

Effects of Task and Task-Switching on Temporal Inhibition of Return, Facilitation of Return, and Saccadic Momentum During Scene Viewing

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During scene viewing, saccades directed toward a recently fixated location tend to be delayed relative to saccades in other directions (“delay effect”), an effect attributable to inhibition of return (IOR) and/or saccadic momentum (SM). Previous work indicates this effect may be task-specific, suggesting that gaze control parameters are task-relevant and potentially affected by task-switching. Accordingly, the present study investigated task-set control of gaze behavior using the delay effect as a measure of task performance. The delay effect was measured as the effect of relative saccade direction on preceding fixation duration. Participants were cued on each trial to perform either a search, memory, or rating task. Tasks were performed either in pure-task or mixed-task blocks. This design allowed separation of switch-cost and mixing-cost. The critical result was that expression of the delay effect at 2-back locations was reversed on switch versus repeat trials such that return was delayed in repeat trials but speeded in switch trials. This difference between repeat and switch trials suggests that gaze-relevant parameters may be represented and switched as part of a task-set. Existing and new tests for dissociating IOR and SM accounts of the delay effect converged on the conclusion that the delay at 2-back locations was due to SM, and that task-switching affects SM. Additionally, the new test simultaneously replicated noncorroborating results in the literature regarding facilitation-of-return (FOR), which confirmed its existence and showed that FOR is “reversed” SM that occurs when preceding and current saccades are both directed toward the 2-back location.

Keywords: gaze control, task-switching, facilitation of return, saccadic momentum, oculomotor inhibition of return

Everyday visual behavior is punctuated by changes in viewing task. For example, after parking a car in a large, crowded lot one might search for a marker that indexes the location of the parking spot. After locating a potential marker, one might evaluate whether it will be effective or not. Finally, once a marker is found and evaluated as effective, aspects of the marker would need to be committed to memory so that it can be identified later. Such an endeavor therefore requires frequent changes in the current task set. Studies of task-set and visual behavior indicate that task-set

influences saccade- and fixation-relevant parameters (Castelhano, Mack, & Henderson, 2009; Henderson, Weeks, & Hollingworth, 1999; Land & Hayhoe, 2001; Land, Mennie, & Rusted, 1999; Mills, Hollingworth, Van der Stigchel, Hoffman, & Dodd, 2011; Torralba, Oliva, Castelhana, & Henderson, 2006; Yarbus, 1967) and studies of task-switching have shown that task performance suffers when switching tasks (see Monsell, 2003, for a brief review). It is unknown, however, whether task-switching impacts visual behavior during scene viewing.

Gaze control is the process of directing fixation through a scene in accordance with task goals and the demands of the environment, and is critical in support of ongoing perceptual, cognitive, and behavioral activity (Henderson, 2003). Although much is known about various factors that contribute to gaze control, relatively little is known regarding their coordination in the context of changing situational demands such as when a viewer must switch from one task to another. A common assumption is that switching tasks requires control processes that enable the system to perform a new task (Monsell, 2003). It is important to note that these processes take time (Meiran, 1996; Rogers & Monsell, 1995) and persist across trials (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 1999; Wylie & Allport, 2000; Yeung & Monsell, 2003), resulting in switch costs (i.e., performance decrements associated with switching to a different task relative to repeating the same

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task). As the same control processes are not required when a task repeats, switch costs can be attributed to the control processes involved in switching tasks. The study of switch costs is of interest because these costs reflect the various factors at play during the operation of control processes, which can reveal how the system flexibly adapts to changing situational demands on behavior. The goal of the present study is to gain insight into the flexible use of gaze during scene viewing by examining if and how the efficiency with which the eyes sample visual information is affected by task-switching.

Real-world visual environments contain countless objects, only a portion of which are relevant for a given task. As such, task performance depends heavily on the ability to sample the environment efficiently. A prominent example of this efficiency is a temporal delay in responding to targets at previously sampled locations relative to targets at novel locations, an effect typically attributed to inhibition of return (IOR), but which we refer to with the more theoretically neutral term *delay effect*. The delay effect was originally demonstrated in a peripheral cueing task (Posner & Cohen, 1984), in which spatially nonpredictive peripheral onset cues preceded targets that required a simple detection response. It was found that when the interval between the onset and the target was short, response times to targets presented at cued locations were faster than to targets presented at uncued locations (facilitation effect). When the interval was extended beyond 200 ms, however, responses to cued locations were slower than to uncued locations (delay effect). The delay effect is commonly attributed to an inhibitory mechanism, IOR (Posner, Rafal, Choate, & Vaughan, 1985), which is thought to encourage orienting toward novel locations by inhibiting attention from returning to a previously attended location and, moreover, is believed to have evolved to maximize sampling of the visual environment (Posner & Cohen, 1984). In this light, sampling efficiency may be operationalized in terms of the behaviorally observed delay effect preceding responses at recently inspected locations.

