RESEARCH ARTICLE

Pro- and antisaccade task-switching: response suppression—and not vector inversion—contributes to a task-set inertia

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Abstract

Alternating between different tasks represents an executive function essential to activities of daily living. In the oculomotor literature, reaction times (RT) for a 'standard' and stimulus-driven (SD) prosaccade (i.e., saccade to target at target onset) are increased when preceded by a 'non-standard' antisaccade (i.e., saccade mirror-symmetrical to target at target onset), whereas the converse switch does not elicit an RT cost. The prosaccade switch-cost has been attributed to lingering neural activity—or task-set inertia—related to the antisaccade executive demands of response suppression and vector inversion. It is, however, unclear whether response suppression and/or vector inversion contribute to the prosaccade switch-cost. Experiment 1 of the present work had participants alternate (i.e., AABB paradigm) between minimally delayed (MD) pro- and antisaccades. MD saccades require a response *after* target extinction and necessitate response suppression for both pro- and antisaccades—a paradigm providing a framework to determine whether vector inversion contributes to a task-set inertia. In Experiment 2, participants alternated between SD pro- and MD antisaccades—a paradigm designed to determine if a switch-cost is selectively imparted when a SD and standard response is preceded by a non-standard response. Experiment 1 showed that RTs for MD pro- and antisaccades were refractory to the preceding trial-type; that is, vector inversion did not engender a switch-cost. Experiment 2 indicated that RTs for SD prosaccades were increased when preceded by an MD antisaccade. Accordingly, response suppression engenders a task-set inertia but only for a subsequent stimulus-driven and standard response (i.e., SD prosaccade). Such a result is in line with the view that response suppression is a hallmark feature of executive function.

Keywords Executive function · Oculomotor · Response suppression · Task-switching

Introduction

Activities of daily living require that we frequently alternate, or switch, between different tasks. For example, an airline pilot is required to provide yoke inputs to adjust an aircraft's attitude and monitor and complete other flight control functions such as ground communication. The ability to effectively fly a plane is therefore contingent upon the pilot's ability to efficiently 'switch' between different tasks. Notably, the executive demands imparted by a task can asymmetrically influence task-switching efficiency. In an original

demonstration of this principle, Allport et al. (1994) had participants alternate between the standard (i.e., word-naming) and non-standard (i.e., colour-naming) variants of the Stroop task using an AABB paradigm (i.e., A = word-naming, B = colour-naming). Reaction times (RTs) for word-naming trials were increased when preceded by a colour-naming trial (i.e., task-switch trials), whereas the converse switch did not influence RT. Moreover, RTs did not vary when word- and colour-naming trials were preceded by their same task-type (i.e., task-repeat trials). Allport et al. proposed that the non-standard stimulus–response (SR) relations associated with a colour-naming task require an executive-mediated 'task-set' that proactively interferes with the planning of a subsequent standard (i.e., word-naming) response (i.e., task-set inertia hypothesis). In turn, the hypothesis contends that a standard response does not elicit a switch-cost because it is implemented independent of an executive-mediated task-set. Support for the hypothesis has been garnered by neuroimaging

and electroencephalographic studies demonstrating that neural activity of the Stroop colour-naming task is increased—and dissipates more slowly—than the word-naming task (Li et al. 2012; Yeung et al. 2006; for meta-analyses, see Derrfuss et al. 2005).

An important consideration of the task-switching findings reported above is that the Stroop task requires non-executive demands such as language and colour processing and therefore does not provide for a goal-directed response associated with most activities of daily living. Accordingly, recent studies by our group (Heath et al. 2016; Weiler and Heath 2012a, b, Weiler and Heath 2014a, b; Weiler et al. 2015) and Barton, Manoach et al. (Barton et al. 2006; Cherkasova et al. 2002; Manoach et al. 2007) employed the pro- and antisaccade task-switching paradigm to examine the dynamics associated with switching from a standard to a non-standard task. A prosaccade is a standard task requiring a goal-directed eye movement (i.e., saccade) to a veridical target location. The overlapping SR spatial relations of prosaccades render motor output via direct retinotopic projections from the superior colliculus (SC) (Wurtz and Albano 1980) that operate largely independent of executive planning mechanisms (Pierrot-Deseilligny et al. 1995). In contrast, antisaccades are a non-standard executive task requiring the inhibition of a prosaccade (i.e., response suppression) and SR decoupling to generate a saccade mirror-symmetrical to a target (i.e., vector inversion). Antisaccades produce longer RTs (Hallett 1978) and increased endpoint error (Dafoe et al. 2007; Gillen and Heath 2014) than prosaccades and these behavioural 'costs' relate to the activation of an extensive frontoparietal executive network (for review, see Munoz and Everling 2004). Work has shown that task-switch prosaccades—but not task-switch antisaccades—are associated with an increase in RT and that such an effect is independent of: (1) whether task-types are presented in predictable (i.e., AABB: A = prosaccade, B = antisaccade) or unpredictable (i.e., AABABB….) trial sets and, (2) the number of antisaccades that preceded a task-switch prosaccade (e.g., Heath et al. 2016; Weiler and Heath 2012a, 2014a, Weiler et al. 2015). Moreover, Weiler et al. (2015) reported that the amplitude of the P300 event-related brain potential (ERP) for task-switch prosaccades was comparable to task-repeat and task-switch antisaccades and was different in amplitude from task-repeat prosaccades. In other words, results demonstrate a unidirectional prosaccade switch-cost and is a finding in line with the task-set inertia hypothesis' assertion that a non-standard task (i.e., antisaccade) engenders an executive task-set that persists inertially and proactively interferes with a subsequent standard task (i.e., prosaccade).

