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RESEARCH ARTICLE

Response suppression produces a switch-cost for spatially compatible saccades

Benjamin Tari[1] · Mohammed A. Fadel[1] · Matthew Heath[1]

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Abstract

Executive function supports the rapid alternation between tasks for online reconfiguration of attentional and motor goals. The oculomotor literature has found that a prosaccade (i.e., saccade to veridical target location) preceded by an antisaccade (i.e., saccade mirror symmetrical to a target) elicits an increase in reaction time (RT), whereas the converse switch does not. This switch-cost has been attributed to the antisaccade task's requirement of inhibiting a prosaccade (i.e., response suppression) and transforming a target's coordinate (i.e., vector inversion)—executive processes thought to contribute to a task-set inertia that proactively interferes with the planning of a subsequent prosaccade. It is, however, unclear whether response suppression and vector inversion contribute to a task-set inertia or whether the phenomenon relates to a unitary component (e.g., response suppression). Here, the same stimulus-driven (SD) prosaccades (i.e., respond at target onset) as used in previous work were used with minimally delayed (MD) prosaccades (i.e., respond at target offset) and arranged in an AABB paradigm (i.e., A = SD prosaccade, B = MD prosaccade). MD prosaccades provide the same response suppression as antisaccades without the need for vector inversion. RTs for SD task-switch trials were longer and more variable than their task-repeat counterparts, whereas values for MD task-switch and task-repeat trials did not reliably differ. Moreover, SD task-repeat and task-switch movement times and amplitudes did not vary and thus demonstrate that a switch-cost is unrelated to a speed accuracy trade-off. Accordingly, results suggest the executive demands of response suppression is sufficient to engender the persistent activation of a non-standard task-set that selectively delays the planning of a subsequent SD prosaccade.

Keywords Executive function · Movement · Oculomotor · Task switching · Vision

Introduction

A salient feature of executive function is the ability to rapidly alternate between tasks to allow online reconfiguration of attentional and motor goals (Diamond 2013). Notably, task-switching efficiency is asymmetrically dependent on the demands of the trial preceding a switch. In a classic demonstration, Allport et al. (1994) had participants alternate between word- (i.e., standard task) and color-naming (i.e., non-standard task) variants of the Stroop task in a standard AABB paradigm (i.e., A = word-naming B = color-naming). Results showed that a word-naming trial preceded by a color-naming trial (i.e., task-switch trial) was associated with an increased reaction time (RT), whereas the converse switch did not influence performance. In turn, RT did not reliably differ when word- and color-naming tasks were preceded by their same task-type (i.e., task-repeat trial). The authors proposed that the non-standard stimulus–response (SR) mapping of color naming engenders an executive task-set that persists inertially and proactively interferes with a subsequent standard response (i.e., task-set inertia hypothesis). As well, the task-set inertia hypothesis contends that alternating from a standard to a non-standard response does not produce a 'switch-cost' because the former is planned independent of an executive task-set (Wylie and Allport 2000; see also; Monsell 2003). In support of the hypothesis, neuroimaging and electroencephalographic studies examining Stroop and inhibitory task switch-costs have reported that a non-standard task results in greater activation within

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✉ Matthew Heath
mheath2@uwo.ca

[1] School of Kinesiology, The University of Western Ontario, London, ON N6A 3K7, Canada

parietal and frontal executive regions than a standard task. The increased non-standard task activity is thought to reflect the neural activity of an executive-based task rule that passively dissipates and interferes with the efficient planning of a subsequent standard task (Li et al. 2012; Yeung et al. 2006; for meta-analyses see Derrfus et al. 2005; Nee et al. 2007)—a result supported by evidence showing that reduced task-irrelevant activity during a standard task-switch trial is related to shorter RTs (Evans et al. 2015).

