prosaccade counterparts. These behavioural 'costs' have been attributed to a two-component process requiring: (1) the suppression of a stimulus-driven prosaccade (i.e., response suppression), and (2) the visual remapping of a target's spatial properties to mirror-symmetrical space (i.e., vector inversion) (Munoz & Everling, 2004). Moreover, neuroimaging and electrophysiological evidence from humans and non-human primates has shown that the preparatory period of antisaccades is associated with increased activity in the 'classic cortical saccade network' (i.e., frontal eye field, supplementary eye field, and lateral intraparietal area) (Brown et al., 2007; Curtis & D'Esposito, 2003; DeSouza et al., 2003; Everling et al., 1998), as well as a respective increase and decrease in collicular fixation and build-up neurons (Everling et al., 1998, Everling et al., 1999). According to Brown et al. (2006), the modulation of oculomotor networks during the antisaccade task represents an oculomotor pre-setting that is designed to inhibit the evocation of a stimulus-driven prosaccade at target onset (i.e., the visual grasp reflex: Pierrot-Deselligny et al., 1995). In other words, pre-setting serves as cortical-based inhibition of the baseline firing rates of saccade neurons.

Recently, our group has shown that a corollary of antisaccade pre-setting is a residual inhibition of stimulus-driven oculomotor networks (Weiler & Heath, 2012a; Weiler and Heath, 2012b). In addressing this issue, participants alternated between pro- and antisaccades using a classic task-switching schedule (i.e., AABB) as well as a pseudo-randomized task-switching schedule (i.e., AABAABB…). Results for both schedules showed that prosaccades preceded by an antisaccade (i.e., task-switch prosaccade) elicited longer RTs than prosaccades preceded by their same task counterparts (i.e., task-repetition prosaccade). In contrast, antisaccades preceded by a prosaccade (i.e., task-switch antisaccade) yielded RTs that were comparable to antisaccades preceded by their same task counterparts (i.e., task-repetition antisaccades). In other words, the completion of an antisaccade imparts a residual inhibition that delays the planning of a to-be-completed prosaccade: a result our group has referred to as the unidirectional prosaccade switch-cost. As well, the prosaccade switch-cost has been shown to selectively manifest following a correct antisaccade (i.e., a response planned mirror-symmetrical to the target) but not an error antisaccade (i.e., a saccade initially, and incorrectly, directed at the veridical target location) (DeSimone et al., 2014). Indeed, that correct - but not error - antisaccades were tied to a prosaccade switch-cost suggests that the constituent elements associated with the *planning* of a correct antisaccade engenders a residual level of oculomotor inhibition that delays the *planning* of a subsequent prosaccade.

An important issue to address is whether the unidirectional prosaccade switch-cost is contingent upon the constituent planning processes of response suppression *and* vector inversion or is limited to response suppression. The basis for this question stems from a countermanding study by Pouget et al. (2011) showing that stimulus-driven prosaccades completed after a successful stop-signal saccade are associated with a delay in the onset of saccade neuron activity in the frontal eye-fields and superior colliculus. In other words, Pouget et al. found that inhibiting a prosaccade leads to a residual inhibition of oculomotor planning networks. Thus, the present investigation sought to determine whether the unidirectional prosaccade switch-cost is a specific consequence of the antisaccade task (i.e., response suppression and vector inversion) or represents a more general phenomenon associated with response suppression. In accomplishing our objective, we had participants alternate between pro- and antisaccades using the task-switching schedule (i.e., AABB; task-switching block) employed in our group's previous work (Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler & Heath, 2014), and in a separate block required that participants complete a series of prosaccades that were randomly interleaved with no-go catch-trials (i.e., go/no-go block). Most importantly, we were interested in contrasting the putative changes in prosaccade RT when preceded by an antisaccade and a no-go catch-trial. Indeed, if the conjoint process of response suppression and vector inversion engenders a residual level of oculomotor inhibition then a selective lengthening of prosaccade RTs should be observed when preceded by an antisaccade but not when preceded by a no-go catch-trial. In contrast, if response suppression alone is responsible for a residual level of oculomotor inhibition then a lengthening of prosaccade RTs should be observed when preceded by either an antisaccade or a no-go catch-trial. Further, if the latter prediction proves correct then a direct comparison of the magnitude of the prosaccade RT lengthening may provide a basis for determining whether common or dissociable mechanisms contribute to the residual inhibition of oculomotor planning mechanisms.

3.2 Methods

3.2.1 Participants

Seventeen participants (7 male, 10 female; age range = 18-20 years) from the University of Western Ontario community volunteered for the current investigation. All participants declared being right-hand dominant and had normal or corrected-to-normal vision. Prior to data collection participants provided informed written consent. This study was approved by the Office of Research Ethics, the University of Western Ontario, and was conducted in accordance with the Declaration of Helsinki.

3.2.2 Apparatus and Procedures

Participants sat at a table with their head stabilized via a head-chin rest for the duration of data collection. Visual stimuli were presented on a 30-inch LCD monitor (60 Hz, 8 ms response rate, 1280 by 960 pixels, Dell 3007WFP, Round Rock, TX, USA) centered on the participant’s midline and located at a viewing distance of 550 mm. The gaze location of the participant’s left eye was obtained via a video-based chin-mounted eye tracking system (Eye-Trac 6: Applied Sciences Laboratories, Bedford, MA, USA) sampling at 360 Hz. Prior to data collection a nine-point calibration of the participant’s viewing space was performed. Two additional monitors that were only visible to the experimenter provided: (1) real-time point of gaze information, (2) a visual depiction of trial-to-trial saccade trajectories (e.g., displacement, velocity), and (3) information about the accuracy of the eye tracking system (i.e., to determine a necessary recalibration or drift correction). All computer events and visual stimuli were controlled via MATLAB (7.6: The Math Works, Natick, MA, USA) and the Psychophysics Toolbox extensions version 3 (Brainard, 1997). The lights in the experimental suite were extinguished during data collection.

Visual stimuli were presented against a high contrast black background. Stimuli included a green and a red fixation cross (1.0°) that were centered horizontally on the monitor and at the eye-level of the participant. In addition, yellow crosses (1.0°) served as targets and were located 10.5° (proximal) or 15.5° (distal) left and right of the fixation cross. All trials commenced with the presentation of the green or the red fixation cross which alerted participants to direct their gaze to its location. After a stable gaze was achieved (±1.5° for 500 ms), a randomized foreperiod (1,000 – 2,000 ms) was introduced during which time the fixation cross remained visible (i.e., no-gap paradigm). Following the foreperiod, the fixation cross was removed and a target stimulus was briefly presented (i.e., 50 ms) in one of the four target locations (i.e., combination of visual space by target eccentricity).

Participants completed two blocks of trials. In one block (i.e., task-switching block), participants alternated between pro- and antisaccades after every second trial (i.e., AABB). Notably, the green fixation cross informed participants to saccade to the veridical target location (i.e., prosaccade), whereas the red fixation cross indicated a saccade to the target's mirror-symmetrical location (i.e., antisaccade) (see Figure 3-1). The trial-to-trial target locations (i.e., proximal or distal eccentricity in left or right visual field) were randomly selected. Participants' responses were categorized as a task-switch (i.e., prosaccade preceded by an antisaccade, or vice versa) or a task-repetition (i.e., pro- or antisaccade preceded by the same task) pro- and antisaccade responses. Each of the four aforementioned trial-types (i.e., task-switch and task-repetition prosaccades; task-switch and task-repetition antisaccades) comprised 36 trials (or 25%) of the 144 trials in the task-switching block. The presentation of the target (and fixation cross removal) cued participants to make their response as "quickly and accurately as possible". The task (i.e., pro-, antisaccade) associated with the first trial in this block was counterbalanced across participants. Trials where a directional error was committed (i.e., prosaccade instead of the instructed antisaccade, or vice versa) were not analyzed. In addition, as the first trial in this block was neither a task-switch nor a task-repetition trial, it was excluded from subsequent analysis.

In the other block (i.e., go/no-go block), participants completed a series of prosaccades randomly interspersed with a series of no-go catch-trials. This block included the same visual stimuli presentation as prosaccades in the task-switching block; that is, a green fixation cross was presented for a variable foreperiod after which time a target was presented (and fixation cross was extinguished) in one of the four potential locations. Importantly, 28 of the 196 trials in this block (14.3%) entailed a situation wherein the green fixation cross was replaced with the red fixation cross 75 ms prior to target onset, and the fixation colour-change instructed participants to withhold their response (i.e., no-go catch-trial; see Figure 3-1). Notably, 14.3% of total trials were used as no-go catch-trials as this frequency is similar to other investigations which have used no-go trials to examine top-down inhibitory control (Kelly et al., 2004; Mostofsky et al., 2003). In addition, our pilot testing demonstrated that a no-go cue occurring either 25 or 50 ms prior to target onset resulted in participants failing to withhold a saccade on 55% and 42% of all no-go trials, respectively. Thus, in order for participants to successfully complete the no-go task but still suppress an expectant saccade (i.e., context-dependent response suppression; Brown et al., 2006), we employed a no-go cue 75 ms prior to target onset. In terms of trial-types, responses were categorized as standard prosaccades (i.e., a prosaccade preceded by a prosaccade) or post catch-trial prosaccades (i.e., prosaccade preceded by a no-go catch-trial). Trials where an error was committed (i.e., a failure to withhold a response during a no-go trial, or no response on a prosaccade trial) were not analyzed and were inserted back into the trial matrix. Recall that in this block we sought to determine the effect of response suppression on a subsequent prosaccade trial. As such, prosaccade completed after an error no-go catch-trial (i.e., failure to suppress a response) were not included in subsequent analyses.

The ordering of the task-switching and the go/no-go blocks was counterbalanced across participants and the different blocks were completed on separate days separated by 24 hours. The separate sessions were used to prevent participants from experiencing mental and/or eye fatigue.

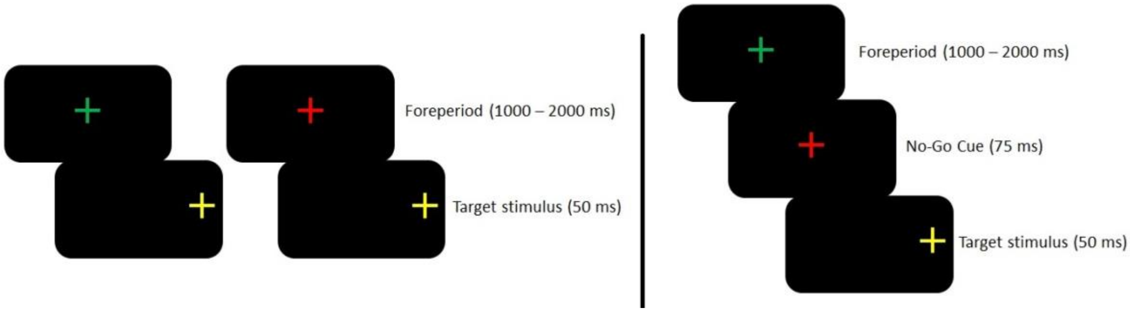

Figure 3-1: Schematic of visual event for pro- and antisaccades in the task-switching block (left of solid line) and no-go trials in the go/no-go block (right of solid line). In the task-switching block green or red fixation cross was visible for a variable foreperiod after which time one of four possible target stimuli was briefly presented. The green and red fixation cross denoted a saccade to the target's veridical (i.e., prosaccade) or mirror-symmetrical (i.e., antisaccade) location, respectively. In the go/no-go block, prosaccade trials were the same as they were in task-switching block. For no-go trials, following the foreperiod the green fixation cross was replaced with a red fixation cross for 75 ms prior to target onset which signaled participants to withhold a prosaccade.

3.2.3 Data reduction

Displacement data were filtered offline using a dual-pass Butterworth filter employing a low-pass cut-off frequency of 15 Hz. Filtered displacement data were used to compute instantaneous velocities via a five-point central finite difference algorithm. Acceleration data were computed similarly via the velocity data. Saccade onset was determined on the basis of velocity and acceleration values that exceeded 30°/s and 8,000°/s^2, respectively. Reaction time (RT) was computed as the time between target presentation and saccade onset. Means and within-participant 95% confidence intervals (Loftus & Masson, 1994) are reported below.

3.3 Results

3.3.1 Alternating between pro- and antisaccades: the unidirectional prosaccade switch-cost

To determine if alternating between pro- and antisaccades resulted in the unidirectional prosaccade switch-cost, RTs associated with the task-switching block were examined via 2 (task: pro-, antisaccade), by 2 (task transition: task-switch, task-repetition) fully repeated measures ANOVA. Results yielded main effects of task, $F(1,16) = 95.51$, $p < 0.001$, task transition, $F(1,16) = 9.29$, $p < 0.01$, and their interaction, $F(1,16) = 5.78$, $p < 0.05$. Task-switch prosaccades produced longer RTs (264 ms, $CI_{95\%} = 10$) than their task-repetition counterparts (243 ms, $CI_{95\%} = 10$), $t(16) = 3.26$, $p < 0.01$, whereas task-switch (326 ms, $CI_{95\%} = 6$) and task-repetition (324 ms, $CI_{95\%} = 6$) antisaccades did not reliably differ, $t(16) = 0.54$, p = n.s. (Figure 3-2). Thus, results demonstrate the unidirectional prosaccade switch-cost. Additionally, we submitted the number of saccade directional errors to the same ANOVA model identified above and observed a main effect of task, F(1,16) = 35.51, $p < 0.001$: prosaccades elicited fewer directional errors (1.8, $CI_{95\%}$ = 0.95) than antisaccades (5.5, $CI_{95\%}$ = 0.95).

3.3.2 No-go catch-trials delay the planning of subsequent prosaccades

In the go/no-go block participants were periodically required to inhibit a prosaccade in response to an infrequent no-go stimulus. To determine whether a no-go catch-trial influenced the planning time for a subsequent prosaccade we contrasted the RTs of standard and post catch-trial prosaccades. Results demonstrated that standard prosaccades (268 ms, $CI_{95\%}$ = 6) had shorter RTs compared to their post catch-trial counterparts (286, $CI_{95\%}$ = 6), t(16) = 4.58, $p < 0.001$, (Figure 3-2). Further, and in line with the task-switching block, we sought to provide a measure of error trials. Recall, however, that error trials in this block (i.e., a failure to withhold a response during a no-go trial, or no response on a standard prosaccade trial) were placed back into the randomized trial matrix. Indeed, we adopted such a strategy to ensure that a sufficient number of post catch-trial prosaccades were preceded by a successful no-go catch-trial. Thus, the total number of attempted no-go catch-trials differed across participants (range = 29 – 54 trials). Given the between-participant differences in number of attempted no-go catch-trials we elected to provide a qualitative analysis of error rates in the go/no-block. Results indicated that catch-trials (9.8) were associated with more errors than standard (0.8), or post-catch trial (1.4) prosaccades.

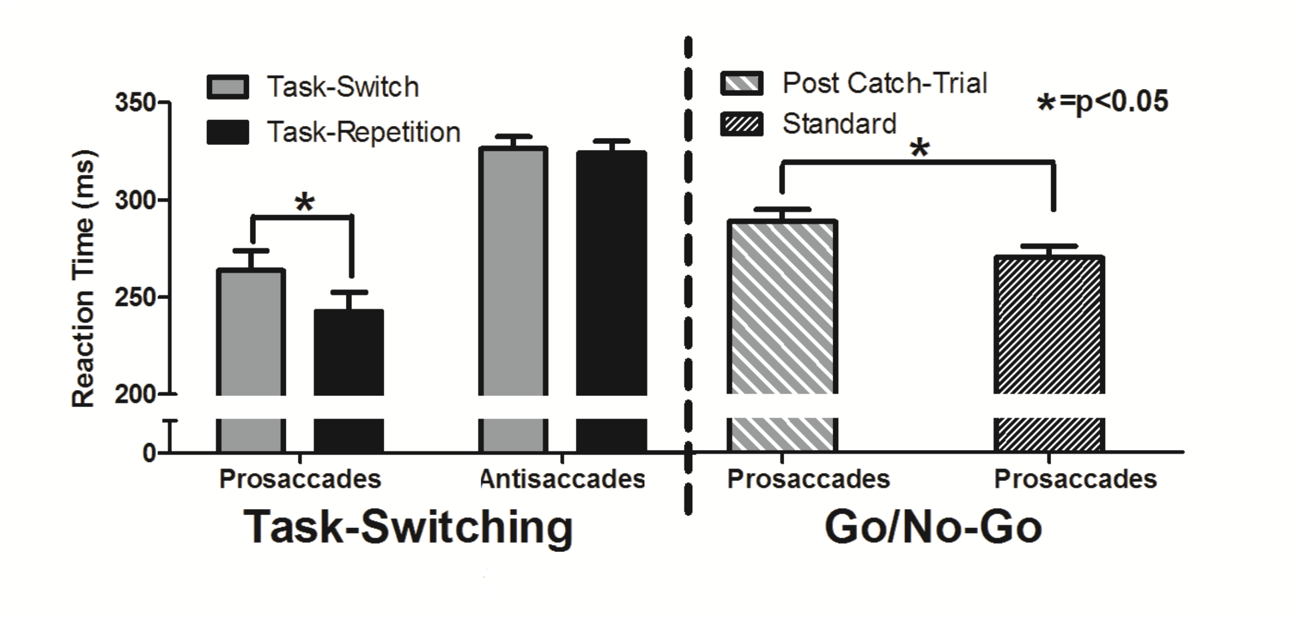

Figure 3-2: Mean reaction times for the task-switching (left) and go/no-go (right) block. Error bars represent 95% within-participant confidence intervals.