From previous work it is unclear whether one or both of the constituent executive demands of antisaccades (i.e., response suppression, vector inversion) contribute to a task-set inertia. This represents a salient issue because Allport

et al.'s (1994) original work proposed that the non-standard SR relations of the colour-naming Stroop task contribute to a task-set inertia. As such, the theory does not consider the possible role that suppressing a standard and stimulus-driven response contributes to a task-set inertia. To address that limitation, our group (Tari et al. 2019) employed an AABB paradigm wherein the same stimulus-driven (SD) (i.e., saccade at target onset) prosaccades employed in previous work were alternated with minimally delayed (MD) prosaccades. MD prosaccades are a non-standard task requiring that participants suppress a response cued by target onset and initiate their response only after target offset. MD prosaccades therefore require response suppression comparable to antisaccades (Knox et al. 2018; Wolohan and Knox 2014); however, they do not require vector inversion. In other words, the comparison of SD and MD prosaccade task-switch and task-repeat trials provide a basis for selectively examining whether response suppression contributes to a task-set inertia. Results showed that RTs for SD prosaccade task-switch trials were longer than their task-repeat counterparts, and that MD prosaccade task-switch and task-repeat trials did not differ. Based on this result, it was proposed that response suppression on its own can engender a task-set inertia. Furthermore, we note that such a result is in line with a recent computational study by Aponte et al. (2019) indicating that the cost of alternating from an antisaccade to a prosaccade is related to a process of inhibition.

What remains unclear is whether the antisaccade executive demands of SR decoupling (i.e., vector inversion) contribute to a task-set inertia. Here, we employed an AABB paradigm in separate experiments involving MD pro- and MD antisaccades (i.e., saccade mirror-symmetrical to a target at target offset) (i.e., Experiment 1), and SD pro- and MD antisaccades (i.e., Experiment 2). In Experiment 1, MD antisaccades were alternated with MD prosaccades because both tasks require response suppression; however, the former requires the executive component of vector inversion. Accordingly, if vector inversion contributes to a task-set inertia, then RTs for MD prosaccades should be increased when preceded by a MD antisaccade. Such a result would be in keeping with the task-set inertia hypothesis' assertion that the executive demands of decoupling SR relations proactively interferes with a response with a standard SR relationship. In Experiment 2, SD prosaccades were alternated with MD antisaccades to (1) determine whether a MD antisaccade contributes to a task-set inertia, and (2) establish that a task-set inertia influences a subsequent trial only when the response is stimulus-driven and only when the response entails a standard SR relationship.

Methods

Participants

Twenty participants (ten female, aged 19–25 years) from the University of Western Ontario community volunteered and completed both Experiments 1 and 2 of this investigation. All participants had normal or corrected-to-normal vision, self-reported right-hand dominance and indicated no previous neurological (including concussion) or neuropsychiatric diagnosis. Participants read a letter of information and gave informed written consent via a protocol approved by the Non-Medical Research Ethics Board, University of Western Ontario.
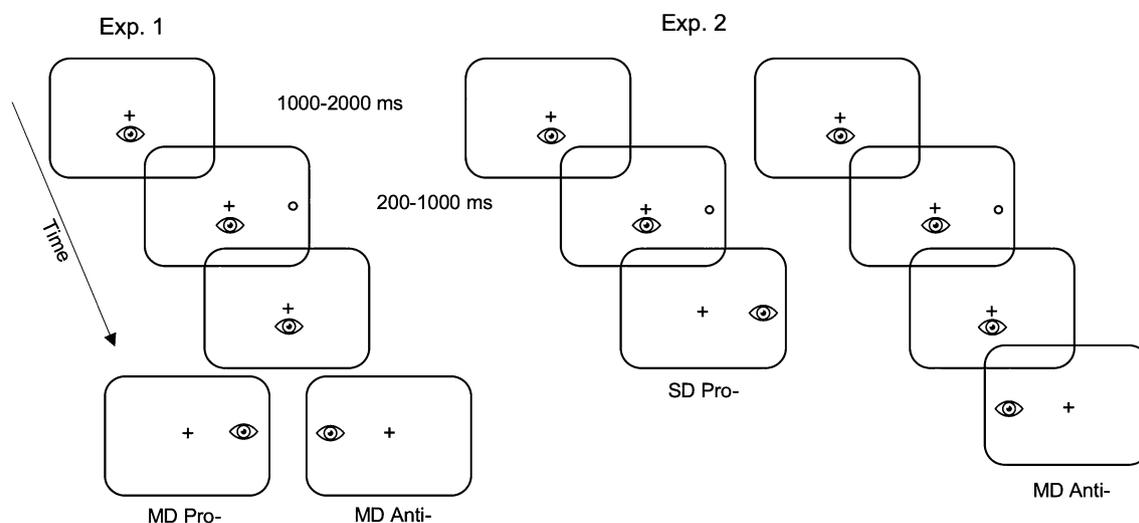
Experiment 1: minimally delayed (MD) pro- and antisaccades

Apparatus and procedures

Participants sat at a height adjustable chair in front of a table on which an LCD monitor (60 Hz, 8 ms response rate, 1280×960 pixels; Dell 3007WFP, Round Rock, TX) was placed 550 mm from the table's front edge. Participants placed their head in a head–chin rest and the gaze location of their left eye was tracked via a video-based eye-tracking system (EyeLink 1000 Plus, SR Research, Ottawa, ON) sampling at 1000 Hz. Prior to data collection, a nine-point calibration and validation of the viewing space were performed

(i.e., $< 1.0°$ of error for each calibration point). Computer events were controlled via MATLAB (R2018b, The Math-Works, Natick, MA, USA) and the Psychophysics Toolbox extensions (v 3.0) (Brainard 1997; Kleiner et al. 2007) including the EyeLink Toolbox (Cornelissen et al. 2002). The lights in the experimental suite were extinguished during data collection.