The task-switching literature is largely dependent on simple button press or oral responses and therefore does not represent tasks involving the concurrent spatiotemporal demands of goal-directed actions. Accordingly, work by our group (Heath et al. 2016; Weiler and Heath 2012a, b, 2014a, b; Weiler et al. 2015) and Barton, Manoach et al. (Barton et al. 2006; Cherkasova et al. 2002; Manoach et al. 2007) examined switch-costs for pro- and antisaccades (see also Chan and DeSouza 2013). Prosaccades are a standard pre-potent response requiring a saccade to veridical target location and are mediated via 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 pre-potent prosaccade (i.e., response suppression) and SR decoupling (i.e., vector inversion) to evoke a saccade mirror symmetrical to a target. Antisaccades have longer RTs (Hallett 1978) and produce less accurate and more variable endpoints than prosaccades (Dafoe et al. 2007; Gillen and Heath 2014). These behavioral costs have been attributed to prefrontal excitatory inputs to the SC that encode the executive task-set necessary for a non-standard response (Everling and Johnston 2013). Results from our group have shown that RTs for a prosaccade preceded by an antisaccade (i.e., task-switch prosaccade) are longer than when a prosaccade is preceded by its same task counterpart (i.e., task-repeat prosaccade). In turn, antisaccade RTs do not vary regardless of whether the response is preceded by a prosaccade (i.e., task-switch antisaccade) or an antisaccade (i.e., task-repeat antisaccade) (Weiler and Heath 2012a, 2014a).[1] Our group has referred to the selective increase in RTs for task-switch prosaccades as the unidirectional prosaccade switch-cost. The unidirectional prosaccade switch-cost is observed in a standard—and predictable—AABB paradigm (i.e., A = prosaccade, B = antisaccade) and when pro- and antisaccades are randomly interleaved. Further, the switch-cost does not vary in magnitude with the number of preceding antisaccades (Weiler and Heath 2012b, 2014b). In addition, the amplitude of the P300 event-related brain potential (ERP) for task-switch prosaccades is comparable to task-repeat and task-switch antisaccades and is different in amplitude from task-repeat prosaccades (Weiler et al. 2015). Convergent behavioral and electroencephalographic evidence therefore suggest the unidirectional prosaccade switch-cost is associated with a task-set inertia arising from a previously activated non-standard response.

An issue that remains to be addressed is whether the unidirectional prosaccade switch-cost is related to a task-set inertia underlying: (1) response suppression, or (2) SR decoupling. The notion that SR decoupling underlies the switch-cost is drawn from the previously outlined Stroop task literature. In contrast, Pouget et al.'s (2011) work involving non-human primates reported that a (pro)saccade preceded by a no-go trial was associated with a delay in the time wherein neural activity in the frontal eye field and SC first began to accumulate. In other words, a task-set inertia from the suppression of a standard prosaccade may represent a candidate explanation for the unidirectional prosaccade switch-cost. Here, we used an AABB paradigm to arrange the same stimulus-driven (SD) prosaccades as our group's previous work (i.e., saccade at target onset) with minimally delayed (MD) prosaccades (i.e., saccade at target offset).[2] SD saccades (i.e., standard task) are characterized by a reflex-like response driven by target onset (i.e., visual grasp reflex) and are mediated by the SC (for review see Munoz and Everling 2004). In contrast, MD saccades (i.e., non-standard task) require that participants withhold their response at target onset, and instead respond when the target is extinguished (e.g., 200–1000 ms after target onset). MD saccades therefore require the same response suppression as antisaccades; however, they do not require SR decoupling, and unlike memory-guided saccades do not require a memory component because the target is visible throughout a central fixation period. Wolohan and Knox (2014) reported that MD saccades produce longer RTs than their SD counterparts—a result the authors attributed to active response suppression to prevent a stimulus-driven response. Accordingly, if the executive demands of response suppression contribute to a task-set inertia then RTs for SD task-switch saccades

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[1] Barton and Manoach's group (e.g., Barton et al. 2006) have reported that an antisaccade delays the RT of any subsequent pro- or antisaccade. Notably, however, Barton and Manoach's group employed a cued saccade paradigm wherein two targets were concurrently presented left and right of a central fixation and remained visible throughout a response. In contrast, our group as well as Chan and DeSouza (2013), have employed a classic antisaccade paradigm (Hallett 1978) wherein a single target is exogenously presented and therefore requires the sensorimotor transformation of a target's coordinates to mirror-symmetrical space (i.e., vector inversion) (see Munoz and Everling 2004). This difference in methodology has been discussed in depth elsewhere (Weiler and Heath 2012a, b, 2014b) and we believe that it provides a parsimonious account for the difference in experimental findings.

[2] For simplicity we henceforth use saccade – instead of prosaccade – to refer to a SR compatible response.

should be longer than their task-repeat counterparts. In contrast, if SD task-repeat and task-switch saccades show equivalent RTs then results would provide indirect evidence that the executive demands of SR decoupling contribute to a task-set inertia in oculomotor control.

Methods

Participants

Experiment 1 involved 19 individuals (9 females: age range: 19–25 years) and Experiment 2 involved a separate set of 15 individuals (8 females: age range: 20–25 years). Participants were recruited from the University of Western Ontario community and all had normal or corrected-to-normal vision and were self-declared right-hand dominant. Participants indicated that they had not been previously diagnosed with a neuropsychiatric/neurological disorder (including concussion) (Webb et al. 2018) or eye injury. Participants read a letter of information and signed a consent form approved by the Non-Medical Research Ethics Board, University of Western Ontario, and this work was conducted according to the Declaration of Helsinki.