3.3.3 Equivalent between-block effects of suppressing a stimulus-driven prosaccade

Results thus far have demonstrated that prosaccades preceded by either an antisaccade or a no-go catch-trial elicited a RT cost. Specifically, task-switch prosaccades showed a 21 ms increase in RT compared to their task-repetition counterparts, whereas post catch-trial prosaccades yielded an 18 ms increase in RT compared to their standard prosaccade counterparts. Here we compared participant-specific RT difference scores for the task-switching (i.e., task-switch prosaccade minus task-repetition prosaccade) and go/no-go (i.e., post-catch trial prosaccade minus standard prosaccade) blocks to determine whether the magnitude of the RT costs differed between blocks. The results of this analysis yielded a null between-block cost, t(16) = 0.51, p = n.s.

3.4 Discussion

A general finding from the task-switching block was that antisaccades produced longer RTs and elicited more directional errors than prosaccades. Such results are in accord with extensive work demonstrating that the constituent components of the antisaccade task (i.e., response suppression and vector inversion) represent time-consuming and measureable processes (Munoz & Everling, 2004). In addition, RTs for prosaccades, but not antisaccades, were found to be influenced by the nature of the preceding task. In particular, task-switch prosaccades produced longer RTs than their task-repetition counterparts, whereas RTs for task-switch and task-repetition antisaccades did not reliably differ. In other words, results provide a faithful replication of the unidirectional prosaccade switch-cost (Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler & Heath, 2014; see also Chan & DeSouza, 2013). As indicated in the Introduction, such a switch-cost has been interpreted to reflect that the constituent components of the antisaccade task engender a residual level of inhibition that reduces the efficiency of the oculomotor networks supporting the planning of stimulus-driven prosaccades.

In the go/no-go block participants completed a series of prosaccade trials that involved the infrequent and random occurrence of no-go catch-trials. A general finding from this block was that participants elicited a larger number of errors for no-go catch-trials compared to post catch-trial prosaccades or standard prosaccades. However, and what is more germane to our investigation, is the observation that RTs for post catch-trial prosaccades were longer than their standard prosaccade counterparts. As well, the RT cost associated with the go/no-go block (i.e., post catch-trial prosaccade minus standard prosaccade) was commensurate to that observed in the task-switching block (i.e., task-switch prosaccade minus task-repetition prosaccade). Further, *a posteriori* correlation revealed that the magnitude of the switch-cost between the task-switching and no-go blocks approached conventional levels of significance ($r = 0.43$, $p = 0.08$). Notably, such a result indicates a consistent inhibitory cost on prosaccade planning networks independent of whether the previous trial was an antisaccade or no-go catch-trial. Taken together, the present results counter the assertion that the constituent elements of the antisaccade task (i.e., response suppression and vector inversion) delay the planning of a subsequent prosaccade. Rather, the current findings indicate that a general consequence of suppressing a prosaccade is a residual inhibition of stimulus-driven saccade networks.

It should be noted that the assertion that response suppression selectively inhibits prosaccade planning mechanisms is not entirely at odds with our group’s previous work. For example, DeSimone et al. (2014) showed that correct antisaccades, but not error antisaccades (i.e., a saccade initially, and incorrectly, directed at the veridical target location), were associated with a delay in the planning time for a subsequent prosaccade. As mentioned in the Introduction, such a result was interpreted to reflect that the conjoint process of response suppression *and* vector inversion contribute to the residual inhibition of stimulus-driven saccade networks. However, DeSimone et al.'s work was not designed to disentangle the putative consequence of response suppression and vector inversion. As a result, an alternative explanation of that work is that error antisaccades do not impart a prosaccade switch-cost because such actions are not associated with the suppression of a stimulus-driven prosaccade. Moreover, it is important to recognize that several studies have documented residual inhibition of oculomotor planning networks when a signal to withhold a saccade is provided after target onset (i.e., stop-signal paradigm). For example, Emeric et al. (2007) had participants perform a series of prosaccades wherein a stop-signal was provided infrequently (and randomly) during a response's RT interval. Results showed that inhibiting the execution of a planned prosaccade was associated with an increase in RT on the subsequent prosaccade trial. In addition, Pouget et al.'s (2011) study of non-human primates interleaved prosaccade trials with infrequent stop-signal trials while concurrently recording the activity of saccade neurons in the frontal eye field and superior colliculus. Their results demonstrated that the successful suppression of a stimulus-driven saccade led to a 17 ms increase in the RT of the subsequent prosaccade: a result that mirrors the respective 21 ms and 18 ms RT costs associated with the task-switching and go/no-go blocks used in the current investigation. Moreover, the RT cost in Pouget et al.'s study was associated with a delay in the onset of activity of frontal eye field and collicular saccade neurons.

Thus, the above-mentioned work in combination with the present results indicate that a consequence of suppressing a stimulus-driven prosaccade is a transient delay in the onset of neural activity associated with the planning of a subsequent prosaccade.

Our interpretation of the present results requires that two issues be addressed. First, trials in the task-switching and go/no-go blocks differed with respect to the time participants were afforded to suppress an upcoming stimulus-driven saccade. Recall that during the task-switching block a red fixation cross presented between 1,000 and 2,000 ms prior to target onset alerted participants of the need to suppress a stimulus-driven saccade; that is, the red fixation cross indicated an antisaccade trial. In contrast, the go/no-go block provided a cue to suppress a stimulus-driven saccade (via a green to red fixation colour-change) 75 ms prior to target onset. As such, between-block temporal differences related to advanced knowledge of response suppression may have led to between-block differences in the inhibition of prosaccade planning mechanisms. A priori, we considered equating for this between-block difference by providing the no-go cue for the same duration as the advanced cuing procedure used in the antisaccade task (i.e., 1,000 – 2,000 ms in advance of target onset). Importantly, however, neuroimaging work has shown that providing a no-go cue well in advance of response cuing (e.g., 2,000 – 7,000 ms) does not result in context-dependent response suppression that is observed in the antisaccade task (Brown et al., 2006). Such a finding reflects that the neural activity associated with planning a movement (e.g., stimulus-driven prosaccade) dissipates when the choice to perform an alternate response (e.g., remain fixated) is selected (Cisek, 2007). In other words, providing a cue mitigating the need to plan an active response disrupts the normal planning mechanisms of stimulus-driven saccade networks (for real-time control of action see Westwood & Goodale, 2003). In order to ameliorate this issue and require that participants engage in context-dependent response suppression, we elected to provide the no-go cue 75 ms to target onset. Indeed, that participants elicited an appreciable number of errors on no-go catch-trials as compared to antisaccade trials indicates that: 1) such trials involved classic prosaccade planning, and 2) the successful completion of a no-go catch-trial was contingent on the top-down process of response suppression. It is worth commenting that the commensurate RT cost between the task-switching and go/no-go blocks may be specific to the 14% no-go catch-trial frequency and no-go cuing (i.e., 75 ms prior to target onset) used in the present investigation. However, what is most notable from the current results is that our findings demonstrate that context-dependent response suppression engenders a residual inhibition to stimulus-driven saccade networks. The second issue to address relates to the fact that task-repetition prosaccades from the task-switching block and standard prosaccades in the go/no-go block represent the exemplar tasks by which responses preceded by a trial requiring response suppression (i.e., task-switch prosaccades and post catch-trial prosaccades) were compared. However, inspection of Figure 3-2 and *a posteriori* analyses indicated that RTs for task-repetition prosaccades (243 ms, $CI_{95\%} = 7$) were shorter than the standard prosaccades used in the go/no-go block (268 ms, $CI_{95\%} = 7$), $t(16) = 5.55$, $p < 0.01$, and within-participant RT variability was reduced in the former (51 ms, $CI_{95\%} = 4$) as compared to the latter (59 ms, $CI_{95\%} = 4$) trial-type, $t(16) = 2.20$, $p < 0.05$. That standard prosaccades were associated with longer and more variable RTs is attributed to the increased level of response uncertainty in the go/no-go block (Heath et al., 2011; Schlicht & Schrater, 2007). Indeed, in the task-switching block participants were explicitly aware of the required response well in advance of target onset, whereas the appropriate response cue (i.e., go versus no-go) was provided to participants only 75 ms prior to target onset in the go/no-go block. In spite of this between-block difference, it is important to recognize that the level of response uncertainty did not influence the magnitude by which response suppression for an antisaccade or a no-go catch-trial delayed the planning times for a subsequent prosaccade. After all, the present findings demonstrate that the magnitude of the response suppression RT cost did not reliably differ across the task-switching and go/no-go blocks. Such a finding suggests that the residual inhibition engendered by response suppression is a phenomenon that needs to be overcome independent of the required planning time associated with a stimulus-driven prosaccade.

3.5 Conclusions

Our results show that the successful completion of an antisaccade or a no-go catch-trial results in a comparable increase in the RT of a subsequent prosaccade. Thus, we conclude that the antisaccade task does not uniquely impede the planning of a subsequent prosaccade; rather, we propose that response suppression imparts a residual inhibition of the oculomotor networks supporting stimulus-driven prosaccades.

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Chapter 4

Oculomotor task-switching: alternating from a non-standard to a standard response yields the unidirectional prosaccade switch-cost

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4.1 Introduction

The demands of our environment require that we periodically override habitual actions to produce a context or task-appropriate response. For example, the Canadian tourist in Ireland must resist the reflexive urge to first look left when crossing a street – and instead first look right – or risk being struck by the traffic coming from an unfamiliar direction. The prosaccade and antisaccade tasks are experimental corollaries to the aforementioned example; indeed, these tasks respectively permit the evaluation of how a pre-potent response (i.e., prosaccade) or its volitional and less-practiced – but goal-relevant – counterpart (i.e., antisaccade) are planned and executed. In particular, the experimentally based prosaccade task requires participants to fixate a central stimulus and subsequently saccade to an exogenously presented target. Notably, the direct overlap between stimulus and response (i.e., standard task) allows retionotopically organized motor maps within the superior colliculus to support prosaccade planning with minimal top-down cognitive control (Wurtz & Albano, 1980; see also Pierrot-Deselligny et al., 1995). In contrast, the antisaccade task is a non-standard response that requires participants to saccade to the mirror-symmetrical location of the exogenously presented target (Hallett, 1978). Extensive evidence has demonstrated that antisaccades yield increased reaction times (RT) (Hallet, 1978) and directional errors (Hallet, 1978; Fischer & Weber, 1996), as well as less accurate and more variable endpoints relative to their prosaccade counterparts (Dafoe et al., 2007; Heath et al., 2010). These behavioural ‘costs’ have been attributed to the top-down and two-component processes of: (1) suppressing a pre-potent prosaccade (i.e., response suppression), and (2) the visual remapping of the target’s spatial location to its mirror-symmetrical position (180° spatial transformation; i.e., vector inversion)

(Zhang & Barash, 2000; for review see Munoz & Everling, 2004). Moreover, neuroimaging and electrophysiology studies have shown that antisaccades produce an increased activity in the classic cortical saccade network (i.e., frontal eye field, supplementary eye field and lateral intraparietal area), dorsolateral prefrontal cortex, and anterior cingulate cortex (Brown et al., 2007; see also Curtis & D'Esposito, 2003; DeSouza et al., 2003; Ford et al., 2005) as well as a respective increase and decrease in the activity of collicular fixation and saccade build-up neurons prior to target onset (Everling et al., 1998; Everling et al., 1999). Such oculomotor modulations have been linked to a preparatory set that decreases the likelihood of evoking a pre-potent prosaccade, and provides the requisite top-down sensorimotor transformation necessary to support a directionally correct antisaccade (Brown et al., 2007).

Recently, our group sought to determine whether the changes in neural activity associated with an antisaccade influence the planning of a *subsequent* pro- or antisaccade. To accomplish that goal, participants were required to alternate between pro- and antisaccades in various task-switching schedules (Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler & Heath, 2014). Results demonstrated that a prosaccade preceded by an antisaccade (i.e., task-switch prosaccade) produced longer RTs than a prosaccade preceded by another prosaccade (i.e., task-repetition prosaccade), and this finding was independent of the predictability (Weiler & Heath, 2012b) and frequency (Weiler & Heath, 2014) that pro- and antisaccades were varied from trial-to-trial. In contrast, the RTs of an antisaccade preceded by either a prosaccade (i.e., task-switch antisaccade) or an antisaccade (i.e., task-repetition antisaccades) did not differ. In other words, the completion of an antisaccade selectively delayed the planning of a subsequent prosaccade: a phenomenon that has been termed *the unidirectional prosaccade switch-cost* (e.g., Weiler & Heath, 2012b). As well, it is important to recognize that during antisaccade trials participants occasionally fail to engage the processes of response suppression and/or vector inversion and execute a saccade to the veridical target location instead of the instructed mirror-symmetrical location (i.e., an antisaccade directional error; see Fischer & Weber, 1996; Mokler & Fischer, 1999). DeSimone and colleagues (2014) demonstrated that antisaccade directional error trials – unlike their correctly executed counterparts – do not lengthen the RT of a subsequent prosaccade. Based on these results, it was proposed that the unidirectional prosaccade switch-cost is attributed to one, or both, of the constituent processes associated with the evocation of a directional correct antisaccade (i.e., response suppression and vector inversion). To further evaluate this issue, Weiler et al. (2014) had participants complete a block of trials wherein prosaccades were infrequently preceded by a no-go catch-trial. Results showed that prosaccades preceded by a catch-trial elicited longer RTs than prosaccades preceded by another prosaccade. Such a finding is notable because the successful execution of a no-go catch-trial requires the suppression of a stimulus-driven prosaccade but does not require a 180° spatial transformation of the target stimulus (i.e., vector inversion). As such, results were taken as evidence that the unidirectional prosaccade switch-cost is not directly related to the antisaccade task per se; rather, results suggest that the top-down process of response suppression engenders a residual inhibition of the oculomotor networks supporting stimulus-driven prosaccades (i.e., *the oculomotor inhibition hypothesis*: see Weiler et al., 2014).

The oculomotor inhibition hypothesis provides a framework for understanding the delayed RTs associated with prosaccades preceded by an antisaccade or a no-go catch-trial. It is, however, important to consider that unidirectional switch-costs have been observed in paradigms outside the oculomotor domain. For example, results from the Stroop paradigm demonstrate that alternating from the non-standard colour-naming response to the pre-potent word-naming response results in reliable RT and error switch-costs, whereas no RT or error switch-costs are observed for the converse switch (Allport et al., 1994; see also Wylie & Allport, 2000). In explaining these findings, Allport (1994) hypothesized that the completion of a task with non-dominant SR mapping (e.g., colour-naming response) requires the implementation of top-down cognitive rules that support the response's execution (i.e., a task-set). As a consequence, the cognitive-based task-set persists inertially and interferes with the planning of a subsequent standard and pre-potent response (e.g., word-naming response) (i.e., *task-set inertia hypothesis*). Notably, task-set inertia provides a framework for understanding the unidirectional prosaccade switch-cost that is independent of the oculomotor inhibition hypothesis' assertion that the switch-cost is attributed to the top-down demands of response suppression. Indeed, the task-set inertia hypothesis predicts that the completion of an oculomotor response with non-dominant SR mapping (e.g., antisaccade; no-go catch-trial) requires the implementation of a cognitively based task-set. As a consequence, the non-standard task set persists inertially and delays the planning of a subsequent standard and pre-potent prosaccade.