Visual stimuli were presented on a black screen (1 cd/m^2) and included a midline located fixation cross (1°) that appeared as green (132 cd/m^2) or red (50 cd/m^2). The colour of the fixation cross-indicated the nature of an upcoming trial. For half of the participants, the green and red fixation crossindicated a pro- (i.e., saccade to veridical target location) and antisaccade (i.e., saccade to a target's mirror-symmetrical location), whereas for the other half the converse mapping was used. The onset of a fixation cross-signalled participants to direct their gaze to its location. Following a stable gaze (i.e., $\pm 1.5°$ for 450 ms), a 1000–2000 ms uniformly distributed randomized foreperiod was initiated, after which a target stimulus (i.e., open white circle, 2.5° in diameter, 127 cd/cm^2) was presented for between 200 ms and 1000 ms (uniformly distributed) left or right of the fixation at an eccentricity of 13° (i.e., proximal target) or 17° (i.e., distal target). The fixation cross-remained visible for the trial duration (i.e., the overlap paradigm). Importantly, participants were instructed to initiate their instructed pro- or antisaccade *after* the target had been extinguished (i.e., minimally delayed (MD) saccade paradigm). The MD paradigm was used here because it required response suppression

Fig. 1 Schematic of the timeline of visual and motor events in Experiments 1 and 2. In Experiment 1, a target was presented for a uniformly distributed 200–1000 ms interval and participants initiated minimally delayed (MD) pro- and antisaccades only after the target was extinguished. In Experiment 2, stimulus-driven (SD) prosaccades required a response to be initiated at target onset. The procedures for the MD antisaccades in Experiment 2 were identical to Experiment 1. Although not depicted in this schematic, the colour of the fixation cross-indicated the nature of an upcoming trial. For simplicity, the schematic depicts a single target eccentricity to the right of fixation, whereas the experimental protocol employed two target eccentricities left and right of fixation

across pro- and antisaccades (see Fig. 1 for timeline of visual and motor events).

Participants completed a single block of 160 trials arranged in an AABB paradigm (e.g., A = MD prosaccade, B = MD antisaccade). Trials were equally divided into 80 task-switch (e.g., MD antisaccade on trial N and MD prosaccade on trial N-1) and 80 task-repeat (e.g., MD antisaccade on trial N and MD antisaccade on trial N-1) trials. Due to the nature of this work (Experiments 1 and 2), we did not provide participants a within-block rest break and report that the average inter-trial interval was 1120 ms—a range consistent with previous work by our group (Heath et al. 2012; Tari et al. 2019; Weiler and Heath 2014a). In addition, it is important to recognize that switch-costs have been reported even when between-trial intervals are self-paced (Wylie et al. 2011). The first trial in an experimental block was randomized (i.e., MD pro- or antisaccade) and because the first trial was neither a task-switch nor task-repeat it was not included in subsequent data analyses.

Experiment 2: minimally delayed (MD) antisaccades and stimulus-driven (SD) prosaccades

Apparatus and procedures

The same general methods used in Experiment 1 were used here with the exception that stimulus-driven (SD) prosaccades were alternated with MD antisaccades. SD prosaccades required that participants initiate their response immediately after target onset, whereas MD antisaccades required that a response be withheld until the target was extinguished (Fig. 1). The SD pro- and MD antisaccades of Experiment 2 were arranged in the same AABB paradigm as Experiment 1 and included the same number of task-switch (i.e., 80) and task-repeat (i.e., 80) trials.

Experiments 1 and 2: data reduction and dependent variables

Gaze position data were filtered offline using a dual-pass Butterworth filter with a low-pass cut-off frequency of 15 Hz. A five-point central-finite difference algorithm was used to compute instantaneous velocities and acceleration. Saccade onset was determined when velocity and acceleration exceeded 30°/s and 8000°/s^2, respectively. Saccade offset was determined when velocity fell below 30°/s for 40 ms. Trials resulting in a signal loss (e.g., an eye blink) or a directional error (i.e., a prosaccade instead of an instructed antisaccade or vice versa) were excluded from further data analyses and accounted for less than 6% of trials. Trials with a directional error were excluded because they are associated with planning mechanisms

distinct from their directionally correct counterparts (DeSimone et al. 2014). Furthermore, trials with an RT less than 50 ms (Wenban-Smith and Findlay 1991) or 2.5 times a participant- and condition-specific mean were excluded (i.e., 6% of trials), as were trials with an amplitude less than 2° or 2.5 times a participant- and condition-specific mean (i.e., < 3% of trials).