Experiment 1: apparatus and procedures

Participants sat in a height adjustable chair in front of a table with their head placed in a head/chin rest. A 30-inch LCD monitor (60 Hz, 8 ms response rate, 1280 × 960 pixels; Dell 3007WFP, Round Rock, TX, USA) was 550 mm from the front edge of the table and centered on participants' midline. The gaze position of participants' left eye was measured via a video-based eye-tracking system (EyeLink 1000 Plus, SR Research, Ottawa, ON, Canada) sampling at 1000 Hz. In advance of data collection, a nine-point calibration of participants' viewing space was performed and confirmed via a validation (i.e., $< 1°$ of error for each point in the calibration grid). Two additional monitors visible to the experimenter provided real-time gaze position and trial-to-trial saccade kinematics. Computer events were controlled via MATLAB (R2018b, The MathWorks, 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 high-contrast black background and included a white fixation cross (1°: 135 cd/m^2) located on the monitor's horizontal midpoint and at participants' eye level. The onset of the fixation cross signaled the participants to direct their gaze to its location. When a stable gaze was achieved (i.e., $\pm 1.5°$ for 450 ms), a fixation cross color change occurred (see details below) and a random foreperiod (uniformly distributed between 1000 and 2000 ms) was initiated after which a target (i.e., open yellow circle 2.5° in diameter: 127 cd/m^2) was presented 13° (i.e., proximal target) or 17° (i.e., distal target) to the left or right of fixation. The target was presented for a uniformly distributed randomized period between 200 and 1000 ms.[3] The fixation cross color change provided advanced information related to the nature of an upcoming trial. For ten participants, a white to green color change indicated to saccade immediately at target presentation (i.e., stimulus-driven saccade: SD), whereas a white to red change indicated a saccade at target offset (i.e., minimally delayed saccade: MD). MD saccades required that participants withhold their response for an unpredictable period of time until target offset and therefore required active response suppression. For nine participants, the red and green fixation color change signaled a SD and MD saccade, respectively. The fixation cross remained visible throughout a trial (i.e., overlap paradigm).

This experiment included a single block of 161 trials with alternating SD and MD saccades after every second trial (i.e., AABB paradigm: e.g., A = SD trial, B = MD trial). Accordingly, trials were equally divided into 80 task-repeat (e.g., SD saccade on trial N preceded by a SD saccade on trial N−1) and 80 task-switch (e.g., SD saccade on trial N preceded by a MD saccade on trial N−1) trials. As well, the block contained an equal number of directional repeats (e.g., a left target on trial N preceded by a left target on trial N−1) and directional switches (e.g., a left target on trial N preceded by a right target on trial N−1). The ordering of directional switches was pseudo-randomized and was unpredictable. Previous studies comparing pro- and antisaccade switch-costs have shown that a directional switch does not influence saccade planning or execution (Weiler and Heath 2012a, b). In spite of those findings, an equal number of directional-repeat and -switch trials were included as an experimental control. The first trial in an experimental block was counterbalanced for task type (i.e., SD or MD), and the first trial of the experiment was excluded from data analyses because it was neither a task-repeat nor a task-switch. Owing to the nature of this study, we did not provide a within-block rest break and report that the average inter-trial interval here was 1175 ms (SD = 59)—a range consistent with earlier work (Weiler and Heath 2012a, b, 2014a, b). Further, we note that switch-costs are observed even when between-trial intervals are self-paced (Wylie and Allport 2000; Wylie et al. 2011).

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[3] Correlations computed separately for SD and MD trials showed that foreperiod durations and RTs were not reliably related ($ps > 0.40$).

Experiment 2: apparatus and procedures

Experiment 2 was identical to Experiment 1 with the exception that SD and MD saccades were performed in separate blocks. Experiment 2 was employed as a supplement to determine whether a putative RT difference between SD task-switch and task-repeat saccades is the result of a switch-cost or reflects that planning times for SD task-repeat saccades are facilitated when preceded by their same task-type.

Experiments 1 and 2: data processing, dependent variables and statistical analyses

Gaze position data were filtered offline using a dual-pass Butterworth filter with a low-pass cutoff 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 involving a blink—or any other signal loss—were excluded, as were trials with: (1) an amplitude less than 2° or two times a participant-specific mean (Weiler and Heath 2014a) and, (2) trials with an RT less than 50 ms (Wenban-Smith and Findlay 1991). Less than 6% of trials were removed for the aforementioned criteria.

For Experiment 1, dependent variables included reaction time (RT: time from response cuing to saccade onset), movement time (MT: time from saccade onset to saccade offset) and gain (i.e., saccade amplitude/veridical target amplitude). Participant-specific median RT values were used for parametric analyses given the positive skew of RT distributions (see Fig. 2) (Bulmer 1979), whereas mean values were computed for MT and gain. In addition, participant-specific interquartile ranges (i.e., IQR) and within-participant standard deviations were computed for RT and gain, respectively. Dependent variables were examined via 2 (task: SD, MD) by 2 (task-transition: task-repeat, task-switch) repeated measures ANOVA. Significant interactions were decomposed via paired-samples *t* tests with a Bonferroni adjusted level of significance ($p = 0.025$). For non-significant post hoc contrasts, the two one-sided tests (TOST) procedure (repeated measures) was used to examine between-condition equivalence (for tutorial see Lakens et al. 2018). Equivalence testing was completed via the TOSTER R package (Lakens 2017).