The oculomotor inhibition and task-set inertia hypotheses predict a unidirectional prosaccade switch-cost; however, both hypotheses are mutually exclusively insomuch as each attributes the delay in prosaccade planning to a distinct mechanism. More specifically, the oculomotor inhibition hypothesis asserts that suppressing a stimulus-driven prosaccades (i.e., response suppression) engenders a residual inhibition of the oculomotor networks that support prosaccade planning. Alternatively, the task-set inertia hypothesis contends that the RT delay is related to a persistent activation of the task-set associated with the previously executed non-standard oculomotor response. Thus, the goal of the current investigation was to determine which of the aforementioned hypothesis provides the most parsimonious account for the unidirectional prosaccade switch-cost. To accomplish our objective, participants alternated between pro- and antisaccades in a single block of trials wherein task instructions were provided in two cuing conditions. In the classic cuing condition participants were informed whether a pro- or antisaccade was required prior to response cuing (i.e., target onset), whereas in the delayed cuing condition participants were provided task instructions – via fixation cross colour change – simultaneous with response cuing. Importantly, responses elicited via the delayed cuing condition require participants to suppress the evocation of a stimulus-driven prosaccade at response cuing (i.e., response suppression) in order to discern the appropriate to-be-performed task. This is an important methodological distinction because the delayed cuing condition equates for the normal between-task differences in response suppression while still allowing pro- and antisaccades to retain their respective dominant or non-dominant SR relations (see Heath et al., 2011; Olk & Kingstone, 2003). Thus, alternating between pro- and antisaccades *within* and *between* the two aforementioned cuing conditions enables the identification of whether the mutually exclusive oculomotor inhibition or task-set inertia hypotheses best accounts for the unidirectional prosaccade switch-cost. In terms of research outcomes, if the oculomotor inhibition hypothesis accounts for the unidirectional prosaccade switch-cost, then the response suppression demands associated with classic and delayed antisaccades, as well as delayed prosaccades, should increase the RT of a subsequent (classic or delayed) prosaccade. In other words, any task requiring response suppression is predicted to elicit a unidirectional prosaccade switch-cost. In contrast, the task-set inertia hypothesis predicts the expression of the unidirectional prosaccade switch-cost only for prosaccades preceded by a task entailing non-dominant SR relations (i.e., classic or delayed antisaccades). Most notably, task-set inertia predicts that the response suppression demands associated with delayed prosaccades will not delay the planning of a subsequent prosaccade (see Figure 4-1 for graphic depiction of experimental predictions).

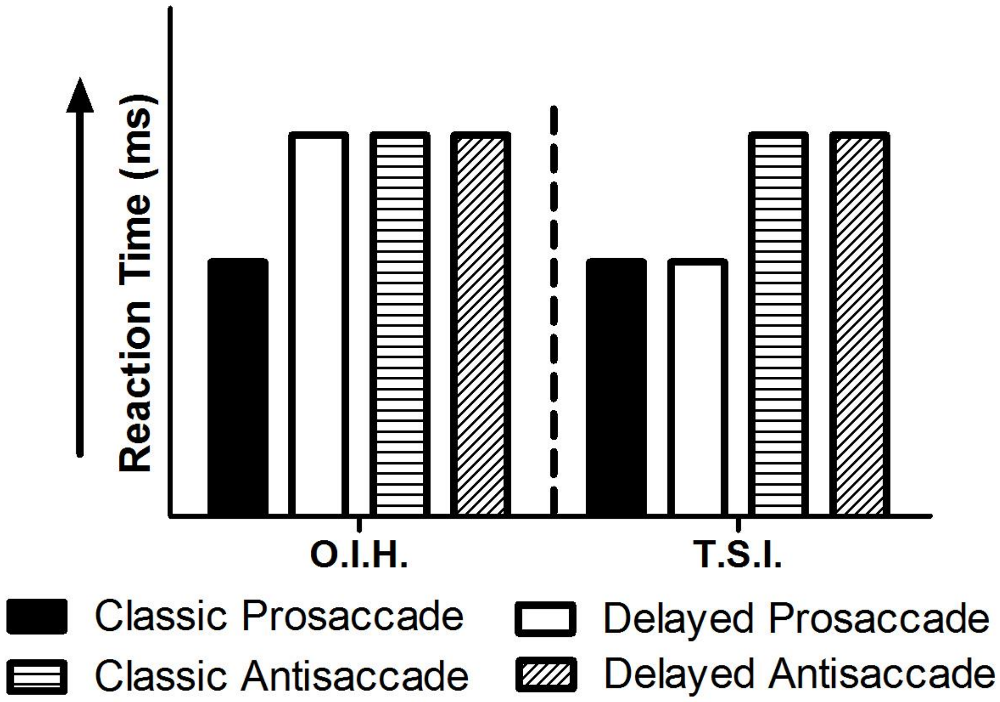

Figure 4-1: Hypothetical RTs of classic prosaccades as a function of being preceded by each of the four saccade trial-types on trial N-1. Left and right panels depict theoretical results predicted by the oculomotor inhibition (O.I.H) and task-set inertia (T.S.I) hypotheses, respectively. If the O.I.H best explains the unidirectional prosaccade switch-cost, then trial-types requiring response suppression (i.e., delayed prosaccades, classic antisaccades, and delayed antisaccades) are predicted to lengthen the RT of a subsequent classic prosaccade. In turn, if the T.S.I. hypothesis best explains the unidirectional prosaccade switch-cost then responses which engender a cognitive task-set to execute a saccade with non-dominant SR mapping (i.e., classic and delayed antisaccades) are predicted to delay the RT of subsequent classic prosaccades.

4.2 Methods

4.2.1 Participants

Sixteen participants (7 male, 9 female; age range = 19 – 31 years) from the University of Western Ontario community volunteered for the current investigation. All participants had normal or corrected-to-normal vision and declared being right-hand dominant. Prior to data collection participants provided informed written consent. This study was approved by the Office of Research Ethics, the University of Western Ontario, and was conducted in accordance with the Declaration of Helsinki.

4.2.2 Apparatus and Procedures

Participants sat at a table with their head stabilized via a head/chin-rest for the duration of data collection. Visual stimuli were presented on a 30-inch LCD monitor (60 Hz, 8 ms response rate, 1280 by 960 pixels, Dell 3007WFP, Round Rock, TX, USA) centered on the participant’s midline and located at a viewing distance of 550 mm. The gaze location of the participant’s left eye was obtained via a video-based chin-mounted eye tracking system (Eye-Trac 6: Applied Sciences Laboratories, Bedford, MA, USA) sampling at 360 Hz. Prior to data collection a nine-point calibration of the participant’s viewing space was performed. Two additional monitors that were visible only to the experimenter provided: (1) real-time point of gaze information, (2) a visual depiction of trial-to-trial saccade trajectories (e.g., displacement, velocity), and (3) information about the accuracy of the eye tracking system. All computer events and visual stimuli were controlled via MATLAB (7.6: The Math Works, Natick, MA, USA) and the Psychophysics Toolbox extensions (ver 3.0; Brainard, 1997). The lights in the experimental suite were extinguished during data collection.

Visual stimuli were presented against a high contrast black (2 cd/m^2) background. Stimuli included a green (90 cd/m^2), a red (35 cd/m^2) and a white (149 cd/m^2) fixations cross (1.0°) that were centered horizontally on the monitor and at the eye-level of the participant. In addition, yellow (134 cd/m^2)[1] crosses (1.0°) served as targets and were located 10.5° (proximal) or 15.5° (distal) left and right of the fixation cross. All trials began with the presentation of either the green, red, or white fixation cross which alerted participants to direct their gaze to its location. After a stable gaze was achieved (±1.5° for 500 ms) a randomized foreperiod was introduced (i.e., 1,000 – 2,000 ms). Following the foreperiod, a target was briefly presented (i.e., 50 ms) in one of the four target locations (i.e., combination of visual space by target eccentricity). The fixation cross remained visible during the foreperiod and was extinguished concurrent with offset of the target stimulus.

Two cuing conditions were used in this experiment. In the classic cuing condition, participants were presented with the green or red fixation cross which indicated the nature of the desired task: The green cross indicated a response to the target's veridical location (i.e., classic prosaccade), whereas the red cross indicated a response to the target's mirror-symmetrical location (i.e., classic antisaccade). As such, the classic cuing condition provided participants knowledge regarding the nature of the required response prior to response cuing[2]. In the delayed cuing condition, participants were presented with a task-irrelevant white fixation cross during the foreperiod. Following the foreperiod, (i.e., at target presentation) the white fixation cross was replaced with either the green or the red fixation cross which respectively informed participants to saccade to the target (i.e., delayed prosaccade) or to the target's mirror-symmetrical location (i.e., delayed antisaccade). Importantly, the delayed cuing condition required that participants suppress a stimulus-driven prosaccade until they had identified the appropriate fixation cross colour and task pairing (Figure 4-2).

Participants completed 400 trials which alternated between each of the four trial-types described above (i.e., classic prosaccades, classic antisaccades, delayed prosaccades, delayed antisaccades) in one of four pre-determined and pseudo-randomized trial-type sequences that could not be predicted. All trial sequences were designed such that each trial-type was preceded by its same trial-type counterpart (e.g., classic prosaccade preceded by a classic prosaccade) 40 times and by each of the other three trial-types (e.g., classic prosaccade preceded by a classic antisaccade / delayed prosaccade / delayed antisaccade) 20 times[3]. The trial-type associated with the first trial in the trial sequence was counterbalanced across participants and trial-to-trial target locations (i.e., visual space by target eccentricity combination) were randomly selected. To avoid mental and/or eye fatigue experimental data were collected across two days (i.e., 200 trials per day). As we sought to determine if saccade planning was influenced by the previous response, the first trial on Day 1 and 2 were not included in subsequent analyses.

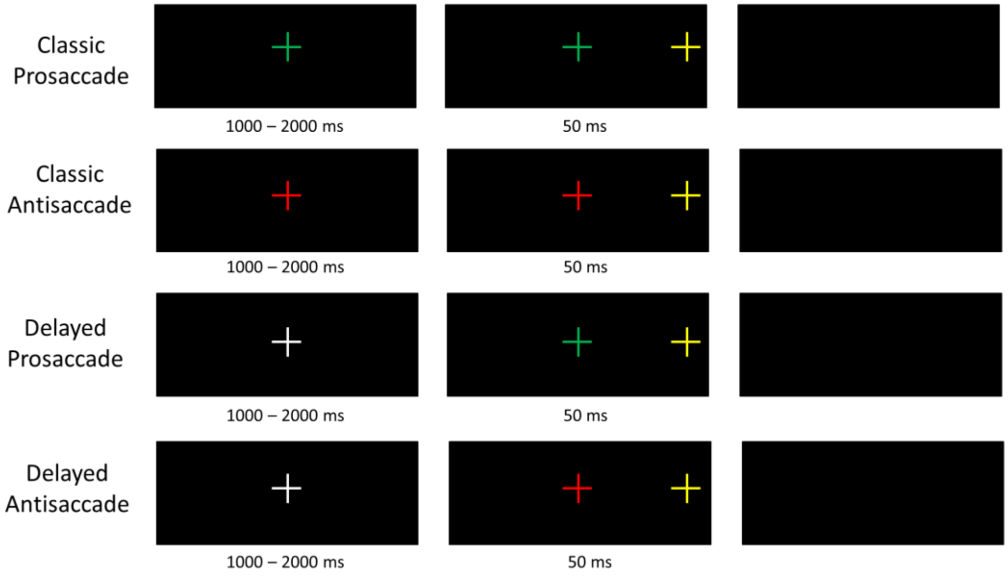

Figure 4-2: Schematic of the presentation and timing of visual stimulus in each of the four trial-types (i.e., classic prosaccade, classic antisaccade, delayed prosaccade and delayed antisaccade).

4.2.3 Data reduction

Displacement data were filtered offline using a dual-pass Butterworth filter employing a low-pass cut-off frequency of 15 Hz. Filtered displacement data were used to compute instantaneous velocities via a five-point central finite difference algorithm. Acceleration data were computed similarly via the velocity data. Saccade onset was determined on the basis of velocity and acceleration values that exceeded 30°/s and $8{,}000°/s^2$, respectively. Trials that involved missing data (i.e., a blink: 2% of total trials) or an anticipatory saccade (i.e., RT < 70 ms: 4%) were omitted from subsequent analyses. Trials where a directional error was committed (i.e., a saccade initiated or completed to the incorrect goal-location) were recorded and presented as the percentage of directional errors below; however, trials involving an error were not included in the RT analysis.

4.2.4 Dependent Variables and Statistical Analyses

We computed RT (i.e., time between target presentation and saccade onset) as well as the percentage of saccade directional errors for each trial-type. An alpha level of 0.05 was set for all statistical comparisons, and Greenhouse-Geisser corrected degrees of freedom (where appropriate) are reported to one decimal place.

4.3 Results

4.3.1 Task repetition trials: The influence of task and cuing condition on reaction time and directional errors

To determine whether pro- and antisaccades across the classic and delayed cuing conditions differentially influenced saccade planning, mean RTs and the percentage of directional errors were submitted to 2 (task: prosaccade, antisaccade) by 2 (cuing condition: classic, delayed) repeated-measures ANOVA[4]. To ensure that results from this analysis were independent of potential switch-costs, only task-repetition trials were used. The results for RT yielded main effects of task, $F(1,15) = 9.95$, $p < 0.01$, cuing condition $F(1,15) = 97.77$, $p < 0.001$, and their interaction, $F(1,15) = 8.75$, $p < 0.01$. In decomposing the interaction, we contrasted pro- and antisaccades separately for classic and delayed conditions. In the classic cuing condition, prosaccades (235 ms, SD = 43)[5] elicited shorter RTs than antisaccades (275 ms, SD = 31), $t(15) = 4.14$, $p < 0.001$, whereas in the delayed cuing condition pro- (312 ms, SD = 43) and antisaccades (318 ms, SD = 45) RTs did not reliably differ, $t(15) = 0.70$, $p = 0.49$ (Figure 4-3).

The analysis of the percentage of directional errors showed that prosaccades (3%, SD = 3) produced fewer directional errors than antisaccades (6%, SD = 7), $F(1,15) = 6.42$, $p < 0.05$, and that fewer errors were associated with the classic (3%, SD = 5) as compared to the delayed (7%, SD = 8.7) cuing condition, $F(1,15) = 8.75$, $p < 0.01$ (Figure 4-4).

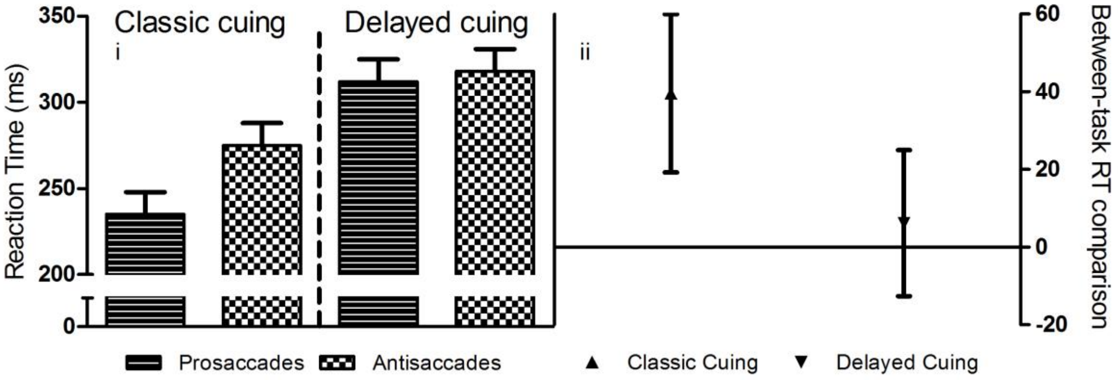

Figure 4-3: The left panel (i) depicts RTs for task-repetition pro- and antisaccades elicited via the classic and delayed cuing condition. Error bars on this panel reflect within-participant 95% confidence intervals (Loftus & Masson, 1994). The right panel (ii) reflects RT difference scores (antisaccade minus prosaccade) computed separately for classic and delayed cuing conditions. Error bars represent 95% confidence intervals (Cummings & Finch, 2005). For this panel, confidence intervals that do not cross zero depict reliable between-task differences ($p < 0.05$).

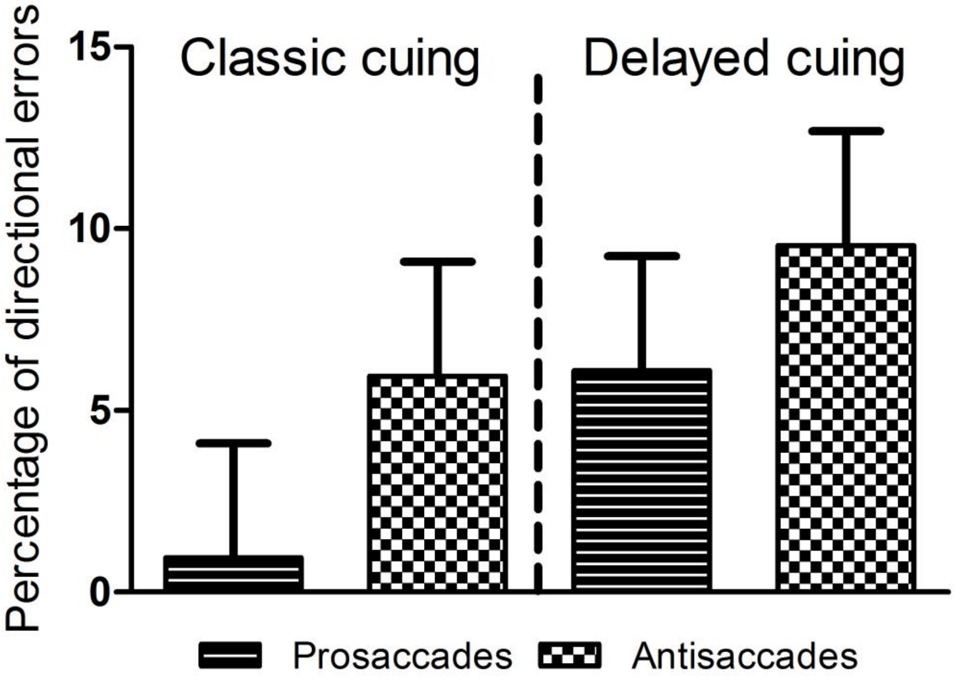

Figure 4-4: Percentage of directional errors for task-repetition pro- and antisaccades elicited via the classic and delayed cuing conditions. Error bars reflect within-participant 95% confidence intervals. Note that the confidence interval for classic prosaccades crosses zero. This is possible given that within-participant confidence intervals are computed as a function of the mean squared error term of the repeated-measured ANOVA and applied to each level of the statistical model (Loftus & Masson, 1994).