Dependent variables included RT (i.e., time from response cueing to saccade onset) and saccade gain (i.e., saccade amplitude/veridical target location). For Experiment 1, median RT (see Figs. 3 and 4 for skewness statistic) and mean gain values were examined via 2 (task: MD prosaccade, MD antisaccade) by 2 (task-transition: task-switch, task-repeat) fully repeated measures ANOVA. The same dependent variables were examined in Experiment 2; however, the variable 'task' in the ANOVA model included SD pro- and MD antisaccades. Simple effects were used to decompose significant interactions. For null findings, the two one-sided test (TOST: for tutorial see Lakens 2017) statistic was used to determine whether conditions were within—or outside—an equivalence boundary. The TOST effect size for RT ($d_z = .71$) was based on the average effect size (Perugini et al. 2014) determined from the pro- and antisaccade task-switching literature (DeSimone et al. 2014; Heath et al. 2015; Weiler and Heath 2012a, b, 2014a, b; Weiler et al. 2015). The aforementioned studies provided a basis for effect size computation via their report of t-ratios for contrasts between task-switch and task-repeat trials. For TOST contrasts of saccade gains we did not have a priori effect sizes and thus employed an effect size benchmark ($d_z = .50$) (Lakens 2017).

Results

Exemplar participant

Figure 2 presents an exemplar participant's position by time profiles for Experiment 1 MD pro- and antisaccade task-switch and task-repeat trials (see left panels) and Experiment 2 SD prosaccade and MD antisaccade task-switch and task-repeat trials (see right panels). The figure demonstrates that for this, participant RTs for MD pro- and antisaccade task-switch and task-repeat trials were comparable (i.e., Experiment 1). In turn, the participant demonstrated RTs for SD prosaccade task-switch trials that were longer—and exhibited greater trial-to-trial variability—than their task-repeat counterparts, whereas MD antisaccade task-switch and task-repeat trials showed comparable values (i.e., Experiment 2). The figure provides a graphic demonstration that this participant exhibited a selective switch-cost for SD prosaccades.
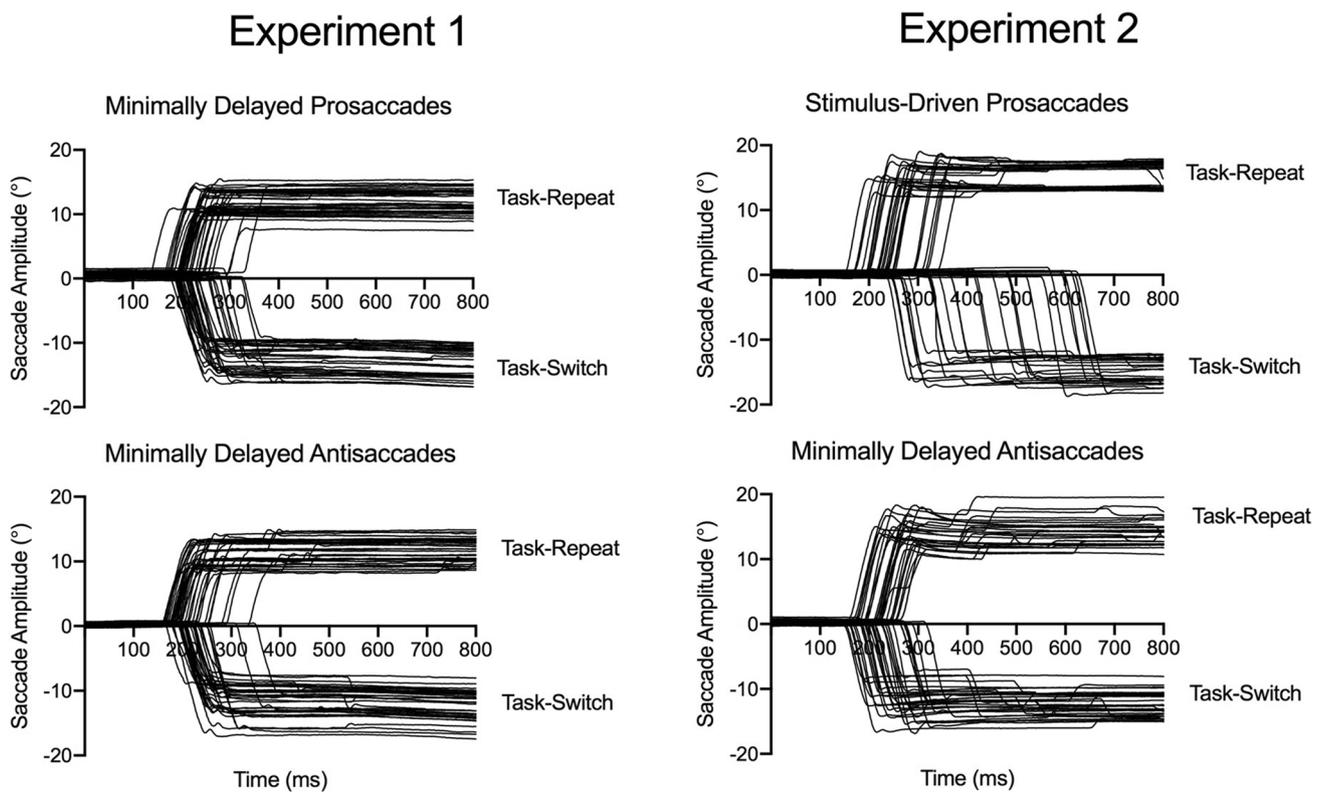
Fig. 2 Trial-by-trial saccade amplitude (°) by time (ms) displacement profiles for an exemplar participant's task-switch and task-repeat trials in Experiments 1 and 2. The ordinate in each panel represents response cuing, and for ease of presentation task-repeat and task-switch trials are depicted as positive and negative displacements, respectively