For Experiment 2, we contrasted participant-specific median RT values for SD and MD saccades to their task-repeat counterparts of Experiment 1. Participants in Experiment 2 were independent of Experiment 1 and involved a different sample size. Thus, RT contrasts were completed via independent samples Welch's *t*- and TOST tests.

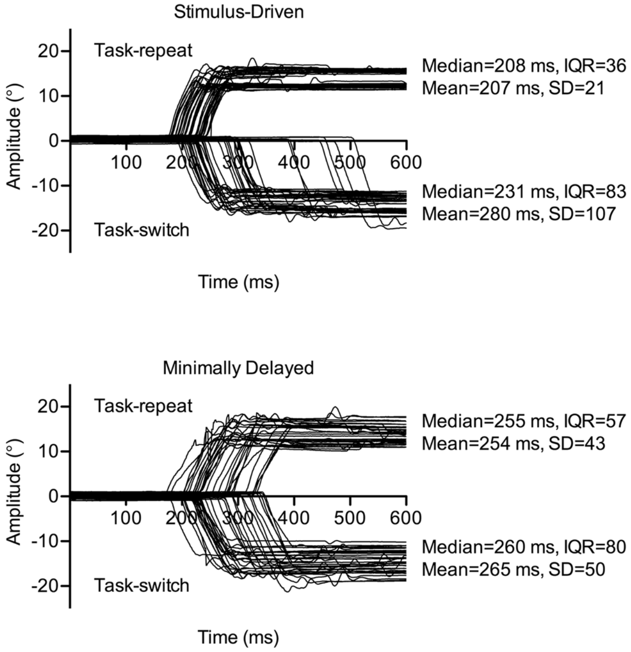

Fig. 1 Trial-to-trial position by time trajectories for an exemplar participant (Note: time zero represents response cuing). The top and bottom panels present stimulus-driven and minimally delayed saccades, respectively. For ease of presentation, task-repeat and task-switch trials are depicted as positive and negative displacements, respectively

Results

Experiment 1: exemplar participant SD and MD trajectories demonstrate distinct planning and amplitude characteristics

Figure 1 shows an exemplar participant's position by time trajectories for SD and MD task-repeat and task-switch trials. The figure shows that RTs for SD task-repeat trials were shorter—and less variable—than their task-switch counterparts, which in turn resembled MD task-repeat and task-switch trials. As well, RTs and RT variability for MD trials were comparable across task-repeat and task-switch trials. In terms of amplitude, SD trials demonstrated greater scaling to target eccentricity than MD trials.

Experiment 1: temporal measures of response planning and execution

The main panels of Fig. 2 show RT percent frequency histograms for SD and MD task-repeat and task-switch trials. The light and dark gray rectangles in each panel show bins for anticipatory (i.e., < 100 ms) and short-latency (i.e., 100 to < 200 ms) responses. SD task-switch trials did not produce anticipatory responses, whereas SD task-repeat and MD task-repeat and task-switch trials did—albeit very low in

