



The unidirectional prosaccade switch-cost: Correct and error antisaccades differentially influence the planning times for subsequent prosaccades



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ABSTRACT

Antisaccades produce longer reaction times (RT) than their prosaccade counterparts and this latency increase has been linked to an oculomotor ‘pre-setting’ that prevents the evocation of a stimulus-driven prosaccade. Moreover, a consequence of oculomotor pre-setting is a lengthening of the RTs associated with a subsequent prosaccade. The goal of the present study was to determine whether the constituent elements associated with *planning* a correct antisaccade (i.e., response suppression and vector inversion) imparts a residual delay that inhibits the *planning* of a subsequent prosaccade. To that end, participants alternated between pro- and antisaccades in a pseudo-randomized task-switching schedule (e.g., AAB-BAAB...) and responses were cued via a paradigm that was designed to evoke frequent error antisaccades (i.e., a saccade initially, and incorrectly, planned to the target stimulus). Results showed that RTs for correct antisaccades were longer than error antisaccades and that prosaccades preceded by the former, but not the latter, trial-type were associated with a reliable increase in RT (i.e., prosaccade switch-cost). In other words, error antisaccades were associated with a failure to withhold a stimulus-driven prosaccade and did not delay the planning of a subsequent prosaccade. Based on these findings we propose that the prosaccade switch-cost is not related to an explicit awareness of task goals; rather, our results are consistent with the assertion that a consequence of response suppression and vector inversion is a residual inhibition of stimulus-driven oculomotor planning networks.

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1. Introduction

Prosaccades are rapid eye movements that are intended to bring a target of interest into central vision. Notably, the spatial coupling between stimulus and response for prosaccades allows for their mediation via direct retinotopically organized motor maps in the superior colliculus (for review see Wurtz & Albano, 1980). It is, however, important to recognize that a stimulus need not reflexively capture one's gaze; rather, a prosaccade can be suppressed in favor of a volitional saccade to another area of interest. Indeed, volitional saccades represent an important area of inquiry because they provide a basis for determining how top-down control influences the oculomotor system's ability to efficiently and effectively execute a response. One paradigm that has been extensively used to examine the issue of top-down oculomotor control is the anti-saccade task. Indeed, the most frequently examined antisaccade

task involves a variant of the classic saccade paradigm whereby a participant is instructed to saccade mirror-symmetrical (i.e., 180° spatial transformation) to the location of a *single* and *exogenously* presented target. Results have shown that antisaccades produce longer reactions times (RTs) (Everling, Dorris, & Munoz, 1998; Hallett, 1978), increased directional errors (Fischer & Weber, 1992; Forbes & Klein, 1996) and less accurate and more variable endpoints (Hallett, 1978; Heath et al., 2010) than their prosaccade counterparts. Furthermore, electrophysiological and neuroimaging evidence from humans and non-human primates has linked the aforementioned behavioral ‘costs’ to a two-component process requiring: (1) the inhibition of a stimulus-driven prosaccade (i.e., response suppression), and (2) the *visual* remapping of target properties (i.e., vector inversion) (for review see Munoz & Everling, 2004).

The preparatory phase of the antisaccade task has been related to an increased level of activation within the “classical saccade networks” (i.e., frontal eye field, supplementary eye field, and lateral intraparietal area) (Brown, Vilis, & Everling, 2007; DeSouza, Menon, & Everling, 2003; Ford et al., 2005) as well as an increase in the activation of collicular fixation neurons and a decrease in

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the activation of collicular build-up neurons (Everling et al., 1999). In particular, Everling and colleagues (Brown, Vilis, & Everling, 2007; Everling & DeSouza, 2005; see also Schlag-Rey et al., 1997) proposed that the modulation of oculomotor networks during the preparatory period of the antisaccade is related to a *pre-setting* that inhibits the evocation of a stimulus-driven prosaccade (i.e., the visual grasp reflex: Pierrot-Deseilligny et al., 1995) and provides sufficient time to implement the constituent elements of the antisaccade task (i.e., response suppression and vector inversion).

A corollary prediction drawn from the pre-setting of antisaccades is a lingering inhibition of oculomotor planning mechanisms. Indeed, Barton and Manoach and their co-workers used a *cued-saccade* paradigm to demonstrate the consequence of switching between task-types in blocked (i.e., AABB) and randomized task-switching schedules (Barton et al., 2002; Barton, Goff, & Manoach, 2006; Cherkasova et al., 2002; Manoach et al., 2002; Manoach et al., 2007; see also Barton et al., 2006). In particular, their work provided participants with two continuously visible targets located left and right of a central fixation stimulus prior to response cuing. Notably, following a preview phase one of the targets was cued via a surrounding annulus. A priori participants were instructed to saccade to the cued (i.e., cued-prosaccade) or un-cued (i.e., cued-antisaccade) target. Results showed a reliable 'switch-cost' for prosaccades; that is, a prosaccade preceded by an antisaccade (i.e., prosaccade task-switch trial) elicited longer RTs than prosaccades preceded by their same task counterparts (i.e., prosaccade task-repetition trial). In addition, a 'paradoxical switch-benefit' was associated with antisaccades such that task-switch antisaccades (i.e., an antisaccade completed after a prosaccade) exhibited shorter RTs than their task-repetition counterparts (i.e., the second of two consecutively completed antisaccades). Further, fMRI work by Manoach et al. (2007) showed that the preparatory interval of pro- and antisaccades completed after an antisaccade were associated with reduced activity in bilateral frontal eye fields and the right supplemental eye field. Given these findings, Barton and Manoach and their co-workers proposed that the completion of an antisaccade results in a lingering inhibition of oculomotor networks that delays the planning of *all* subsequent saccades.