Experiment 1

Reaction Time The main panels of Fig. 3 show RT percent frequency histograms for MD pro- and antisaccade task-switch and task-repeat trials with the light and dark grey rectangles in each panel indicating the percentage of anticipatory (i.e., < 100 ms) and short-latency (i.e., 100 to < 200 ms) responses, respectively. The figure demonstrates that across all trial-types, a low frequency of anticipatory and short-latency responses occurred—a result attributed to the response suppression demands of each trial-type. The non-parametric Kolmogorov–Smirnov (KS) statistic indicated that MD prosaccade task-switch and task-repeat trials ($D = .02$, $p = .85$) and MD antisaccade task-switch and task-repeat trials ($D = .04$, $p = .40$) were derived from the same distribution. ANOVA results for RT did not produce main effects or an interaction, all $F(1,19) < 1$, $ps > .47$, all $\eta_p^2 < .03$ (Fig. 3a), and the TOST statistic indicated that MD prosaccade task-switch and task-repeat trials and antisaccade task-switch and task-repeat trials were within an equivalence boundary (all $t(19) = 2.65$ and 2.03, $ps = .008$ and .028).

Saccade Gain The grand mean for gain was 0.80 (SD = 0.18)—a result in keeping with the well-documented saccade undershooting bias (Becker 1989; Harris 1995).

The ANOVA for mean saccade gain did not reveal main effects or an interaction, all $F(1,19) < 2.11$, $ps > .16$, all $\eta_p^2 < .10$, and the TOST statistic indicated that MD antisaccade task-switch (0.77, SD = .22) and task-repeat (0.73, SD = .18) trials were within an equivalence boundary ($t(19) = 1.67$, $p = .028$), whereas MD prosaccade task-switch (0.83, SD = .13) and task-repeat (0.85, SD = .17) trials approached—but did not attain—a conventional level of significance for an equivalence boundary (t(19) = 1.36, $p = .094$).

Experiment 2

Reaction Time The main panels of Fig. 4 show RT percent frequency histograms for SD prosaccade and MD antisaccade task-switch and task-repeat trials. The figure demonstrates that SD prosaccade task-switch trials had fewer anticipatory and short-latency responses than their task-repeat counterparts, whereas for MD antisaccades the frequency of each trial-type did not vary across task-switch and task-repeat trials. The KS statistic indicated that SD prosaccade task-switch and task-repeat trials were from different distributions ($D = .33$, $p < .001$), whereas MD antisaccade task-switch and task-repeat trials were from the same