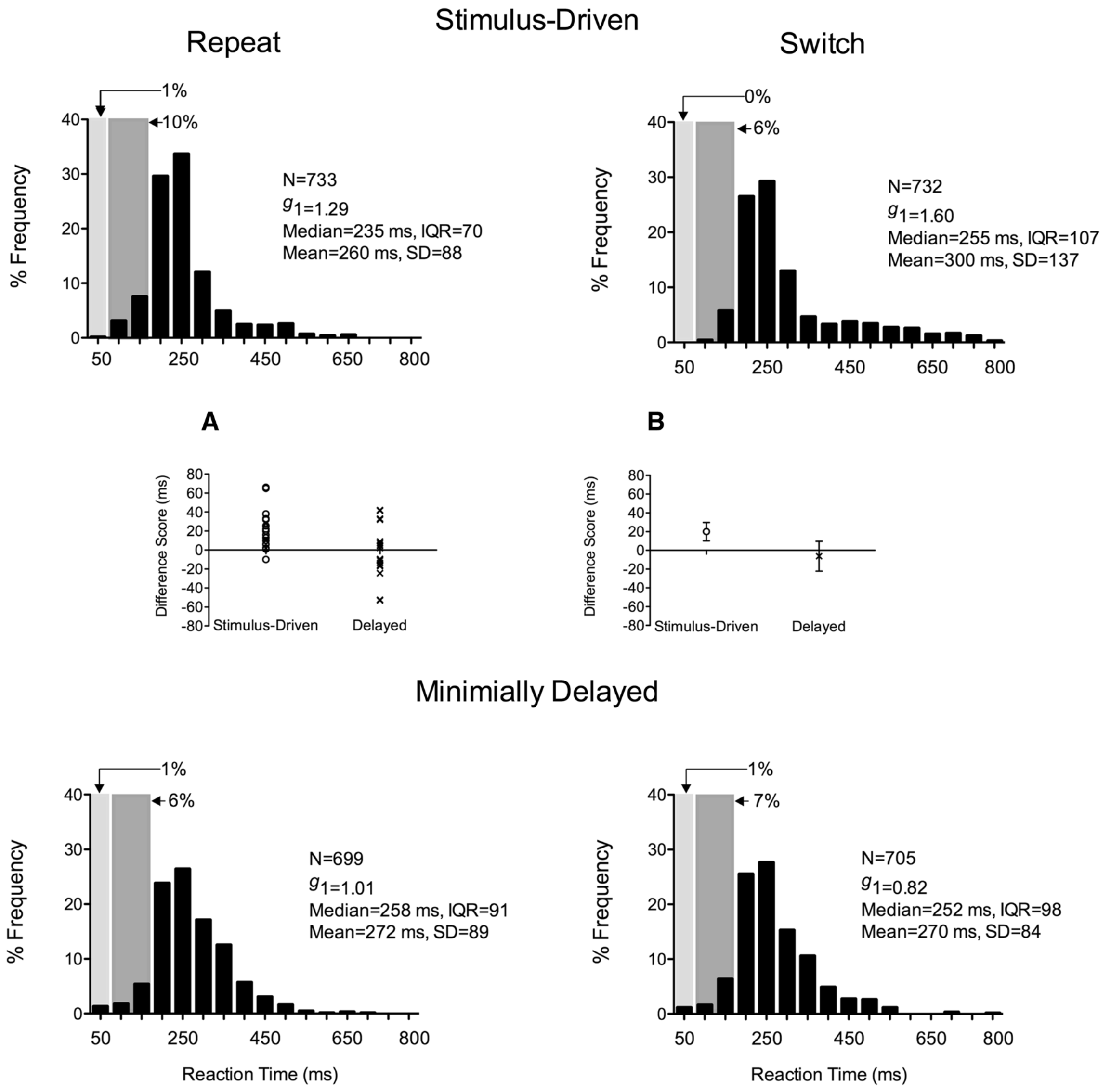

Fig. 2 The main panels show reaction time (ms) percent frequency histograms for stimulus-driven (SD and top panels) and minimally delayed (MD and bottom panels) task-repeat (left panels) and task-switch (right panels) saccades with bin widths of 50 ms. The text box in each panel provides descriptive statistics including skewness (i.e., g_1). The inset left panel (**a**) shows difference scores (i.e., task-switch minus task-repeat) for SD and MD saccades computed from each participant's median reaction time (RT). **a** Shows that for SD saccades all, but one, participant exhibited a RT switch-cost, whereas MD saccades did not produce a consistent switch-cost. The inset right panel (**b**) shows group mean reaction time difference scores—and associated 95% between-participant confidence intervals—for SD and MD saccades. The absence of overlap between an error bar and zero (i.e., the horizontal line) indicates a reliable difference inclusive to a test of the null hypothesis

frequency. As well, Fig. 2 shows that all conditions produced a roughly equivalent number of short-latency responses. We analyzed RT distributions via the non-parametric Kolmogorov–Smirnov test and found that SD task-repeat and task-switch trials were associated with different distributions ($D = 0.12$, $p < 0.001$), whereas MD task-repeat and task-switch trials were not ($D = 0.04$, $p = 0.48$). Parametric analysis (i.e., ANOVA) of RT indicated a task by task–transition interaction, $F(1,18) = 5.69$, $p = .0.028$, $\eta_p^2 = 0.26$.[4] Figure 2a

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[4] The text boxes in the main panels of Fig. 2 present skewness ($g1$) for each experimental condition and demonstrate a positive skew for each. We therefore employed median RT and RT IQR values in our ANOVA model. Notably, however, analysis of mean RT also revealed a task by task-transition interaction, $F(1,18) = 7.76$, $p = 0.012$, $\eta_p^2 = 0.30$. RTs for SD task-repeat and task-switch trials differed ($t(18) = 3.48$, $p = 0.003$, $d = 0.80$), whereas MD task-switch and task-repeat did not ($t(18) = -0.31$, $p = 0.075$, $d = -0.07$).

shows participant-specific RT difference scores (i.e., task-switch minus task-repeat) and demonstrates that for SD trials all but one participant showed a switch-cost, whereas MD trials did not reveal a switch-cost. Figure 2b shows mean group difference scores—and 95% between-participant confidence intervals—and demonstrates a reliable switch-cost for SD but not MD trials ($ts(18) = 7.97$ and -0.31, $p < 0.001$ and 0.75, $d_z = 1.82$ and -0.07). The TOST procedure indicated that MD task-switch and task-repeat trials were within an equivalence bound ($t(18) = 2.02$, $p = 0.03$); that is, the aforementioned conditions did not meaningfully differ.