4.3.2 The influence of the previous trial-type on reaction time and directional errors

To determine if saccade planning was influenced by the saccade on the previous response (i.e., trial N-1), mean RTs and the percentage of directional errors for each trial-type (i.e., classic prosaccade, classic antisaccade, delayed prosaccade, delayed antisaccade) were analyzed separately via one-way repeated measures ANOVAs with *trial-type on trial N-1* as the within-participant factor. Recall that the experimental trial sequences were designed such that a trial-type executed on trial N was preceded by either its same trial-type counterpart or by one of the three other trial-types. Thus, responses completed on trial N could be categorized as a task-repetition response (i.e., same trial-type on trial N compared to trial N-1) or a task-switch response (i.e., different trial-type on trial N compared to trial N-1). One-way ANOVAs yielding reliable effects were decomposed by contrasting the task-repetition response to each of the three task-switch counterparts (Kiesel et al., 2010). For example, the post hoc analysis for classic prosaccades entailed contrasting classic prosaccades when preceded by other classic prosaccade on trial N-1 with classic prosaccades when preceded by: (1) classic antisaccades on trial N-1, (2) delayed prosaccades on trial N-1, and (3) delayed prosaccades on trial N-1. Test statistics and p-values of post-hoc contrasts for these analyses are found in Table 1 (RT) and Table 2 (percentage of directional errors).

The analyses for classic prosaccades demonstrated that RTs, $F(3,45) = 5.45$, $p < 0.01$, and the percentage of directional errors, $F(3,45) = 2.82$, $p < 0.05$, were influenced by preceding trial-type. Specifically, classic prosaccades preceded by other classic prosaccades had shorter RTs (235 ms, SD = 43) and a reduced percentage of directional errors (1%, SD = 2) than classic prosaccades preceded by classic antisaccades (252 ms, SD = 50) (5%, SD = 8) or delayed antisaccades (252 ms, SD = 46) (5%, SD = 7). In turn, the RT and error rates of classic prosaccades preceded by other classic prosaccades did not reliably differ from classic prosaccades preceded by delayed prosaccades (232 ms, SD = 49) (2%, SD = 4), (Figure 4-5A & Figure 4-6A).

The analyses for classic antisaccades demonstrated that RTs, $F(3,45) = 1.10$, $p = 0.36$., and the percentage of directional errors, $F(3,45) = 0.25$, $p = 0.86$, were refractory to the previous trial-type. In other words, RTs and directional errors for classic antisaccades preceded by other classic antisaccades (275 ms, SD = 31: 6%, SD = 6), classic prosaccades (269 ms, SD = 33: 7%, SD = 8), delayed antisaccades (275 ms, SD = 30: 5%, SD = 6) or delayed prosaccades (279 ms, SD = 38: 7%, SD = 9) did not reliably differ (Figure 4-5B & Figure 4-6B).

Results for delayed prosaccades demonstrated that RTs, $F(2.1,31.3) = 4.83$, $p < 0.05$, and the percentage of directional errors, $F(3,45) = 10.68$, $p < 0.001$, were influenced by previous trial-type. Delayed prosaccades preceded by other delayed prosaccades produced shorter RTs (312 ms, SD = 43) and elicited fewer directional errors (6%, SD = 6) than delayed prosaccades preceded by classic antisaccades (332 ms, SD = 55) (20%, SD = 19) or delayed antisaccades (339 ms, SD = 60) (19%, SD = 18). In turn, the RTs and error rates of delayed prosaccades preceded by other delayed prosaccades did not reliably differ from delayed prosaccades preceded by classic prosaccades (313 ms, SD = 29) (8%, SD = 12) (Figure 4-5C & Figure 4-6C).

RTs for delayed antisaccades were not reliably influenced by previous trial-type, $F(3,45) = 1.87$, $p = 0.15$. In other words, delayed antisaccades preceded by other delayed antisaccades (318 ms, SD = 45), classic antisaccades (310 ms, SD = 36), delayed prosaccades (320 ms, SD = 52) or classic prosaccades (328 ms, SD = 49) did not differ. However, the results for directional errors produced a reliable effect, $F(3,45) = 13.58$, $p < 0.01$, such that delayed antisaccades preceded by delayed antisaccades elicited a reduced percentage of directional errors (10%, SD = 11) compared to delayed antisaccades preceded by classic (17%, SD = 16) or delayed prosaccades (23%, SD = 13). In turn, the percentage of directional errors of delayed antisaccades preceded by their same task counterparts did not reliably differ from delayed antisaccades preceded by classic antisaccades (8%, SD = 10) (Figure 4-5D & Figure 4-6D).

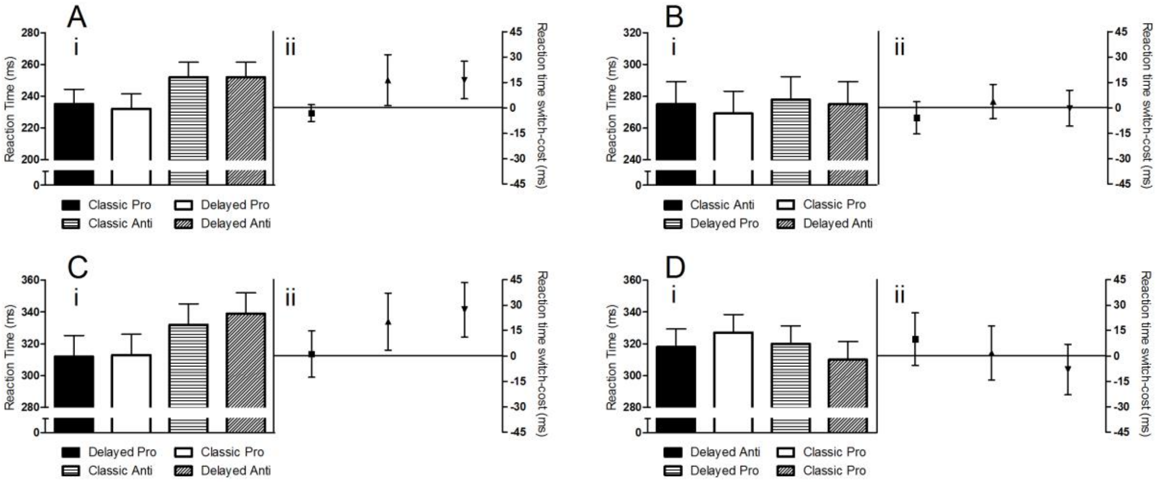

Figure 4-5: RT results for each of the four trial-types (i.e., A: classic prosaccades; B: classic antisaccades; C: delayed prosaccades; D: delayed antisaccades. The left panels (i) represent the RT of each trial-type (i.e., classic prosaccade, classic antisaccade, delayed prosaccade and delayed antisaccade) as a function of being preceded by its same task counterpart and the remaining trial-types. Trial-types completed on the previous trial are indicated in the legend. Error bars represent within-participant 95% confidence intervals (Loftus & Masson, 1994). The right panels (ii) represent the difference scores comparing the task-repetition trial (1^{st} data point from left panel) with task-switch trials (2^{nd}, 3^{rd}, & 4^{th} data point from left panel). Error bars represent 95% confidence intervals (Cummings & Finch, 2005). For this panel, confidence intervals that do not cross zero represent reliable differences ($p < 0.05$).

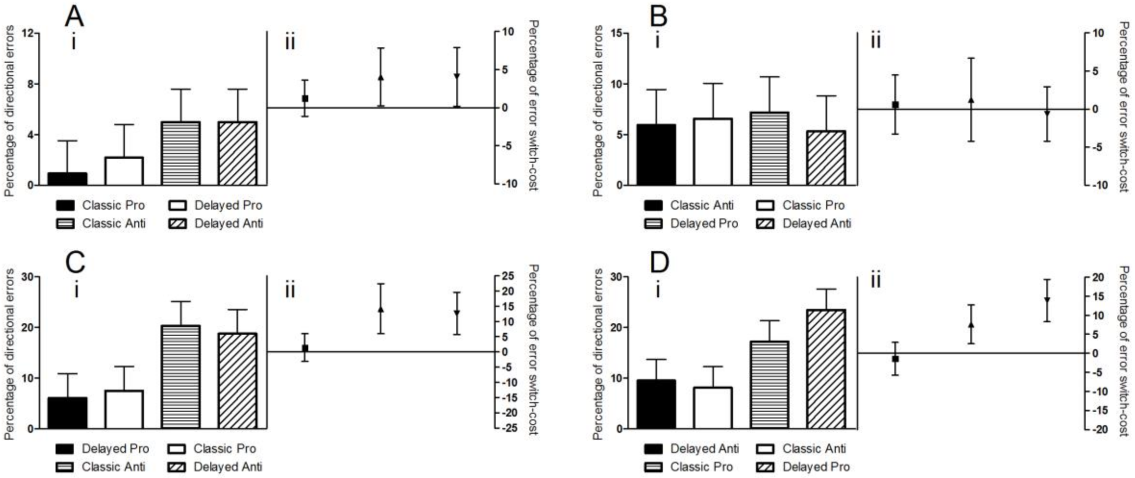

Figure 4-6: Percentage of directional errors for each of the four trial-types (i.e., A: classic prosaccades; B: classic antisaccades; C: delayed prosaccades; D: delayed antisaccades. The left panels (i) represent the percentage of directional error of each trial-type (i.e., classic prosaccade, classic antisaccade, delayed prosaccade and delayed antisaccade) as a function of being preceded by its same task counterpart and the remaining trial-types. Trial-types completed on the previous trial are indicated in the legend. Error bars represent within-participant 95% confidence intervals. Note that classic prosaccade preceded by two trial-types (i.e., classic, and delayed prosaccades) have confidence intervals cross zero. This is possible given that within-participant confidence intervals are computed as a function of the mean squared error term of the repeated-measured ANOVA and applied to each level of the statistical model (Loftus & Masson, 1994). The right panels (ii) represent the difference scores comparing the task-repetition trial (1st data point from left panel) with task-switch trials (2nd, 3rd, & 4th data point from left panel). Error bars represent 95% confidence intervals (Cummings & Finch, 2005). For this panel, confidence intervals that do not cross zero represent reliable differences ($p < 0.05$).

Table 4-1: Statistical information of post-hoc contrasts for RT

	t(15)	p-value
Classic prosaccades preceded by classic prosaccades compared to:		
Classic prosaccades preceded by		
• Classic antisaccades	2.38	< 0.05
• Delayed antisaccades	3.15	< 0.01
• Delayed prosaccades	0.49	0.63
Delayed prosaccades preceded by delayed prosaccades compared to:		
Delayed prosaccades preceded by		
• Classic antisaccades	2.56	< 0.05
• Delayed antisaccades	3.57	< 0.01
• Classic prosaccades	0.17	0.87

Table 4-1: Statistical information of post-hoc contrasts for the percentage of directional errors

	t(15)	p-value
Classic prosaccades preceded by classic prosaccades compared to:		
Classic prosaccades preceded by		
• Classic antisaccades	2.28	< 0.05
• Delayed antisaccades	2.25	< 0.05
• Delayed prosaccades	1.12	0.28
Delayed prosaccades preceded by delayed prosaccades compared to:		
Delayed prosaccades preceded by		
• Classic antisaccades	3.69	< 0.01
• Delayed antisaccades	3.58	< 0.01
• Classic prosaccades	0.66	0.52
Delayed antisaccades preceded by delayed antisaccades compared to:		
Delayed antisaccades preceded by		
• Classic prosaccades	3.19	< 0.01
• Delayed prosaccades	5.34	< 0.001
• Classic antisaccades	0.69	0.50

4.4 Discussion

The current investigation provides three general findings. First, classic prosaccades produced shorter RTs and a reduced percentage of directional errors compared to classic antisaccades. This result is consistent with an extensive literature employing the classic cuing paradigm and is taken to evince that antisaccades require the top-down and time-consuming demands of response suppression and vector inversion (for review see Munoz & Everling, 2004). Second, the delayed cuing condition eliminated the difference between pro- and antisaccade RTs; that is, the pre-movement requirement to suppress a stimulus-driven response resulted in comparable pro- and antisaccade RTs. This result is in-line with Olk and Kingstone's (2003) assertion that the antisaccade RT cost observed in the classic cuing condition is primarily accounted for by the demands of response suppression (see also Heath et al., 2011). More importantly, this result demonstrates that the delayed pro- and antisaccade trial-types used in the current investigation were equated for response suppression. Third, the RTs of classic prosaccades were lengthened by preceding classic antisaccades, whereas the RTs of classic antisaccades were not influenced by preceding classic prosaccades. This finding is consistent with previous work showing that the classic cuing condition elicits a unidirectional prosaccade switch-cost (Chan & DeSouza, 2013; DeSimone, et al., 2014; Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler & Heath, 2014; Weiler, et al., 2014).

4.4.1 Task-set inertia explains the unidirectional prosaccade switch-cost

The primary goal of this study was to test the competing predictions of the oculomotor inhibition and task-set inertia hypotheses. Our goal stems from the fact that the former hypothesis attributes the unidirectional prosaccade switch-cost to the top-down process of response suppression. In contrast, the latter hypothesis contends that the switch-cost is related to the persistent activation of the task-set invoked to execute a response with non-dominant SR mapping. Thus, the most salient result from the current investigation was that classic and delayed antisaccades – but not delayed prosaccades – increased the RT of subsequent classic and delayed prosaccades. This result is of particular importance because classic and delayed antisaccades, as well as delayed prosaccades, required participants to engage the top-down process of response suppression. Indeed, that delayed prosaccades did not lengthen the RT of a subsequent classic or delayed prosaccade counters the oculomotor inhibition hypothesis' assertion that response suppression contributes to the unidirectional prosaccade switch-cost (Weiler et al., 2014). Instead, that only classic or delayed antisaccades lengthened the RT of a subsequent classic or delayed prosaccades indicates that the task-set engendered to execute a response with non-dominant SR mapping (i.e., an antisaccade) interfered with the efficient and effective planning of a subsequent prosaccade. Additionally, it is important to recognize that the unidirectional prosaccade switch-cost observed here was not restricted to stimulus-driven (i.e., classic) prosaccades; rather, the RT of delayed prosaccades were also delayed by preceding antisaccade trial-types. Thus, the completion of an antisaccade does not selectively inhibit the oculomotor networks involved in the planning of stimulus-driven prosaccades; rather, the antisaccade task-set delays the planning of any subsequent response entailing direct SR mapping. This finding is an important addition to the oculomotor task-switching literature as previous work has selectively evaluated the expression of the unidirectional prosaccade switch-cost via a classic cuing paradigm (e.g., Chan & DeSouza, 2013; DeSimone, et al., 2014; Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler & Heath, 2014; Weiler, et al., 2014).

The results for the percentage of directional errors generally mirrored the pattern of RT findings. More specifically, the completion of a classic or delayed antisaccade increased the percentage of directional errors for subsequent classic and delayed prosaccades. This result is in-line with earlier oculomotor (Weiler & Heath, 2014) and Stroop (Allport et al., 1994) task-switching experiments demonstrating that the execution of a non-standard response (e.g., antisaccade / colour-naming response) increased the percentage of errors associated with a subsequent standard pre-potent response (e.g., prosaccade / word-naming response). Additionally, the present errors findings demonstrate that the antisaccade task-set does not exclusively delay the planning of a subsequent prosaccade; rather, the prosaccade error switch-cost indicates that the antisaccade task-set has the capability to override a pre-potent prosaccade and produce an action with the same non-dominant SR mapping as was completed on the previous trial.