Experiment 1

Task- Switch

Task- Repeat

Minimally Delayed Prosaccades
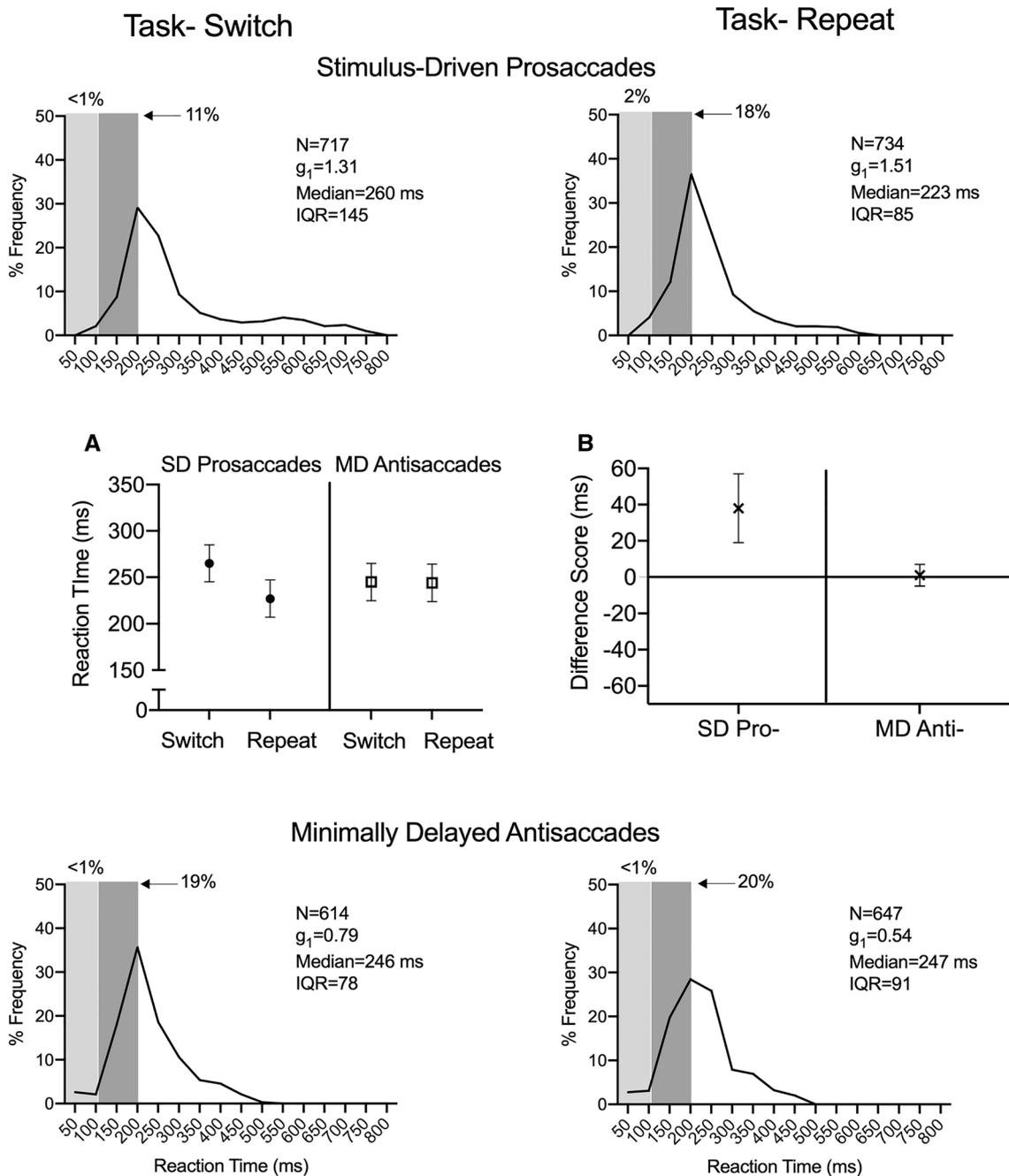

Minimally Delayed Antisaccades
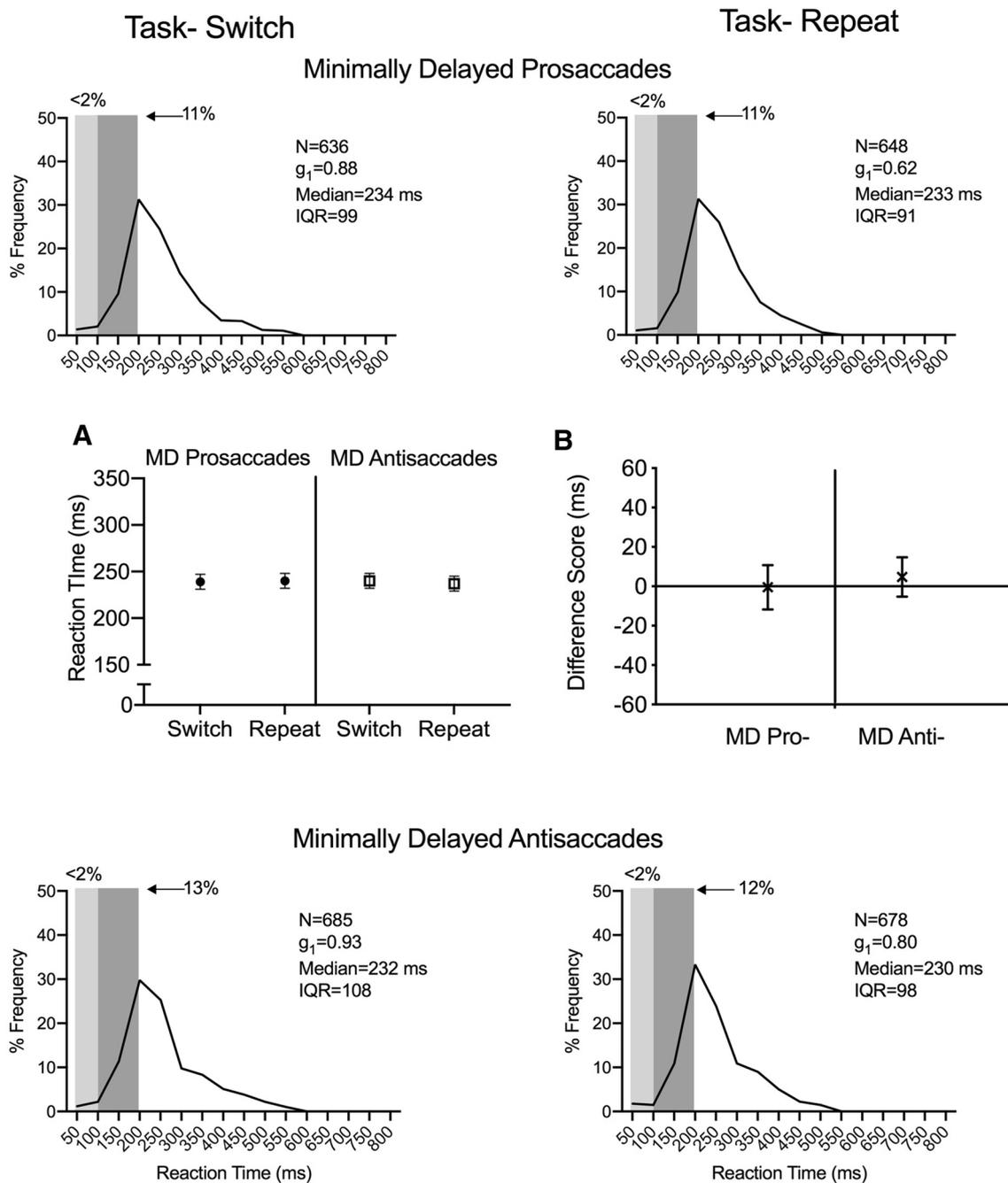
Fig. 3 *Experiment 1* The main panels show reaction time (RT: ms) percent frequency histograms for minimally delayed (MD) pro- (top panels) and antisaccade (bottom panels) task-switch and task-repeat trials. The light and dark grey rectangles in each main panel denote anticipatory (i.e., < 100 ms) and short-latency (i.e., 100–200 ms) responses, respectively. The left inset panel (3a) shows group mean