The work of Barton and Manoach and their group provides a direct demonstration that alternating between task-types can influence oculomotor planning times. Notably, however, an important consideration is that the cued-antisaccade paradigm used in their work may not require vector inversion (see also Edelman, Valenzuela, & Barton, 2006). Recall that in their paradigm both pro- and antisaccade target locations were visible prior to, and throughout a response. Thus, their antisaccade task may not require the visual remapping of the target's spatial properties (i.e., vector inversion); rather, the un-cued target may serve as the location for planning a veridical (antisaccade) movement endpoint.¹ As well, other work involving the continued presence of a target during response execution has revealed discrepant pro- and antisaccade RT switch-costs (Reuter et al., 2006; Olk & Jin, 2011). In addressing the aforementioned issues, Weiler and Heath (2012a, 2012b) examined oculomotor task-switching via a classic saccade paradigm wherein participants were instructed to pro- or antisaccade to a single, and briefly (i.e., 50 ms) presented target in blocked (e.g., AABB: Weiler & Heath, 2012a, 2012b) and pseudo-randomized (Weiler & Heath, 2012b) task-switching schedules. Indeed, in such a paradigm both pro- and antisaccade planning and execution occurs without the continued presence of a veridical target, and the antisaccade task

requires the obligatory remapping of the target's spatial location in mirror-symmetrical space. In line with Barton and Manoach's group, task-switch prosaccades elicited longer RTs than their task-repetition counterparts. In contrast, task-switch and task-repetition antisaccades exhibited comparable RTs: a finding that differs from the paradoxical switch-benefit observed by Barton and Manoach's group. In support of our results, Chan and DeSouza (2013) recently found that task-switching RT effects in the classic saccade paradigm were restricted to task-switch prosaccades. As such, results from the classic saccade paradigm indicate that the completion of an antisaccade selectively delays the planning of a to-be-completed prosaccade (i.e., the unidirectional prosaccade switch-cost). Based on this result, Weiler and Heath proposed an *oculomotor inhibition hypothesis* wherein the constituent elements of the antisaccade task (i.e., response suppression and vector inversion) imparts a residual inhibition that delays the planning mechanisms supporting stimulus-driven prosaccades. Indeed, the hypothesis contends that both response suppression and vector inversion contribute to the residual inhibition because each process requires the top-down and cognitive control of action (Rossetti et al., 2005). Notably, the hypothesis is drawn from the previously mentioned neuroimaging and electrophysiological evidence showing that an oculomotor pre-setting characterizes antisaccade performance (e.g., Brown, Vilis, & Everling, 2007). As well, the unidirectional nature of the hypothesis is derived from behavioral evidence showing that the active inhibition of a standard or familiar task (e.g., prosaccade) persists inertially following the planning of a non-standard (or unfamiliar) task, whereas no such persistence exists following the planning of a standard task (i.e., task-set inertia: see Allport, Styles, & Hsieh, 1994; see also Wylie & Allport, 2000).

The foundation for the oculomotor inhibition hypothesis is that the *planning* of an antisaccade (including response suppression and vector inversion) delays the *planning* of a subsequent prosaccade. Thus, it is proposed that the unidirectional prosaccade switch-cost should selectively manifest following the completion of a correct (i.e., a response planned and executed mirror-symmetrical to the target) but not an error antisaccade (i.e., a response planned and initially executed to the target and not its mirror-symmetrical location). Indeed, the basis for this assertion is that the pre-setting associated with the planning of a correct antisaccade produces a level of residual inhibition that delays the planning of a to-be-completed prosaccade. In contrast, an error antisaccade entails a reduced, or incomplete, level of pre-setting and therefore results in the evocation of a prosaccade; that is, the participant fails to suppress a stimulus-driven response (see Everling, Dorris, & Munoz, 1998). As a consequence, it is predicted that the planning for a subsequent prosaccade would not be subjected to a residual level of oculomotor inhibition.

The present investigation used the classic saccade paradigm to examine the proposal that the unidirectional prosaccade switch-cost manifests following a correct, but not an error, antisaccade. Of course, in accomplishing our objective we recognized that it was important to design a task-switching schedule and target presentation paradigm that elicited a sufficient corpus of error antisaccades. Thus, we sought to induce frequent error antisaccades by employing a pseudo-randomized pro- and antisaccade task-switching schedule wherein target stimuli were presented in a gap paradigm (i.e., fixation cross removed prior to target onset) paired with a task-irrelevant tone. Notably, increased antisaccade errors have been shown to occur when performed in an unpredictable as opposed to blocked presentation schedule (Olk & Kingstone, 2003), and saccade countermanding errors have been shown to increase under gap and task-irrelevant tone paradigms (for no-gap vs. gap paradigm see Fig. 1 of Munoz & Everling, 2004; for task-irrelevant tone paradigm see Colonius & Arndt, 2001; Corneil & Munoz, 1996). In terms of research predictions, if the oculomotor

¹ An anonymous reviewer indicated that antisaccades performed in a cued saccade-paradigm may require vector inversion because participants are responding to the position of the annulus and not the "markers" that serve as the location for the saccade endpoint. Notably, evaluation of this issue awaits a directed study contrasting task-switch costs in cued- and classic-saccade paradigms.

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