Results for RT IQR produced a main effect of task–transition, $F(1,18) = 7.13$, $p = 0.016$, $\eta_p^2 = 0.28$, and a task by task–transition interaction, $F(1,18) = 4.45$, $p = 0.049$, $\eta_p^2 = 0.19$. Values for SD task-repeat trials (70 ms, SD = 30) were less than task-switch trials (107 ms, SD = 57) ($t(18) = 2.81$, $p = 0.012$, $d_z = 0.64$), whereas MD task-repeat (91 ms, SD = 32) and task-switch (98 ms, SD = 35) trials did not differ ($t(18) = 0.89$, $p = 0.32$, $d_z = 0.20$). The TOST statistic indicated between-condition equivalence for MD task-switch and task-repeat trials ($t(18) = 1.87$, $p = 0.039$). MT produced a main effect of task, $F(1,18) = 93.53$, $p < 0.001$, $\eta_p^2 = 0.84$; SD trial (54 ms, SD = 6) values were shorter than MD trials (63 ms, SD = 9).

Experiment 1: saccade gain and gain variability

The main panels of Fig. 3 present gain percent frequency histograms for SD and MD task-repeat and task-switch trials. The figure shows that gains were generally less than unitary—a result keeping in with a well-documented saccade undershooting bias (Becker 1989; Harris 1995). Kolmogorov–Smirnov tests indicated that distributions for SD ($D = 0.08$, $p = 0.09$) and MD ($D = 0.04$, $p = 0.49$) task-repeat and task-switch trials did not reliably differ. ANOVAs for gain and gain variability produced main effects for task, all $F(1,18) = 5.08$ and 6.47, $p = 0.037$ and 0.02, $\eta_p^2 = 0.22$ and 0.26. Gains for SD trials were closer to unitary (0.92, SD = 0.07) and less variable (0.11, SD = 0.08) than MD trials (gain: 0.89, SD = 0.11; gain variability: 0.14, SD = 0.07). Figure 3a and b show that SD and MD gains did not produce a switch-cost.

Experiment 2: comparison between blocked presentation SD and MD saccades and their task-repetition counterparts

RTs for SD (232 ms, SD = 23) and MD (256 ms, SD = 33) saccades performed in separate blocks (Experiment 2) did not reliably differ from their Experiment 1 task-repeat counterparts (SD: 235 ms, SD = 22; MD: 258 ms; SD = 40; see also Fig. 2) ($ts(<31.9) < 0.89$, $ps > 0.38$, all $d_z < 0.13$). The TOST procedure revealed equivalence between MD trials in Experiment 1 and 2 ($t(31.9) = 1.89$, $p = 0.034$). In contrast, SD trials in Experiment 1 and 2 did not attain a conventional level of significance to be considered within an equivalence boundary ($t(29.5) = 1.64$, $p = 0.056$). It is, however, important to note that the mean RT for SD trials in Experiment 2 was longer than Experiment 1.

Discussion

We sought to determine whether response suppression contributes to a task-set inertia delaying the planning of a subsequent SD saccade. Before addressing this question, we first discuss the general differences between SD and MD task-repeat trials to provide a framework for how task-type influenced response planning and execution.

SD vs. MD task-repeat trials: response suppression influences the efficiency and effectiveness of saccade planning and control

SD task-repeat trials produced shorter RTs than their MD counterparts. This expected finding is attributed to an abrupt target onset activating a visual grasp reflex (Munoz and Everling 2004) mediated via direct retinotopic motor maps in the SC (Wurtz and Albano 1980). Moreover, because expectancy influences SC activity (Trappenberg et al. 2001), it is likely that the advanced information provided to participants that a SD response was to be performed (i.e., between 1000 and 2000 ms prior to target onset) increased SC build-up neuron activity and optimized response planning (Everling et al. 1999). In contrast, longer MD saccade RTs are taken as evidence of the executive cost of suppressing a pre-potent response via a decrease in SC build-up neuron activity (i.e., to prevent an unintended SD saccade) (Wolohon and Knox 2014). In line with this view, RTs for MD trials were more variable than SD ones—a finding consistent with evidence that an imposed delay increases variability in the growth rate of saccade-related SC activity (Schall 2002).