RTs for MD task-switch and task-repeat pro- and antisaccades with error bars representing 95% within-participant confidence intervals. The right inset panel (3b) shows RT difference scores (task-switch minus task-repeat) for MD pro- and antisaccades with error bars representing 95% between-participant confidence intervals

distribution ($D = .02$, $p = .58$). The ANOVA findings for RT yielded a main effect of task-transition, $F(1,19) = 9.68$, $p = .006$, $\eta_p^2 = .34$, and a task by task-transition interaction,

$F(1,19) = 9.31$, $p = .007$, $\eta_p^2 = .33$. Figure 4a shows that RTs for SD prosaccade task-switch trials were longer than their task-repeat counterparts ($t(19) = 3.14$, $p = .005$, $d_z = .70$). In

Experiment 2

Task- Switch

Task- Repeat

Stimulus-Driven Prosaccades

N=717
g_1=1.31
Median=260 ms
IQR=145

N=734
g_1=1.51
Median=223 ms
IQR=85

Minimally Delayed Antisaccades

N=614
g_1=0.79
Median=246 ms
IQR=78

N=647
g_1=0.54
Median=247 ms
IQR=91

Fig. 4 *Experiment 2* The man panels show reaction time (RT: ms) percent frequency histograms for stimulus-driven (SD) task-switch and task-repeat prosaccades (top panels) and minimally delayed (MD) task-switch and task-repeat antisaccades (bottom panels). The light and dark grey rectangles in each main panel denote anticipatory (i.e., < 100 ms) and short-latency (i.e., 100–200 ms) responses, respectively. The left inset panel (4a) shows group mean RTs for SD task-switch and task-repeat prosaccades and MD task-switch and task-repeat antisaccades with error bars representing 95% within-participant confidence intervals. The right inset panel (4b) shows RT difference scores (task-switch minus task-repeat) for SD pro- and MD antisaccades with error bars representing 95% between-participant confidence intervals. For this panel, the absence of overlap with an error bar with zero represents a reliable difference that can be interpreted inclusive to the null hypothesis

contrast, RTs for MD antisaccade task-switch and task-repeat trials did not reliably differ ($t(19) = 0.31$, $p = .76$, $d_z = 0.06$), and the TOST statistic demonstrated that values were within an equivalence boundary ($t(19) = 1.92$, $p = .035$).

Saccade Gain ANOVA findings for gain produced a main effect for task, $F(1,19) = 13.15$, $p = .002$, $\eta_p^2 = .41$: values were larger for SD prosaccades (0.88, SD = .08) than MD antisaccades (0.76, SD = 0.16). Results did not yield a main effect of task-transition or a task by task-transition interaction, all $F(1,19) < 1.24$, $ps > .27$, all $\eta_p^2 < .06$. The TOST statistic indicated that SD prosaccade task-switch (0.87, SD = .09) and task-repeat (0.88, SD = .06) trials were within an equivalence boundary ($t(19) = 1.81$, $p = .043$), whereas MD antisaccade task-switch (0.77, SD = .16) and task-repeat (0.74, SD = .16) trials were not ($t(19) = 1.32$, $p = .10$).

Experiments 1 and 2: participant-specific difference scores

We computed participant-specific RT difference scores (task-switch minus task-repeat) for MD pro- and antisaccades (Experiment 1) and SD pro-and MD antisaccades (Experiment 2) and present mean difference scores—and 95% between-participant confidence intervals—in Figs. 3b and 4b. The figures show that error bars for SD prosaccades (Fig. 4b) did not overlap with zero and thus indicates a reliable switch-cost inclusive to a test of the null hypothesis. In turn, error bars for all MD conditions (pro- and antisaccade: Figs. 3b and 4b) overlapped with zero; that is, results did not evince a switch-cost. Furthermore, for all MD conditions the TOST statistic (one-sample test) indicated that values were within an equivalence boundary with zero (all $t(19) > 1.86$, $ps < .039$).

Discussion

The present study sought to determine whether the executive demands of response suppression and/or SR decoupling (i.e., vector inversion) contribute to an oculomotor switch-cost, and determine whether such a switch-cost is expressed only when a stimulus-driven *and* standard response is preceded by a non-standard response.

Experiment 1 (MD pro- and antisaccades): no evidence that vector inversion contributes to a task-set inertia

Previous work reported that MD prosaccades produce RTs that are longer than their SD counterparts (Knox et al. 2018; Tari et al. 2019; Wolohan and Knox 2014). In Experiment 1 of the present work, RTs for MD prosaccades were longer than the SD prosaccades of Experiment 2 ($t(19) = 2.34$,

$p = .030$; $d_z = 0.52$). As originally proposed by Knox et al. (2018), such a difference reflects the time-consuming executive demands of response suppression independent of the additional executive process (i.e., vector inversion) operating in the antisaccade task. Accordingly, the MD pro- *and* antisaccades used in Experiment 1 required response suppression and therefore provided a framework to determine whether decoupling SR spatial relations (i.e., vector inversion) in the latter task contribute to a prosaccade switch-cost. Results for Experiment 1 indicated that RTs for MD pro- *and* antisaccades were equivalent and did not vary across task-switch and task-repeat trials. This result is notable because it demonstrates that an oculomotor switch-cost, and associated task-set inertia, does not reflect the executive demands of vector inversion (i.e., SR decoupling).