The results described above demonstrate that the task-set inertia hypothesis provides the most parsimonious accounts for the unidirectional prosaccade switch-cost. Moreover, such an explanation also accounts for the results reported by DeSimone et al. (2014) who demonstrated that prosaccade RTs are *not* lengthened when preceded by a directionally incorrect antisaccade. Recall that the *successful* completion of a non-standard task requires a cognitively mediated task-set. Thus, task-set inertia predicts that the planning time for a prosaccade preceded by a directionally incorrect antisaccade will not be increased because the erroneous antisaccade is not associated with cognitively mediated task-set with non-standard SR rules. Notably, these behavioural findings are in line with emergent literature examining the neural correlates of task-set inertia in oculomotor control. For example, Hussein et al. (2014) demonstrated that transient deactivation of the inferior dorsolateral prefrontal cortex of a non-human primate impaired the animal's ability to correctly switch to the antisaccade task, and disrupted the maintenance of antisaccade task-rules in working memory. As well, Kovel et al. (2011) demonstrated that transient deactivation of the dorsolateral prefrontal cortex eliminated the preparatory differences between pro- and antisaccades within the superior colliculus (see Everling et al., 1999) and increased the proportion of antisaccade directional errors. Thus, the dorsolateral prefrontal cortex plays a crucial role preparing the oculomotor system to execute an antisaccade. What is more, neuroimaging work has also shown that the implementation of a cognitively mediated task-set is dependent on the dorsolateral prefrontal cortex (Pochon et al., 2001) – a result indicating that Hussein et al.'s and Kovel et al.'s findings may reflect an inability to adopt an appropriate antisaccade task-set due to transient deactivation of the dorsolateral prefrontal cortex. In the context of the current work, these collective investigations suggest that the evocation of an antisaccade requires that the dorsolateral prefrontal cortex to adopt a non-standard task-set that may persist inertially and delay the planning of a subsequent prosaccade.

In addition to the above, the results from the current work may provide insight as to *how* the antisaccade task-set influences the planning of a subsequent prosaccade. As noted previously, the prosaccade error switch-cost indicates that the persistently active antisaccade task-set is capable of overriding the subsequent pre-potent prosaccade. Thus, to ensure prosaccade directional errors are not committed following an antisaccade trial, the persistently active and competing antisaccade task-set must be eliminated. In addition, recall that the RTs of task-repetition classic prosaccades (235 ms) were shorter than their task-repetition delayed prosaccade counterparts (312 ms). Despite these differences in RT, however, a posteriori analysis demonstrated that the completion of classic or delayed antisaccades lengthened the RT of subsequent classic (18 ms, SD = 15) and delayed (24 ms, SD = 27) prosaccades to the same extent, t(15) = 0.98, p = 0.34. That the magnitude of the switch-cost was not modulated between the classic and delayed cuing conditions indicates that the antisaccade task-set was active until the presentation of the visual stimulus used to cue the initiation of the subsequent prosaccade. In accounting for these findings, we propose that the eliminating or reconfiguring the persistently active antisaccade task-set is: (1) triggered by an exogenous stimulus (for exogenous task-set reconfiguration, see Kiesel et al., 2010; Monsell et al., 2000) and, (2) is a time-consuming process that must be completed prior to planning the subsequent classic or delayed prosaccade. In other words, ameliorating the antisaccade task-set delays the onset of neural activity that supports the planning of a subsequent saccade with direct SR compatibility. Notably, two lines of evidence support this proposal. First, work by our group demonstrated that alternating from an anti- to a prosaccade did not modulate the amplitude of the P3 event-related brain potential when the electroencephalography (EEG) signal was time-locked to the task-cue indicating the nature (i.e., pro- vs. antisaccade) of the forthcoming response. In contrast, the converse switch engendered a reliable modulation in the P3 amplitude (Weiler et al., 2014). This is a notable finding as modulation of the P3 has been shown to reflect task-set updating when the SR rules associated with an upcoming response differ from the preceding response (Barceló et al., 2002; Barceló et al., 2008; Nicholson et al., 2005). Second, Pouget and colleagues' (2011) work involving non-human primates found that the competition of a non-standard stop-signal response resulted in a 17 ms increase in RT of the subsequent prosaccade: results that reflect the RT switch-cost observed in the current experiment (see also Weiler & Heath 2014). Moreover, the increase in RT reported by Pouget et al. was specifically linked to a delay in the onset of activity in collicular saccade neurons and did not reflect a change in the saccade neurons' baseline levels of activity, rate of accumulation, or threshold to elicit a response. In other words, stop-signal trials did not alter the oculomotor activity involved in planning a subsequent prosaccade; rather, the stop-signal trials delayed when the activity began. The present findings indicate that it is unlikely that Pouget et al.'s results are linked to the response suppression requirements of the stop-signal trial. After all, if that were the case then delayed prosaccades – which required response suppression – would have lengthened the RTs of subsequent prosaccades. It is, however, important to recognize that an alternative explanation for Pouget et al.'s results is that their animals were simply 'waiting to respond' to ensure that the subsequent trial was not another stop-signal trial. However, in light of our behavioural and EEG results, we interpret the delay in onset of saccade neuron activity – and increase in RT – following a non-standard stop-signal trial to reflect the time-consuming process of eliminating the persistently active stop-signal task-set that was required before prosaccade planning could commence. Notably, this interpretation provides a parsimonious explanation for the neurophysiological and behavioural results reported by Pouget et al., our EEG findings (Weiler et al., 2014), and for the unidirectional prosaccade switch-cost observed in the current and previous studies.

4.5 Conclusion

The RTs of classic and delayed prosaccades were lengthened by preceding classic and delayed antisaccades – but not by delayed prosaccades. This result counters our group's previous assertion that response suppression engenders a residual inhibition of the oculomotor networks involved in the planning of stimulus-driven prosaccades (i.e., the oculomotor inhibition hypothesis). Instead, the present results are in accord with the assertion that the task-set associated with a non-standard response persists inertially and decreases the efficiency and effectiveness of planning a subsequent response with standard or direct SR mapping (i.e., task-set inertia hypothesis). Moreover, we propose that the persistently active antisaccade task-set must be eliminated before the onset of oculomotor activity that supports prosaccade planning can begin to accumulate.

4.6 Footnotes

1. Luminance differences for pro- and antisaccade fixation crosses have been shown to not influence response planning or control (Dafoe et al., 2007).
2. The term 'classic cuing' was used because the first experiment to employ the antisaccade task used the presentation of the visual target as the movement imperative cue (see Hallett, 1978).
3. There were 40 trials wherein the current trial-type and the trial-type on trial N-1 were the same (i.e., task-repetition response) compared to 20 trials wherein the current trial-type differed from trial N-1 (i.e., task-switch response). This design ensured that a response subsequent to a task-repetition trial had an equal probability of being any of the four trial-types.
4. Visual space (i.e., left, right) and target eccentricity (proximal, distal) were not included as factors in this or subsequent analyses as we have demonstrated that these factors do not influence saccade planning (Heath, et al., 2010; Heath, et al., 2011).

5. Within the body of the text, SD represents *between-participant* standard deviation.

4.7 References

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Chapter 5

The unidirectional prosaccade switch-cost: electroencephalography evidence of task-set inertia in oculomotor control

5.1 Introduction

The rapid reorientation of gaze towards a salient visual target (i.e., prosaccade) represents the most frequent motor response that humans perform on a day-to-day basis (Irwin and Carlson-Radvansky 1996). Notably, prosaccades require minimal top-down control due to their mediation via retinotopically organized motor maps within the superior colliculus (Wurtz & Albano, 1980; see also Pierrot-Deseilligny et al., 1995). It is, however, possible to decouple direct stimulus and response (SR) relations and 'look' to any desired region of the visual field (i.e., non-standard task: see Fitts & Seeger 1953; Korblum et al., 1990). Indeed, non-standard tasks represent an important area of inquiry because they provide a framework for understanding how top-down cognitive control influences oculomotor networks. The antisaccade is an exemplar non-standard task and requires decoupling SR relations and the evocation of a saccade to a target's mirror-symmetrical location (Hallett, 1978; Hallett & Adams, 1980). Extensive behavioural evidence has demonstrated that antisaccades have longer reaction times (RT) (Hallett, 1978), increased directional errors (Fischer & Weber, 1996; Hallett, 1978), and less accurate and more variable endpoints (Dafoe et al. 2007; Gillen & Heath, 2014; Heath et al., 2010) than prosaccade. These behavioural 'costs' have been attributed to the top-down suppression of a stimulus-driven prosaccade (i.e., response suppression) and the visual remapping (i.e., 180° spatial transformation) of the target's spatial location (i.e., vector inversion) (Funahashi, et al., 1993; Zhang & Barash, 2000; for review of the antisaccade task see Munoz & Everling, 2004). Moreover, antisaccades have been linked to increased activity in an extensive fronto-parietal network (frontal eye field, supplementary eye field, dorsolateral prefrontal cortex, anterior cingulate cortex, and lateral intraparietal cortex)

(Brown et al., 2007; Curtis & D'Esposito, 2003; DeSouza et al., 2003; Ford et al., 2005) and show a respective increase and decrease of collicular fixation and buildup neurons prior to target presentation (Everling et al, 1998; Everling et al, 1999). The aforementioned changes within the oculomotor system are thought to reflect a preparatory response set that withholds a reflexive prosaccades so that the sensorimotor transformation required for an antisaccade can be completed (Brown et al., 2007).

In addition to the above-mentioned behavioural and neural changes linked to the antisaccade task, a series of recent studies have shown that the execution of an antisaccade lengthens the RT of a *subsequent* prosaccade (Chan & DeSouza, 2014; Cherkasova et al., 2002; DeSimone et al., 2014; Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler et al., 2014; Weiler & Heath, submitted). More specifically, results from our group have shown that the RT of a prosaccade completed after an antisaccade (i.e., task-switch prosaccade) are between 10-20 ms longer than a prosaccade completed after a prosaccade (i.e., task-repetition prosaccades). In contrast, RTs for task-switch and task-repetition antisaccades do not differ. As such, we have termed the selective increase in the RTs of task-switch prosaccades as the *unidirectional prosaccade switch-cost* and have shown that such an effect is not accounted for by the independent or interdependent effects of response suppression (Weiler & Heath, submitted) and vector inversion (Weiler & Heath 2014; see also DeSimone et al., 2014). In accounting for the unidirectional prosaccade switch-cost our group extended Allport et al's (1994) task-set inertia hypothesis to the oculomotor domain and proposed that responses entailing non-dominant SR mapping (e.g., an antisaccade) require the implementation of cognitively meditated task-rules (i.e., a task-set) for their successful execution. Moreover, the hypothesis asserts that the cognitively mediated task-set persists inertially and delays the planning of a subsequent response with standard and dominant SR mapping (e.g., a prosaccade). In turn, the hypothesis contends that the completion of a response with dominant SR relations does not require the activation of a cognitively based task-set and therefore does not influence the planning of a subsequent response with non-dominant SR mapping. Thus, task-set inertia asserts a null cost when switching from a prosaccade to an antisaccade.

An important issue to revolve is *how* a persistently active antisaccade task-set delays the planning of a subsequent prosaccade. In other words, identifying the component element of prosaccade planning that is influenced by the antisaccade task-set would provide a direct explanation of how the task-set inertia hypothesis accounts for the unidirectional prosaccade switch-cost. One possible explanation is shown in Figure 5-1. In particular, the figure shows that advanced information specifying antisaccade task-cuing (time A) results in the adoption of a cognitively mediated antisaccade task-set in advance of the exogenous stimulus cuing the response (i.e., response-cuing; see time B). Importantly, the figure further shows that the antisaccade task-set persists inertially and is present throughout a subsequent prosaccade task- (time C) and response-cuing (time D) interval. Indeed, it is predicted that an appropriate prosaccade task-set is adopted only after response-cuing (time E) which thereby allows the planning of a response with standard SR rules. Put more simply, we propose that the basis for the prosaccade switch-cost is that the antisaccade task-set persists inertially and delays *when* the prosaccade task-set can be adopted. Furthermore, and as outlined in the preceding paragraph, Figure

1 (time G) shows that the prosaccade task-set does not persist inertially and delay the adoption of a non-standard antisaccade task-set.

Our explanation of the unidirectional prosaccade switch-costs is predicated on the assertion that the antisaccade task-set persists inertially and delays the adoption of the prosaccade task-set until after response-cuing. In other words, we propose that the preparatory interval (i.e., time between task-cuing and response-cuing) associated with task-switch prosaccades is associated with an antisaccade task-set, whereas the preparatory interval for task-repetition prosaccades is associated with its own distinct standard task-set (see Figure 5-1). In order to test this hypothesis, the present investigation directly compared behavioural responses and examined changes in the human event-related brain potential (ERP) evoked by pro- and antisaccade task-switching. Notably, we identified the P3 ERP component as a means to measure the task-set inertia hypothesis because an extensive literature has shown that modulation of this waveform reflects the updating of an internal 'mental model' when the relationship between the task-goal and stimulus changes (for review see Donchin & Coles, 1988). Indeed, previous work in the motor control literature has shown that the amplitude of the P3 – time-locked to task-cuing –differs between pro- and antipointing (i.e., the respective manual response analogues of pro- and antisaccades; Heath et al., 2012) and that the amplitude of the P3 is modulated when propointing must engage in an online trajectory correction to account for an unexpected target 'jump' (Krigolson et al., 2008). More directly, the different P3 amplitudes for pro- and antipointing and for target jump and no-jump trials have been interpreted to reflect the task-set commensurate with current task-goals. Similarly, results from the perceptual literature have shown that task-switch and task-repetition trial-types are associated with distinct P3 amplitudes. For example, Gajewski and Falkenstein (2011) demonstrated an increase in the amplitude of the P3 when switching from identifying the magnitude to the parity – or vice versa – of a to-be-presented numerical digit. According to the authors, the increase in P3 amplitude for task-switch trials reflected the adoption of the 'new' task-set required to successfully complete the response (see also Barceló et al., 2008; Barceló et al., 2002; Nicholson et al., 2005). Thus, convergent evidence indicates that modulation of the P3 amplitude reflects the adoption of a task-set required to meet the demands of the upcoming response.

In the current experiment we examined the concurrent behavioural and ERP data evoked when alternating between pro- and antisaccades. In particular, participants initially viewed a task-irrelevant fixation cross and were then provided task instructions – via a fixation cross colour-change – which indicated whether to execute a pro- or antisaccade in response to an upcoming visual stimulus (i.e., task-cuing). The presentation of the target stimulus (i.e., response-cuing) occurred between 1,000 and 2,000 ms following the task-instruction cue. Importantly, we examined changes in P3 amplitude time-locked to, and evoked by, the task-instruction cue (i.e., the fixation cross colour-change) as this was the time-point when participants were informed whether to maintain or adopt a new task-set for the upcoming response. As such, the P3 time-locked to fixation cross colour-change provides an analogue of participants' premovement task-set. In terms of research predictions, if the unidirectional prosaccade switch-cost is explained by the task-set inertia hypothesis then antisaccade trial-types (i.e., task- switch and repetition) and task-switch prosaccades should exhibit comparable P3 amplitudes.

Indeed, such a finding would indicate that the increase in prosaccade RT following an antisaccade is due to the persistent activation of a task-set associated with non-standard SR rules. Moreover, it is predicted that task-repetition prosaccades will elicit a P3 amplitude that is different from the aforementioned trial-types – a result that would be consistent with the assertion that the preparatory interval for task-switch and task-repetition prosaccades are associated with non-standard and standard task-sets, respectively. Moreover, reliable differences between prosaccade task-switch and task-repetition P3 amplitudes would evince that the task-set associated with a response with dominant SR mapping does not persist and delay the adoption of a task-set linked to non-standard task-rules.

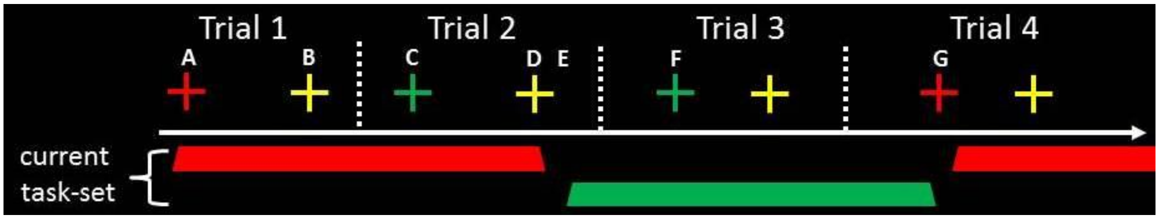

Figure 5-1: Theoretical predictions for how task-set inertia elicits a unidirectional prosaccade switch-cost. Trials 1 through 4 represent task-repetition antisaccades (trial 1), task-switch prosaccades (trial 2), task-repetition prosaccades (trial 3) and task-switch antisaccades (trial 4). Red and green crosses denote anti- and prosaccade task-cues, respectively. Yellow crosses denote response-cuing (i.e., target presentation). Red and green rectangles at the bottom of the figure represent anti- and prosaccade task-sets, respectively. Notably, the figure shows that the task-cue for task-switch prosaccades (time C) are associated with an antisaccade task-set whereas the task-cue for task-repetition prosaccades (time F) are associated with a task-set distinct from all other trial-types. That is, time F in the panel demonstrates a task-set with direct SR relations.