MD task-repeat trials had longer MTs, reduced gains, and increased gain variability compared to SD trials. The longer MTs are similar to the increase in response duration and lower peak velocities between pro- and antisaccades, and between visually guided and memory-guided saccades (Becker and Fuchs 1969; White et al. 1994; Zambarbieri et al. 1995; see also; Pierrot-Deseilligny et al. 1995). Indeed, Edelman and Goldberg's (2001) work involving non-human primates indicates that the presence of a visual target at a saccade goal location from the time of response cuing to response onset increases SC activity and "…serves to make saccades faster and more precise" (p. 690). Recall that target offset cued the MD trials used here and as a result a visual target was not available throughout response cuing

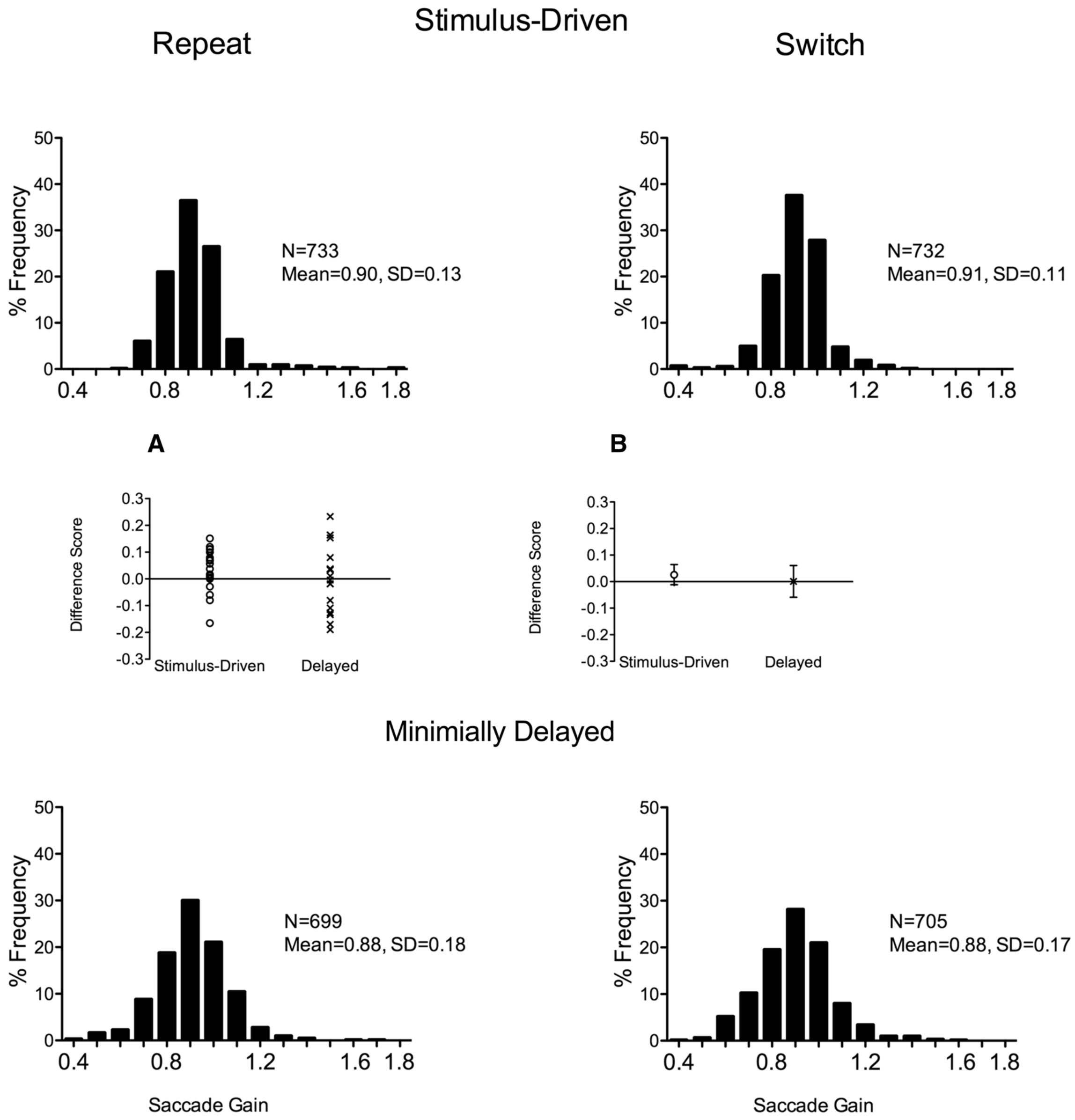

Fig. 3 The main panels show saccade gain (i.e., saccade amplitude/veridical target location) percent frequency histograms for stimulus-driven (SD and top panels) and minimally delayed (MD and bottom panels) task-repeat (left panels) and task-switch (right panels) saccades with bin widths of 0.1. The inset left panel (**a**) shows gain difference scores (i.e., task-switch minus task-repeat) for SD and MD saccades computed from each participant's mean gain value. **a** Shows that neither SD nor MD saccades produced a switch-cost. The inset right panel (**b**) shows that group mean gain difference scores did not reliably differ from zero

to response offset (see Westwood et al. 2003). Accordingly, MD saccades may be associated with a similar decrease in saccade-related activity as memory-guided ones. As well, the endpoint properties of MD saccades support evidence that a response requiring executive control is mediated by visual information (i.e., relative) functionally distinct from the direct retinotopic coordinates of SD saccades (Gillen and Heath 2014). Accordingly, the present findings suggest that MD saccades are an executive task supported by an active response suppression task-set.