In accounting for the results of Experiment 1, MD pro- and antisaccade task-switch and task-repeat trials produced gains that did not reliably differ and were associated with values that approached— or attained—a conventional level of statistical equivalence (i.e., see TOST statistic). This finding demonstrates that participants did not evoke an implicit (or explicit) strategy of maintaining RTs across the different task-types at the expense of decreased endpoint accuracy (i.e., speed-accuracy trade-off) (Fitts 1954). In addition, we note that the group average RT for MD prosaccades (243, SD = 37) did not reliably vary from a previous study by our group ($N = 15$, 256 ms, SD = 33) ($t(31.9) = 0.82$, $p = .41$), wherein MD prosaccades were completed in an individual trial block that employed the same target presentation and delay interval as used here. This is a notable finding because it demonstrates that RTs for MD prosaccades do not reliably differ regardless of whether the task is completed in an interleaved task-switching paradigm (i.e., AABB) or performed in a separate block of trials. It is, however, possible that our conclusion regarding the absence of a switch-cost is related to the fact that the 200–1000 ms MD interval used here provided a sufficiently long interval for the decay of a vector inversion task-set. That being said, Tari et al. (2019) contrasted SD and MD prosaccade task-switch and task-repeat trials using the same delay interval and found a reliable switch-cost attributed to response suppression. As well, in the general task-switching literature, 'large' switch-costs are reported when participants are provided 1200 ms to prepare their response (Rogers and Monsell 1995) and are observed during self-paced trials (Wylie et al. 2011).

As identified above, MD pro- and antisaccades produced equivalent RTs. At first glance, this may seem a surprising finding given that MD antisaccades require the additional executive demand of vector inversion. In reconciling this finding, it is important to consider that the MD paradigm entailed a target presentation that ranged between 200 and 1000 ms after which target offset served as the movement imperative. As such, the length of the target presentation

provided participants sufficient time to complete the vector inversion process prior to response cuing. Support for this view stems from a series of event-related brain potential (ERP) studies demonstrating that the visual—or visuomotor—transformations supporting antipointing (Heath et al. 2012) and visuomotor rotation (saccade- and limb-based) (Heath et al. 2015, 2018) tasks occurs when a delay is introduced between target presentation and response cuing. More specifically, Heath et al. (2012) presented a target for a 100–1100 ms interval after which a fixation colour-change cued participants to complete a pro- or antipointing response. Results showed that pro- and antipointing RTs were equivalent; however, the amplitude of the P300 ERP time-locked to target onset reliably differed between tasks and was taken as evidence that a visual vector inversion process occurs prior to response cuing (see also Moon et al. 2007).

Experiment 2 (SD prosaccades and MD antisaccades): response suppression delays the planning of a subsequent stimulus-driven and standard prosaccade

Previous work involving SD pro- and antisaccades in an AABB paradigm reported an average unidirectional prosaccade switch-cost on the order of 40 ms (Heath et al. 2016; Weiler and Heath 2012a, b, 2014a, b; Weiler et al. 2015; see also Chan and DeSouza 2013). In the present work, when SD pro- and MD antisaccades were performed in an AABB paradigm, RTs for SD prosaccade task-switch trials were on average 38 ms ($CI_{95\%} = 19$) longer than their task-repeat counterparts. In contrast, MD antisaccade task-repeat and task-switch trials produced comparable RTs. The present results therefore demonstrate that a SD prosaccade preceded by a MD antisaccade elicits a switch-cost, and that such a cost is equivalent in magnitude to previous work employing SD antisaccades (e.g., Weiler and Heath 2012a, b; see also Chan and DeSouza 2013). This result is important in contextualizing the results of Experiment 1 because it demonstrates that MD antisaccades contribute to an oculomotor switch-cost. Moreover, the combined results of Experiments 1 and 2 demonstrate that the process of response suppression (and not vector inversion) selectively delays the planning time of a subsequent response only when the response is stimulus-driven *and* only when the response entails direct SR spatial relations. In other words, response suppression imparts a task-set inertia that delays the planning of a subsequent SD prosaccade.

An important issue to address is why response suppression selectively delays the planning of a subsequent SD prosaccade. In accounting for this result, we first note that response suppression is a hallmark feature of executive control that entails a more extensive neural network than vector inversion (see Verbruggen and Logan 2008; Zhang and Barash 2000). As well, Pouget et al.'s (2011) work involving non-human primates found that RTs for SD prosaccades were increased by 17 ms when preceded by a stop-signal trial (i.e., withhold a response at target onset). The RT delay was independent of a change in the baseline level of neural activity in the superior colliculus (SC) and was instead linked to a delay in the onset of SC neuron activity. Furthermore, Everling and Johnston (2013) proposed that the response suppression demands of the antisaccade task require task-set excitatory inputs from the prefrontal cortex to the SC. It may be that prefrontal cortex signalling to the SC necessary for response suppression contributes to lingering network activity (i.e., task-set inertia) that delays the onset of 'standard' saccade neuron activity in the SC. This view is in keeping with the finding that the P300 ERP amplitude for task-switch prosaccades is comparable to antisaccades (i.e., task-switch and repeat) and is different in amplitude to prosaccade task-repeat trials. Notably, this explanation provides a parsimonious account for why response suppression—and not vector inversion—contributes to a delay in the planning of a subsequent *stimulus-driven* and *standard* (i.e., SD prosaccade) oculomotor response.

Conclusion

RTs for MD pro- and antisaccades were refractory to the preceding task-type. This result demonstrates that the executive demands of vector inversion do not contribute to a task-set inertia. In contrast, RTs for SD prosaccades were delayed when preceded by a MD antisaccade, whereas the converse did not result in a switch-cost. We therefore propose that response suppression engenders a task-set that persists inertially and delays the planning of a subsequent standard and stimulus-driven response (i.e., SD prosaccade).

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