5.2 Methods

5.2.1 Participants

Fourteen individuals (11 females, 3 males; mean age 20.6 years, SD = 2.8) volunteered for the current investigation. All participants had normal or correct-to-normal vision and declared being right hand dominant. Prior to data collection participants provided informed written consent. This study was approved by the local ethics boards of the University of Western Ontario and was conducted in accord with the guidelines of the Declaration of Helsinki.

5.2.2 Apparatus and procedure

Participants completed the experiment in an isolated testing suite while seated at a table with their head stabilized via a chin-rest. Visual stimuli were presented on a 22 inch LCD monitor (75 Hz, 2 ms response rate, 1680 by 1050 pixels, LG W2242TQ-GF, Seoul, South Korea) centered on the participant's midline at a viewing distance of 630 mm. The gaze location of the participant's left eye was obtained by a video-based desk-mounted eye-tracking system (Eye-Link 1000: SR Research, Ottawa, Ontario, Canada) sampling at 500 Hz. Prior to data collection a nine-point calibration of the participant's viewing space was completed and immediately validated. Outside the testing suite, the experimenter viewed two additional monitors that provided: (1) real-time point of gaze information, (2) a visual depiction of trial-to-trial saccade trajectories (e.g., displacement, velocity), and (3) information about the accuracy of the eye tracking system (i.e., to determine a necessary recalibration or drift correction). All computer events and visual stimuli were controlled via MATLAB (7.6: The Math Works, Natick, MA, USA) and the

Psychophysics Toolbox extensions (ver 3.0; Brainard, 1997). The lights in the testing suite were extinguished during data collection.

Visual stimuli were presented against a high contrast black background and consisted of a fixation cross (1.0°) – appearing as white, green or red in colour (see details below) – that was centered horizontally on the monitor and at the eye-level of the participant. As well, yellow crosses (1.0°) served as target stimuli and were presented 12.5° left or right of the fixation cross and in the same horizontal meridian. Each trial began with the presentation of a task-irrelevant white fixation cross which alerted the participant to direct their gaze to its location. After a stable fixation was achieved (±1.5° for 500 ms) the white cross remained visible for an additional 1,000 ms. The white fixation cross was then replaced by either the green or the red fixation cross for a variable foreperiod (i.e., 1,000 – 2,000 ms). Following the foreperiod a target was briefly presented (i.e., 50 ms) and the fixation cross was simultaneously extinguished. The presentation of the target stimulus – and removal of the fixation cross – served as the response-cue to execute a required pro- or antisaccade (see details below) (see Figure 5-2 for schematic of a within-trial time-line).

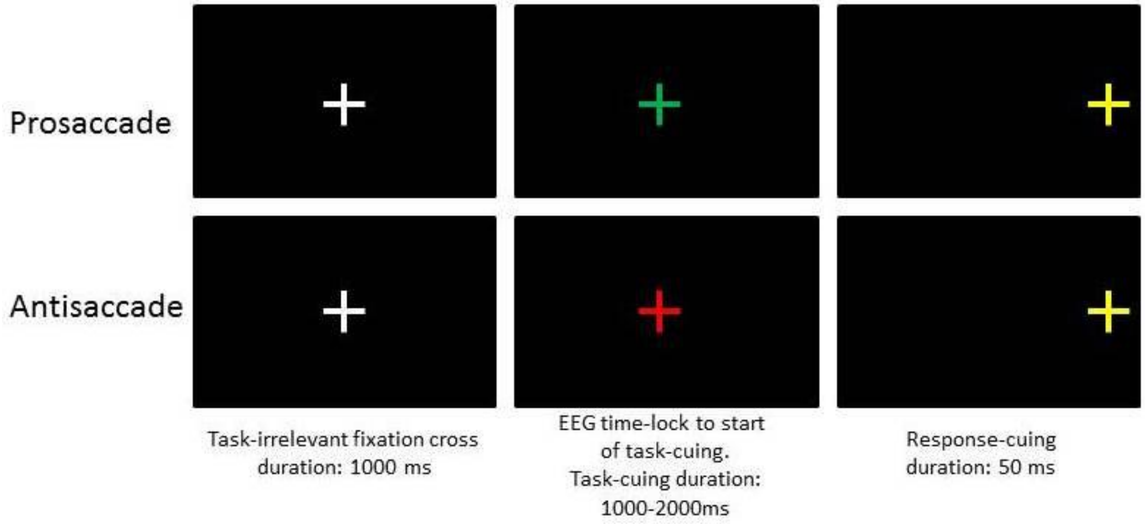

Figure 5-2: Schematic of a within-trial time-line. Participants viewed a task-irrelevant white fixation cross (1,000 ms) and were then presented with the task-instruction required for the upcoming trial. The EEG data was time-locked to the fixation cross colour-change which denoted task-instructions. After a variable foreperiod (1,000 – 2,000 ms) a target stimulus was presented and served as the imperative for response-cuing. Participants alternated between the two saccade tasks on a trial-by-trial basis in a pseudo-randomized order that could not be predicted.

As mentioned above, the white fixation cross was task-irrelevant; however, the subsequent presentation of the green or red fixation cross denoted the participant's required response: The green fixation cross indicated a saccade to the target's veridical location (i.e., a prosaccade), whereas the red fixation cross indicated a saccade to the target's mirror-symmetrical location (i.e., an antisaccade). Participants alternated between pro- and antisaccades in one of four pseudo-randomized task-switching schedules that could not be predicated (e.g., AABAABB….). All task-switching schedules contained 80 task-repetition (i.e., pro- or antisaccade preceded by its same task counterpart) and task-switch (i.e., prosaccade preceded by an antisaccade or vice versa) pro- and antisaccade trials resulting in 320 experimental trials. The visual field in which the target was presented was randomly selected on a trial-by-trial basis. As the first trial in the experiment was neither a task-repetition nor a task-switch trial, it was not included in subsequent analyses.

5.2.3 Electroencephalography (EEG) recording

Prior to data collection participants were fitted with a 64-electrode EEG cap. The electrodes were mounted in the standard 10-20 layout and were recorded using BrainVision PyCorder software (Version 1.0.4, Brainproducts GmbH, Munich, Germany) with a virtual ground built into the amplifier (reference-free acquisition). Electrooculograms were obtained by electrodes placed above and below the right eye and on the outer canthi of the left and right eyes. Electrical impedances for all electrodes were kept below 20kΩ at all times. The EEG data was sampled at 500 Hz, amplified (ActiCHamp, Revision 2, Brainproducts GmbH, Munich, Germany) and filtered through an antialiasing low-pass filter of 8 kHz.

5.2.4 Data processing

Point of gaze data were filtered offline using a dual-pass Butterworth filter employing a low-pass cut-off frequency of 15 Hz. Filtered displacement data were used to compute instantaneous velocities via a five-point central finite difference algorithm. Acceleration data were computed similarly via the velocity data. Saccade onset was determined on the basis of velocity and acceleration values that exceeded 30°/s and 8,000°/s^2, respectively. Saccade offset was marked when saccade velocity fell below 30°/s for 15 consecutive frames (i.e., 30 ms). Trials displaying an anticipatory response (i.e., RT < 70 ms), a delayed response (i.e., RT > 700 ms) or missing data (e.g., blinks) accounted for 5.3% of trials were excluded from subsequent analysis.

For each participant the continuous EEG data were filtered offline through a phase shift-free Butterworth filter (0.1 – 20 Hz pass-band) and referenced to the two mastoid electrodes. Subsequent to this, 800 ms epochs of data (starting from 200 ms prior to fixation cross colour-change) were extracted from the continuous EEG signal for each trial and experimental condition (see above). Following the creation of epochs for all conditions, ocular artifacts were corrected via the algorithm described by Gratton and colleagues (1983). Next, the final 200 ms of the task-irrelevant white fixation cross immediately preceding the conditional colour-change were used to baseline the EEG epochs. Finally, an artefact rejection algorithm discarded epochs wherein the change in voltage at any channel exceeded 10 µV per millisecond or the change across the entire epoch (maxima – minima) was greater than 100 µV (2.3 % of total trials).

ERP waveforms were created by averaging the epoched EEG data as a function of experimental condition (i.e., task-switch / task-repetition pro- and antisaccades) for each electrode channel and participant. In order to define the P3, we examined difference waveforms (as recommended by Luck, 2005) computed by subtracting within task-type (task-repetition prosaccade minus task-switch prosaccade and task-repetition antisaccade minus task-switch antisaccade). Based on previous literature (Polich, 2007) and on an examination of the within-task difference waveforms (Figure 5-3a), the P3 was defined as the mean voltage 350 to 400 ms following the fixation cross colour-change on each of the conditional ERP waveforms. Our analysis focused on electrode channel Cz, where the prosaccade difference waveform was maximal (see Figure 5-3b).

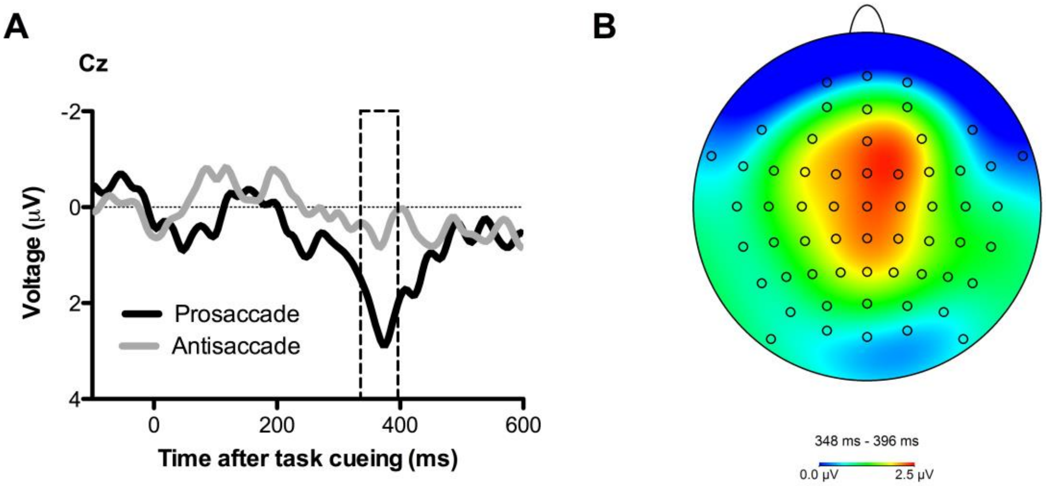

Figure 5-3: A: Difference waveforms computed by subtracting within task-type (task-repetition prosaccade minus task-switch prosaccade and task-repetition antisaccade minus task-switch antisaccade). Dashed line shows the window of analysis: 350 – 400 ms. B: Scalp topography for the prosaccade difference waveform, maximal at electrode site Cz.

5.2.5 Dependent variables and statistical analysis

Dependent variables included mean RT (time between target onset and saccade onset), the number of directional errors (a saccade initiated and/or executed to the incorrect goal-location), the accuracy (i.e., signed error relative to veridical target location) and variability of saccade endpoints in the primary movement direction (i.e., horizontal), as well as P3 amplitude. Dependent variables were submitted to 2 (task: prosaccade, antisaccade) by 2 (task-transition: task-switch, task-repetition) repeated-measures ANOVA. To determine whether there were task-specific switch-costs, reliable interactions were decomposed via within-task comparisons; that is, we compared: (1) task-switch prosaccades with task-repetition prosaccades, and (2) task-switch antisaccades with task-repetition antisaccades (see Kiesel et al., 2010).

5.3 Results

5.3.1 Behavioural data

Analysis of RT yielded a main of task, $F(1,13) = 74.23$, $p < 0.001$, task-transition, $F(1,13) = 9.72$, $p < 0.01$, and their interaction, $F(1,13) = 21.63$. Figure 5-4 shows that prosaccade task-switch trials (227 ms, SD = 46) produced longer RTs than their task-repetition counterparts (206 ms, SD = 34), $t(13) = 4.33$, $p < 0.001$, whereas antisaccade task-switch (289 ms, SD = 40) and task-repetitions (289 ms, SD = 34) trials did not reliably differ, $t(13) = 0.06$, p = n.s.

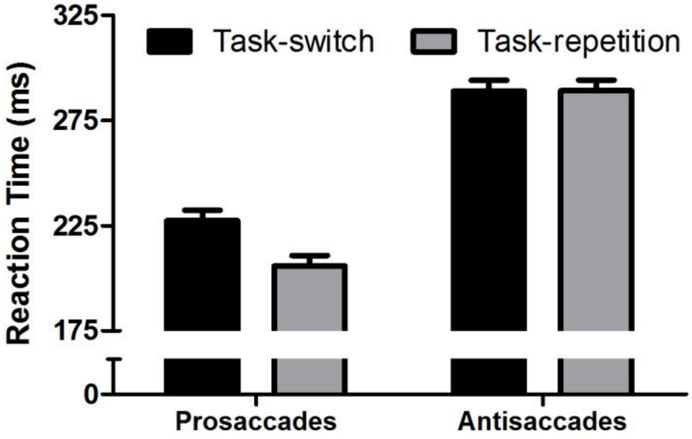

Figure 5-4: Reaction time data for pro- and antisaccade as a function of task-switch and task-repetition trial-types. Results demonstrate the unidirectional prosaccade switch-cost. Error bars represent within-participant 95% confidence intervals (Loftus and Masson, 1994).

Analysis of saccade directional errors yielded a main effect of task, F(1,13) =18.26, $p < 0.001$, and task-transition, F(1,13) = 14.05, $p < 0.01$. More directional errors were associated with antisaccades (7.0, SD = 4.75) than prosaccades (3.21, SD = 3.06), and more errors were associated with task-switch (6.71, SD = 4.61) than task-repetition (3.50, SD = 3.57) trials.

Analysis of saccade accuracy and variability yielded main effects of task, Fs(1,13) = 13.54 and 47.81, respectively for accuracy and variability, ps < 0.01. Prosaccade endpoints were more accurate (-0.8°, SD = 1.7) and less variable (1.7°, SD = 0.5) compared to antisaccades (accuracy: -2.4°, SD = 1.8; variability: 2.5°, SD = 0.6).

5.3.2 P3 amplitude time-locked to task-instruction

Analysis of the P3 amplitude yield main effects of task, F(1,13) = 5.0, $p < 0.05$, task-transition, F(1,13) = 9.58, $p < 0.01$, and their interaction, F(1,13) = 6.49, $p < 0.05$. Task-switch prosaccades (2.13 μV, SD = 3.31) and task-repetition prosaccades (4.59 μV, SD = 3.56), t(13) = 4.05, $p < 0.05$ produced different P3 amplitudes, whereas task-switch (1.94 μV, SD = 3.80) and task-repetition (2.44, SD = 3.74) antisaccades produced P3 amplitudes that did not reliably differ, t(13) = -0.81, p = n.s. Moreover, and as outlined in the Introduction, our primary objective was to determine whether the unidirectional prosaccade switch-cost arises from an interially persistent non-standard task-set associated with a preceding antisaccade. In other words, we sought to determine whether the P3 amplitude associated with task-switch prosaccades was comparable to task-switch and task-repetition antisaccades. In addressing this issue we first note that the EEG waveforms shown in Figure 5-5 qualitatively demonstrates that task-switch prosaccades as well as task-switch and task-repetition antisaccades produced comparable amplitudes at the P3 epoch and that these amplitudes differed from task-repetition prosaccades. Moreover, we addressed this issue quantitatively by contrasting the P3 amplitudes between: (1) task-repetition antisaccades and task-switch prosaccades and, (2) task-repetition prosaccades and task-switch antisaccades. The P3 amplitudes for task-repetition antisaccades and task-switch prosaccades did not reliably differ, $t(13) = 0.74$, p = n.s., whereas a difference was observed between task-repetition prosaccades and task-switch antisaccades, $t(13) = 2.90$, $p < 0.05$.