Task-repeat vs. task-switch trials: SD saccades show a selective switch-cost

Previous work by our group (see also Chan and DeSouza 2013) contrasting pro- and antisaccades demonstrated a 10–40 ms unidirectional prosaccade switch-cost (Heath et al. 2016; Weiler and Heath 2012a, b, 2014a, b; Weiler et al. 2015). In the present work, SD task-repeat RTs (and RT variability) were less than task-switch trials, and this result was reflected in 18 out of 19 participants (see Fig. 2a).

In contrast, MD task-repeat and task-switch trials produced comparable RTs (and RT variability) and Fig. 2a emphasizes this point in that participants were equally likely to have longer task-repeat than task-switch RTs (i.e., 10 of 19) than the converse (i.e., 9 of 19). Furthermore, the magnitude of the switch-cost observed here (21 ms, SD = 18) is in accord with the previously reported unidirectional prosaccade switch-cost. The present findings therefore demonstrate that: (1) a switch-cost selectively manifests when a standard response (i.e., SD saccade) is preceded by an executive-mediated non-standard response (i.e., MD saccade), (2) a switch-cost is not dependent on the combined constituent elements of the antisaccade task (i.e., response suppression and vector inversion); rather, results demonstrate that the executive demands of response suppression are sufficient to contribute to a task-set inertia, and (3) a switch-cost is associated with increased planning variability. Of course, we recognize that our study cannot rule out a possible role of vector inversion in contributing to a switch-cost; however, we believe that our findings add importantly to the literature insomuch as they—as well as stop-signal studies in humans (Weiler et al. 2014) and non-human primates (Pouget et al. 2011)—demonstrate that response suppression is a major component contributing to an oculomotor task-set inertia. Further, our results suggest that the Stroop task switch-cost reported when a word-naming trial (i.e., standard task) is preceded by a color-naming trial (i.e., non-standard task) may not entirely relate to SR decoupling (e.g., Allport et al. 1994). Instead, our results suggest the switch-cost may—in part—relate to an inertially activated task-set arising from the response suppression requirements of color naming.

Three important issues require addressing. First, it has been argued that in an AABB paradigm, task-repeat trials may not serve as an appropriate baseline to examine a switch-cost, because differences between task-repeat and task-switch trials may represent decreased RTs in the former (Wylie and Allport 2000). In other words, a task-repeat trial may be facilitated when preceded by its same task-type. To address this issue, Experiment 2 employed the same protocol as Experiment 1 with the exception that SD and MD saccades were performed in separate blocks. RTs for blocked condition SD and MD saccades were subsequently compared to their task-repeat counterparts in Experiment 1. Results for null hypothesis and equivalence testing showed that RTs for MD saccades did not differ, and for SD saccades null hypothesis testing showed that RTs did not reliably vary between experiments. We did, however, observe that for equivalence testing the RTs for SD saccades in Experiment 1 and 2 were outside of an equivalence boundary. That said, SD saccades in Experiment 1 (235 ms) were longer than Experiment 2 (232 ms). This finding indicates that task-repeat trials were not associated with a RT benefit and thus supports the contention that the switch-cost reported in Experiment 1 was attributed to increased RTs for SD task-switch saccades (see also Weiler and Heath 2014b). Second, it is possible that increased SD task-switch RTs underlie a strategic response designed to increase endpoint accuracy (i.e., speed/accuracy trade-off) (Fitts 1954). Such an explanation is, however, discounted by the comparable MTs and endpoint metrics (i.e., gain and gain variability) associated with SD task-repeat and task-switch trials, and by the fact that RTs for task-switch trials were more variable than task-repeat trials. Third, our behavioral results raise the issue of the neural correlate associated with the oculomotor task-set inertia. A possible candidate for this is the prefrontal cortex (PFC) given its contextual control over saccade generation (Stuphorn and Schall 2006). In particular, Everling and Johnston (2013) contend that PFC excitatory inputs to the SC encode the behavioral rule(s) and task-set associated with an oculomotor response. It may be that inertial activation of a PFC mediated non-standard task-set contributes to the oculomotor switch-cost observed here and elsewhere (e.g., Chan and DeSouza 2013; Weiler and Heath 2012a, b).

Conclusion

The completion of a MD saccade selectively increased RT (and RT variability) of a subsequent SD saccade. We therefore propose that a unidirectional (pro)saccade switch-cost relates to a task-set inertia arising from the executive demands of response suppression.

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