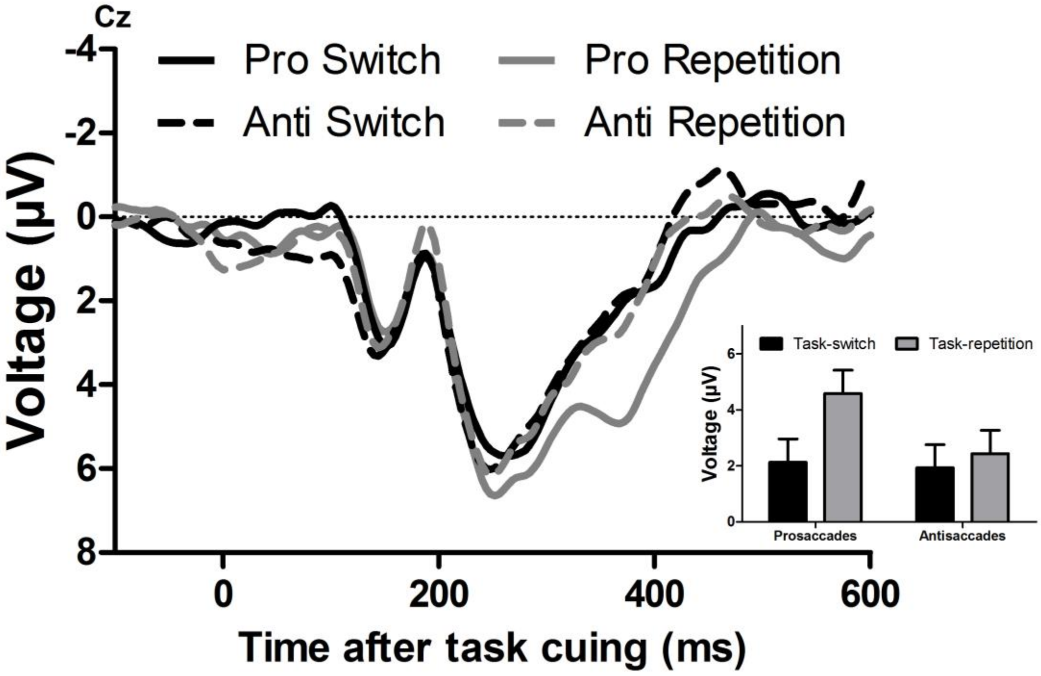

Figure 5-5: Grand averaged waveforms – time-locked to task-cuing – for each of the four trial-types. Task-switch prosaccades as well as task-switch and task-repetition antisaccades exhibited comparable P3 amplitudes that were different from task-repetition prosaccades. The inset panel represents mean P3 amplitude for each of the four trial-types. Error bars on the inset panel represent within-participant 95% confidence intervals (Loftus and Masson, 1994).

5.4 Discussion

5.4.1 Pro- and antisaccade behaviour in oculomotor task-switching

The behavioural findings from this experiment were that antisaccades elicited longer RTs, more directional errors, and were associated with less accurate and more variable endpoints than their prosaccade counterparts. These results are in accord with an extensive literature and are taken as evidence that antisaccades require the top-down and time-consuming processes of response suppression and vector inversion (see Munoz & Everling, 2004). Moreover, the present findings show that the completion of an antisaccade selectively delayed the RT of a subsequent prosaccade; that is, results demonstrate the unidirectional prosaccade switch-cost (Chan & DeSouza, 2014; DeSimone et al., 2014; Weiler & Heath, 2012a; Weiler & Heath, 2012b; Weiler et al., 2014; Weiler & Heath, submitted). As well, results showed that pro- and antisaccade endpoint accuracy and variability were not modulated across task-switch and task-repetition trials. The results for saccade execution (i.e., endpoint accuracy and variability) are notable because they demonstrate that the unidirectional prosaccade switch-cost is limited to response planning.

5.4.2 Antisaccades delay the updating of SR relations: Electrophysiological evidence of a persistent task-set

The primary objective of this study was to test the task-set inertia hypothesis' contention that the prosaccade switch-cost results from a persistently active non-standard task-set. To address that issue, we measured the P3 amplitude across pro- and antisaccade task-switch and task-repetition trials. Notably, we time-locked our EEG data to a task-cuing stimulus (i.e., fixation cross colour-change) that provided participants with advanced information regarding the nature (i.e., pro- vs. antisaccade) of an upcoming trial (see Figure 5-2) (see also Barcelo et al., 2008; Barcelo et al., 2002, Nicholson et al., 2003). Figure 5-5 shows that task-switch prosaccades as well as task-switch and task-repetition antisaccades elicited comparable P3 amplitudes, and that the former trial-types differed from task-repetition prosaccades. These results are notable for at least three reasons. First, the results show that the preparatory period (i.e., interval from task-cuing to response-cuing) of task-switch prosaccades was associated with the same underlying neural processes as that associated with task-switch and task-repetition antisaccades and was distinct from that associated with task-repetition prosaccades. Second, the ERP findings in combination with the selective increase in RT for task-switch prosaccades provides convergent support for the task-set inertia hypothesis' assertion that a prosaccade switch-cost arises from the persistent activation of a non-standard task-set. Third, the fact that task-repetition prosaccades produced a P3 amplitude that was distinct from task-switch antisaccades and that RTs for the latter task-type did not show evidence of a switch-cost further indicates that a task-set associated with a response with dominant SR mappings (e.g., a prosaccade) does not influence adopting the task-set for a subsequent response.

Two additional aspects of the EEG results should be addressed. First, recall that participants were provided a task-irrelevant white fixation cross and following a stable foreperiod its colour was changed in order to provide task-relevant instructions (i.e., green: prosaccade; red: antisaccade). Notably, the EEG data were time-locked to the onset of the fixation cross colour-change. As such, it could be argued that the modulation of the P3 amplitude observed here reflects the fixation cross colour-change because the waveform has been shown to be sensitive to the presentation of novel or unexpected stimuli (i.e., *oddball effect*; for review see Friedman et al., 2001). However, such an explanation is countered by the fact that each colour-change was unexpected given that pro- and antisaccades was pseud-randomized and could not be predicted by the participants. Thus, our observation of a *selective* modulation of the P3 as a function of the saccade executed on the previous trial indicates that the results are due to task-set updating – or lack thereof – and not an oddball effect. Second, we note that there was a reduction in the amplitude of the P3 for task-switch antisaccades relative to task-repetition prosaccades – a change in the waveform that we have attributed to the immediate adoption of an antisaccade task-set required to complete the upcoming trial. Indeed, we raise this as an issue because some work in the cognitive task-switching literature has shown that ‘switch’ trials are associated with an increase in the amplitude of the P3 (e.g., Gajewski & Falkenstein, 2011). Notably, however, results from the motor control literature indicate that the P3 amplitude is reduced for antipointing relative to propointing (Heath et al., 2011). Thus, in terms of goal-directed actions, the amplitude of the P3 may reflect the task-set that specifies the movement vector transformation (i.e., SR rules) that is to be implemented for the upcoming response.

5.5 Conclusion

We showed that the completion of an antisaccade selectively increased the RT of a subsequent prosaccade; that is, results demonstrated a unidirectional prosaccade switch-cost. Importantly, the P3 amplitude associated with task-switch prosaccades was comparable to task-switch and task-repetition antisaccades and the aforementioned trial-types were reliably different from task-repetition prosaccades. Thus, the concurrent behavioural and ERP findings suggest that selective increase in RTs for task-switch prosaccades relates to the persistent activation of a non-standard antisaccade task-set.

5.6 References

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Chapter 6

General Discussion

6.1 Summary of dissertation studies

The objective of this dissertation was to further describe and ultimately provide a mechanistic explanation for the unidirectional prosaccade switch-cost (Weiler and Heath, 2012a; Weiler and Heath, 2012b). Chapter Two through Chapter Five contain distinct – but interrelated – experiments that were completed in order to meet that objective.

The experiment contained in Chapter 2 had two goals. The first goal was to determine whether repetitive antisaccade execution increases the magnitude of the prosaccade switch-cost. Notably, this work was motivated by Wylie and Allport's (2000) work showing that increasing the number of consecutive non-standard colour-naming trials of the Stroop task increased the magnitude of the RT switch-cost imparted on the standard word-reading response. The general pattern of results reported by Wylie and Allport, however, does not hold true for task-switching in oculomotor control. Indeed, Chapter Two showed that the completion of two or four antisaccades imparted a comparable prosaccade RT switch-cost – a finding which indicates that repetitive antisaccade execution does not engender additive inhibitory effects within the oculomotor system (Figure 2-2). The secondary goal of Chapter 2 was to identify the specific locus of the unidirectional prosaccade switch-cost; that is, I sought to determine whether the *relative* RT difference between task-switch and task-repetition prosaccades was attributed to a lengthening or shortening of RT associated with the respective former or latter trial-type. As such, I compared pro- and antisaccade task- switch and repetition trial-types with their same-task counterparts completed in their own block of trials. Results demonstrated that antisaccade trial-types (i.e., task-switch, task-repetition and blocked) elicited compared RTs. Notably, the RTs of task-switch prosaccades were longer than blocked condition prosaccades, whereas the RT of blocked and task-repetition prosaccades did not reliably differ (Figure 2-3). Such a finding is important because it demonstrates that the completion of an antisaccade lengthens the RT of a subsequent (i.e., task-switch) prosaccade (Weiler & Heath, 2014).

I sought to extend on the results observed in Chapter Two by determining what aspect of an antisaccade was responsible for lengthening the RT of the next prosaccade trial. Notably, work by Pouget and colleagues (2011) demonstrated that suppressing a stimulus-driven prosaccade in response to a stop-signal resulted in a lengthened RT on the subsequent prosaccade trial, and that the lengthened RT was linked to a delay in the accumulation of neural activity that supports prosaccade execution. Thus, I hypothesized that response suppression – a top-down requirement of the antisaccade task – was responsible for the unidirectional prosaccade switch-cost. To test this hypothesis, in Chapter 3 I had participants alternate between pro- and antisaccades in one block of trials, whereas in another block participants completed only prosaccades trials that were randomly and infrequently interleaved with no-go catch-trials. Results demonstrated that the completion of an antisaccade and no-go catch-trial imparted a similar RT ‘cost’ on a subsequently completed prosaccade (Figure 3-2). In turn, I concluded that the unidirectional prosaccade switch-cost cannot be attributed to the antisaccade task, *per se*; rather, I proposed that the top-down process of response suppression engenders a residual inhibition of the oculomotor networks involved in the planning of stimulus-drive prosaccades (i.e., the oculomotor inhibition hypothesis; Weiler et al., 2014).

The results from Chapter 3 indicated that the unidirectional prosaccade switch-cost is attributed to response suppression. However, I failed to consider an alternative option that the cognitive task-switching literature has frequently used to explain unidirectional switch-costs (e.g., Allport et al., 1994; Meuter & Allport, 1999). More specifically, Allport et al's task-set inertia hypothesis asserts that non-standard and cognitively demanding tasks engender task-rules (i.e., a task-set) that persist and delay the planning of a subsequent standard and well-learned response. In other words, the task-set inertia hypothesis predicts the unidirectional prosaccade switch-cost. Thus, the response suppression requirements of antisaccades and no-go catch-trials may not have accounted for the delay in RT of subsequent prosaccades; rather, the non-standard task-set associated with the cognitively demanding antisaccade (i.e., look mirror-symmetrical target) or no-go catch-trial (i.e., do not look at the target) may have persisted and imparted a RT cost on the next prosaccade trial. The goal of Chapter 3 was to determine which hypothesis (i.e., oculomotor inhibition or task-set inertia) provided the most parsimonious account of the unidirectional prosaccade switch-cost. Participants alternated between pro- and antisaccades wherein task-instructions were provided prior to (i.e., classic cuing) or concurrent with (i.e., delayed cuing) response cuing. The two different cuing paradigms employed in this chapter are noteworthy because they enable an assessment of whether response suppression (i.e., oculomotor inhibition) or non-standard task-rules (i.e., task-set inertia) account for the prosaccade switch-cost. Indeed, if the former accounted for the unidirectional prosaccade switch-cost, then delayed condition prosaccades – which require response suppression for their successful execution (see Heath et al., 2011; Olk & Kingstone, 2003) – should have lengthened the RT of subsequent prosaccades. This, however, was not observed; rather, only trial-types with non-standard task-rules (i.e., classic and delayed antisaccades) imparted a RT cost on subsequently completed prosaccades (Figure 4-5). Thus, results demonstrated that the oculomotor inhibition hypothesis does not account for the unidirectional prosaccade switch-cost. Instead, the results of the Chapter 4 are in line with the predictions of the task-set inertia hypothesis; that is, the results indicate that the task-set associated with the non-standard antisaccade persist and delays the planning of a standard response that entails direct SR compatibility.

A corollary prediction of the task-set inertia hypothesis is that the antisaccade task-set should persist into the preparatory interval (i.e., time between task- and response cuing) of the following prosaccade trial. In other words, at task-cuing prosaccade task-switch trial-types should be associated with the same task-set engendered to meet the demands of the previously executed antisaccade response (Figure 5-1). In Chapter 5 I tested this prediction by examining the behavioural responses and an event-related brain potential (ERP) evoked when participants alternated between pro- and antisaccades. Specifically, I measured the amplitude of the P3 – time-locked to task-cuing – because this ERP provides the neural correlate of the task-set required for a to-be-completed response (Barceló et al, 2008; Barceló et al, 2002; Nicholson et al, 2005). As expected, the behavioural results yielded a reliable unidirectional prosaccade switch-cost. Moreover, there was a reliable modulation of the P3 amplitude when trials were switched from a prosaccade to an antisaccade; however, no reliable modulation was observed when switching from an antisaccade to a prosaccade (Figure 5-5). That prosaccades completed after antisaccades exhibited an increase in RT and demonstrated a P3 amplitude comparable to those of antisaccades provides compelling evidence that a persistently active antisaccade task-set is the mechanism that accounts for the unidirectional prosaccade switch-cost.

6.2 The dorsolateral prefrontal cortex implements the antisaccade task-set

Chapters Two through Chapter Five provide evidence that the unidirectional prosaccade switch-cost is best explained by a persistently active antisaccade task-set. This proposal leads to fundamental question that remains to be addressed: What is the neural mechanism that supports a so-called antisaccade task-set? In other words, how or where (or both) is neural activity modulated so that an oculomotor response with non-dominant SR rules can be executed? Indeed, this is a fundamental consideration as it directly reflects how a ‘persistently active antisaccade task-set’ may influence subsequent oculomotor responses.

A long-held view in oculomotor control is that the dorsolateral prefrontal cortex is responsible for inhibiting the visual grasp reflex (Guitton et al., 1985; Pierrot-Deseilligny et al, 1991). This view was based on evidence from clinical neuropsychology which has shown that patients with prefrontal lesions display an increased proportion of antisaccade directional errors compared to cortically intact controls (Pierrot-Deseilligny et al, 1991). Moreover, this position was strengthened by neuroimaging and single-cell recording studies which reported that the completion of a antisaccade is related to increased activity within the dorsolateral cortex and to a respective increase and decrease in the activity of collicular fixation and build-up saccade neurons (Brown et al., 2007; Ford et al., 2005; Everling et al., 1998; Everling et al., 1999). Recent work tested this inhibitory control model by transiently deactivating the unilateral aspect (i.e., single hemisphere) of the dorsolateral prefrontal cortex. Indeed, if the dorsolateral prefrontal cortex is responsible for inhibiting reflexive stimulus-driven saccades, then the unilateral deactivation of this structure should attenuate inhibitory control performance within the ipsilateral superior colliculus. This, however, was not observed; rather, the unilateral deactivation of the dorsolateral prefrontal cortex delayed the onset of ipsilateral collicular saccade neuron activity (Johnston et al., 2014). To account for this finding, Everling and Johnston (2013) put forth a heterodox proposal which asserts that the dorsolateral prefrontal cortex is not responsible for oculomotor inhibitory control. Instead, Everling and Johnston propose that the dorsolateral prefrontal cortex provides excitatory input to the superior colliculus to modulate activity of fixation and saccade neurons in order to meet the demands of the upcoming goal-directed saccade. In other words, the signals projecting from the dorsolateral prefrontal cortex to the superior colliculus reflect the task-set required for the upcoming response.

The proposal put forth by Everling and Johnston (2013) asserts that the dorsolateral prefrontal cortex engenders an antisaccade task-set by modulating collicular neuron activity to meet the demands for the upcoming antisaccade trial. Thus, a persistently active antisaccade task-set – evidenced by the increased RT of task-switch prosaccades and the ERP results reported in Chapter 5 – may reflect sustained output from the dorsolateral prefrontal cortex to increase and decrease the activity of collicular fixation and buildup neurons, respectively. It is, however, important to note that there were prosaccade error switch-costs observed in Chapter 2, 4 and 5 of this dissertation in addition to RT switch-costs; that is, the results of my work also show that the completion of an antisaccade increased the proportion of directional errors made during subsequent prosaccade trials. Such a finding is difficult to reconcile by the simple assertion that the dorsolateral prefrontal cortex selectively modulates activity within the superior colliculus as a means of imparting an antisaccade task-set. Thus, I propose that the dorsolateral prefrontal cortex may also influence cortical regions associated with sensorimotor transformations (e.g., lateral intraparietal area; Zhang & Barash, 2000) to engender an antisaccade task-set, and that this persistent output results in the occasional execution of a prosaccade directional error.

6.3 Conclusion

The goal of this dissertation was to further describe and ultimately provide a mechanistic explanation for the unidirectional prosaccade switch-cost. The results of the four experiments I conducted coalesce and provide evidence that the prosaccade switch-cost is attributed to a persistently active antisaccade task-set. Current research suggests that the dorsolateral prefrontal cortex is the cortical region responsible for imparting an antisaccade task-set on structures which comprise the oculomotor system. Thus, I propose that the persistently active antisaccade task-set reflects sustained antisaccade task-set output from the dorsolateral prefrontal cortex.

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Appendices

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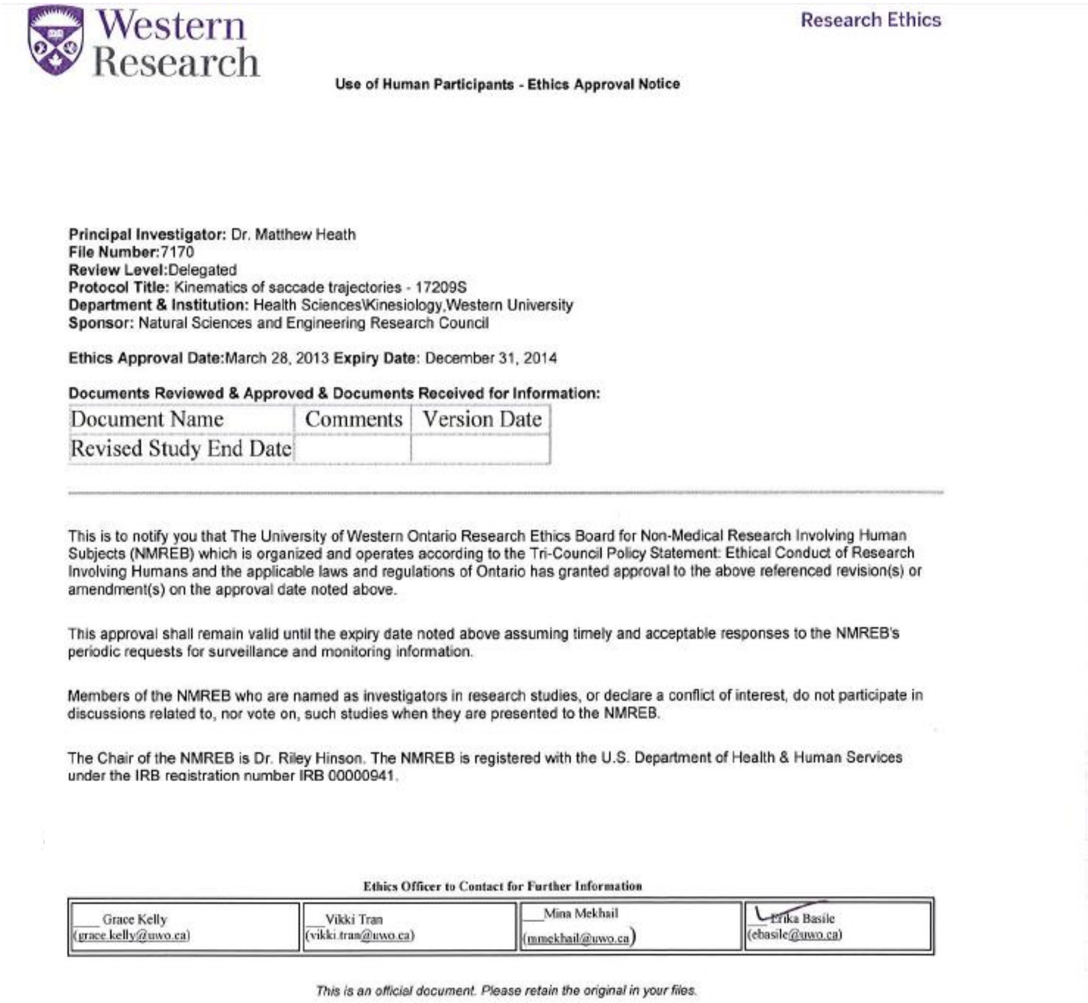

Western Research

Research Ethics

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Matthew Heath
File Number:7170
Review Level: Delegated
Protocol Title: Kinematics of saccade trajectories - 17209S
Department & Institution: Health Sciences\Kinesiology,Western University
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: March 28, 2013 **Expiry Date:** December 31, 2014

Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised Study End Date		

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Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is Dr. Riley Hinson. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Ethics Officer to Contact for Further Information

___ Grace Kelly (grace.kelly@uwo.ca)	___Vikki Tran (vikki.tran@uwo.ca)	___Mina Mekhail (mmekhail@uwo.ca)	✓ Erika Basile (ebasile@uwo.ca)

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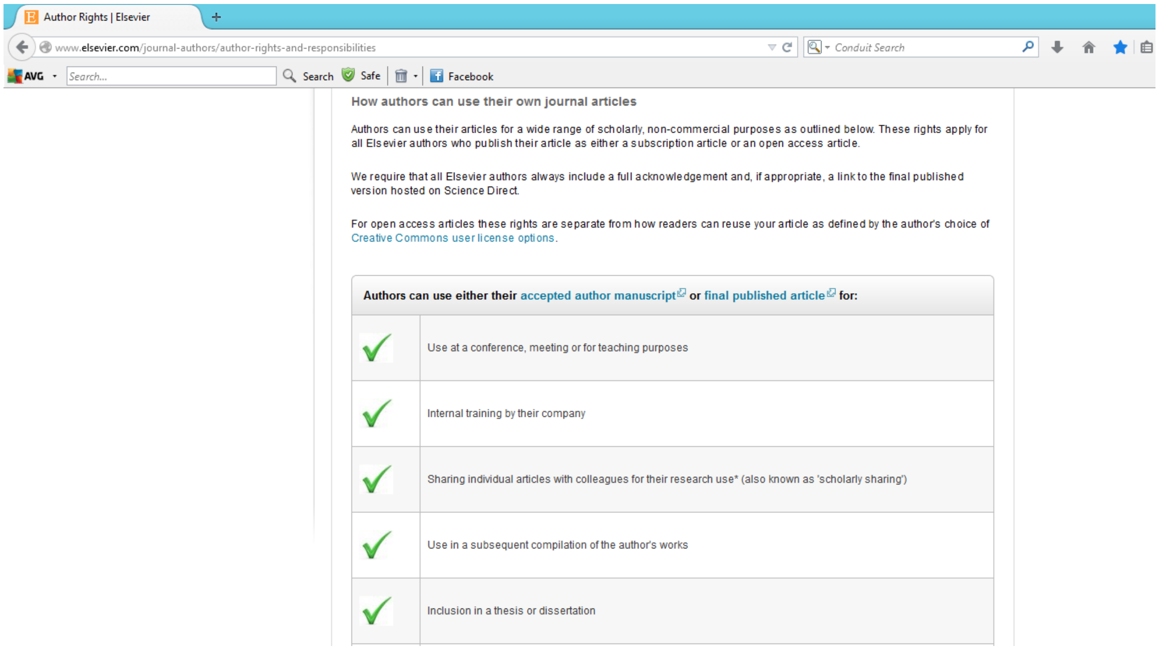

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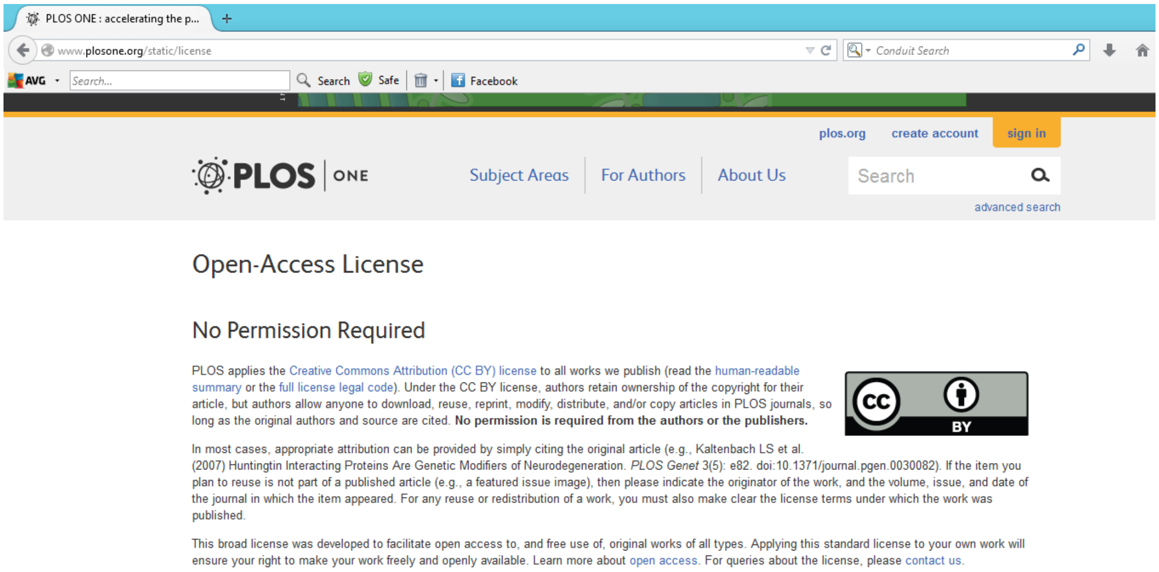

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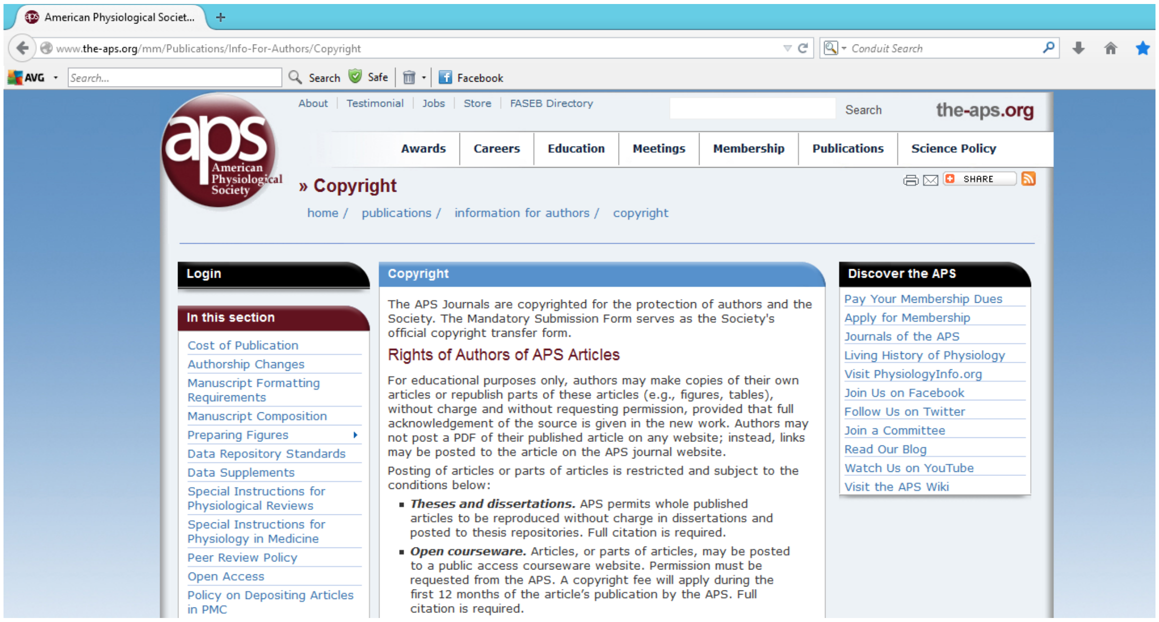

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Curriculum Vitae

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Heath, M., **Weiler, J.**, Marriott, K., & Welsh, T. 2011.Vector inversion diminishes the online control of antisaccades. *Experimental Brain Research, 209*, 117-127.

Manuscripts in Preparation

Weiler, J., Hassell, C., Heath, & M., Krigolson, O. Electroencephalography evidence of task-set inertia in oculomotor control: The unidirectional prosaccade switch-cost.

Weiler, J. The “New Statistic” for repeated measures ANOVAs: Interpretation of confidence intervals and null-hypothesis testing is equivalent. Letter to Editor of *Psychological Sciences*

Heath, M., Starrs, F., Macpherson, E., & **Weiler, J**. Saccade switch-costs are independent of the sensory modality that defines target location.

Weiler, J., & Heath, M. Behavioural aspects of saccades are sensitive to varying degrees of top-down control.

Reviewer for Academic Periodicals

Experimental Brain Research

Frontiers in Human Neuroscience

Oral Presentations

Canadian Society for Psychomotor Learning and Sport Psychology — Kelowna, October 2013
Task-switching in oculomotor control: What drives the prosaccade switch-cost?
(Frank Henry Young Scientist Presentation)

Oculomotor planning (deficits) in coronary artery disease and mild cognitive impairment

Southern Ontario Motor Behaviour Symposium — Toronto, May 2013
The residual effects of suppressing the oculomotor system

Canadian Society for Psychomotor Learning and Sport Psychology — Halifax, November 2012

The inhibition of oculomotor networks that delays prosaccade execution is not modulated by an increase in the number of previously completed antisaccades

Canadian Society for Psychomotor Learning and Sport Psychology Winnipeg, October 2011
Task switching modulates the online control of stimulus-driven saccades

Atlantic Provinces Exercise Scientists Oak Island, March 2007
The effects of sprint training on endurance performance

Poster Presentations

Vision Sciences Society St Pete Beach, Florida, May 2014
Weiler, J., Hassall C, Krigolson, O., & Heath, M. *Unidirectional switch-costs in oculomotor control is the result of stimulus-response updating: Evidence from electroencephalography*

Cognitive Neuroscience Society Boston, Massachusetts, April 2014
Weiler, J., & Heath, M. *Oculomotor task-switching: Unidirectional prosaccade switch-cost when alternating from a non-standard to a standard response*

Progress in Motor Control Montreal, July 2013
Weiler, J., & Heath, M. *Archetypal and cued antisaccades yield fundamentally different oculomotor behaviours*
DeSimone, J., **Weiler, J.**, & Heath, M. *Directionally correct antisaccades reduce the effectiveness and efficiency of stimulus-driven saccade networks*

Vision Sciences Society Naples, Florida, May 2013
Gillen, C., **Weiler, J.**, & Heath, M. *Target range properties do not influence oculomotor undershooting bias*

Vision Sciences Society Naples, Florida, May 2012
Weiler, J., & Heath, M. *The prior-antisaccade effect: Decoupling stimulus and response inhibits the planning and control of subsequent prosaccades*

Vision Sciences Society Naples, Florida, May 2011
Weiler, J., Holmes, S., Mulla, A., & Heath, M. *Distinct response latencies do not influence pro- and antisaccade trajectories*
Heath, M., **Weiler, J.**, Marriott, K., & Welsh, T. *The antisaccade task: dissociating stimulus and response influences online saccade control*

Canadian Society for Psychomotor Learning and Sport Psychology Ottawa, October 2010
Weiler, J., & Heath, M. *The manual following response: in-motion or stationary background cues do not influence the online control of reaching movements*

Vision Sciences Society Naples, Florida, May 2010
Weiler, J., Mulla, A., Bingley, T., & Heath, M. *Extrinsic manipulations of the mental number line do not impact SNARC-related influences of the planning and control of action*

Crossroads — Halifax, May 2007

Weiler, J., & Westwood, D. *Paradoxical effects of a three dimensional size contrast illusion on stepping height and perceived object size*

Awards and Scholarships

- Frank Henry Young Scientist Award – SCAPPS — October, 2013
- Western Kinesiology Research and Service Award — June 2013
- Ontario Graduate Scholarship — May 2012 – April 2014
- Queen Elizabeth II Graduate Scholarship in Science and Technology — May 2011 – April 2012
- The University of Western Ontario Graduate Studies Entrance Scholarship — September 2009
- Canadian Interuniversity Sport Top 8 Award — April 2007
    - Awarded to the top eight academic student-athletes in Canada

Teaching Experience

Guest Lecturer

Introduction to Psycho-motor Behaviour — *The University of Western Ontario*, April 4, 2014

- Topic: Neural Control of Balance
    - Class Enrollment: 500

Introduction to Psycho-motor Behaviour — *The University of Western Ontario*, February 5, 2014

- Topic: The Scientific Method
    - Class Enrollment: 500

Movement Neuroscience

- Topic: The Cerebellum — *The University of Western Ontario*, September 23, 2013
    - Class Enrollment: 50

A Survey of Physical Growth and Motor Development — *The University of Western Ontario*, October 12, 2012

- Topic: Central Nervous System
    - Class Enrollment: 100

Introduction to Psycho-motor Behaviour — *The University of Western Ontario*, February 6, 2012

- Topic: Information Processing
    - Class Enrollment: 500

Course Instructor

Volleyball Skills — *The University of Western Ontario*, Summer 2011

Teaching Assistant

Introduction to Psycho-motor Behaviour *The University of Western Ontario*, Spring 2010 & 2011

Movement Neuroscience *The University of Western Ontario*, Fall 2010 & 2011

Human Nutrition *Dalhousie University*, Spring 2007

Professional or Academic Membership

- Canadian Society for Psychomotor Learning and Sport Psychology 2009 – Present
- Vision Sciences Society 2009 – Present
- Cognitive Neuroscience Society 2013 – Present
- Society for Neuroscience 2013 – Present
- Society of Graduate Students, The University of Western Ontario 2009 – Present