Klein (1988) extended this account, proposing that the delay effect may facilitate sampling in attention-demanding tasks (e.g., serial search) by discouraging orienting toward previously sampled locations. Evidence for this “foraging facilitator” hypothesis has been provided by Klein and MacInnes’ (1999) “Where’s Waldo” study, in which participants search for a target in a complex scene. During search, an onset probe appeared at either the immediately previous fixation location (1-back), the one before that (2-back), or at equidistant novel locations. Participants were instructed to fixate the probe as soon as it appeared. Results showed that saccadic latencies to probes presented at the 2-back location were slower than to probes presented at novel locations. Thus, a delay effect was observed, which was interpreted as temporal evidence in support of the “foraging facilitator” hypothesis (i.e., that inhibition at recently inspected locations discourages orienting back toward that location, thereby biasing orienting toward novel locations).

Another interpretation of the delay effect, however, is that the temporal delay is caused by facilitation at novel locations, as opposed to inhibition at previously fixated locations. Using a memory task and real-world scenes, Smith and Henderson (2009) found that freely executed saccades directed back toward the 2-back fixation location were preceded by longer fixations than saccades directed toward locations perpendicular to and straight

ahead from the 2-back location, a pattern consistent with a delay effect. To determine whether the delay effect was attributable to inhibition or facilitation, the duration of fixations preceding saccades that landed exactly at the 2-back location were compared with those preceding saccades directed at the 2-back location but which over- or undershot it (“interaction test” for dissociating inhibition and facilitation). Inhibition is assumed to be maximal for saccades landing at a previous fixation location and to decrease as the distance between the landing position and the previous fixation location increases (Bennett & Pratt, 2001; Dorris, Taylor, Klein, & Munoz, 1999; Hooge & Frens, 2000). Therefore, if the delay effect was due to IOR, then the delay should be larger for saccades landing at the 2-back location than saccades in the same direction not landing at this location. Instead, the results showed an equivalent delay for saccades similar in direction, regardless of the distance between the landing position and the 2-back location. As such, they attributed the delay effect to saccadic momentum (SM; the oculomotor cost associated with changing the direction of a saccade). It is worth noting, however, that IOR (Klein & MacInnes, 1999) and SM (Smith & Henderson, 2009) are not mutually exclusive. For instance, Smith and Henderson (2009) also measured the delay effect at the 1-back location and found that in addition to a general dependency of fixation duration on saccade direction (indicative of SM), there was also a spatially localized inhibitory effect (indicative of IOR).

Regardless of whether IOR or SM best accounts for the delay effect, the point relevant to the present study is that sampling efficiency may be operationalized profitably in terms of the behaviorally observed temporal delay preceding saccades to recently inspected locations. For instance, Dodd, Van der Stigchel, and Hollingworth (2009) showed that the expression of the delay effect is task-dependent. They had participants perform either a search, memorization, preference rating, or free-view task, during which an onset probe was presented. Consistent with Klein and MacInnes (1999), they found evidence of temporal delay in the search task, which was interpreted as IOR. In the other three tasks, however, saccades to probes presented at a previously fixated location were actually executed faster than saccades to probes presented at novel locations, which they describe as temporal facilitation of return (temporal-FOR). A dependency on task suggests that the delay effect is under strategic control of task-set and/or moment-to-moment processing requirements. If the delay effect is a component of some, but not all, task-sets, then it is possible that the expression of the delay effect will be affected by switching from one to the other. For example, switching from a previous task in which temporal delay is not a component of task-set (e.g., memorization) to a current task in which temporal delay is a component (e.g., search) may dampen the expression of the delay effect in the current task. Conversely, switching from a previous task in which temporal delay is a component of task-set to a current task in which it is not may induce a delay effect in the current task.

To gain insight into the flexible use of gaze during scene viewing, the present study examined effects of task-switching on the efficiency with which the eyes sample visual information during scene viewing. Sampling efficiency was operationalized in terms of the delay effect (i.e., temporal delay in the initiation of saccades directed toward a previous fixation location relative to other locations), which was measured as the time taken to execute a saccade as a function of its direction relative either to the immediately previous fixation location (1-back) or the one before that (2-back). A cued task-switching

procedure was used in which participants were cued on every trial to either search, memorize, or rate a scene. Tasks were executed in one of two different contexts: (a) pure-task blocks (isolated blocks of each task), or (b) a mixed-task block (task either repeats or switches from trial-to-trial). Thus, there were three types of trials: single-task trials (within pure-task blocks), as well as repeat and switch trials (within the mixed-task block). The combination of pure- and mixed-task blocks allowed examination of two different aspects involved in switching tasks (Braver, Reynolds, & Donaldson, 2003; Koch, Prinz, & Allport, 2005; Kray & Lindenberger, 2000; Los, 1996; Meiran, Chohov, & Sapir, 2000; Rubin & Meiran, 2005; Shaffer, 1965). One aspect concerns control processes required for the initiation and execution of the actual task-set switch, which are assumed to reflect processes that provide online control of high-level control settings. Costs of this switching process (switch cost) were estimated as the difference in the delay effect between switch and repeat trials (within the mixed-task block). The second aspect concerns control processes that are required for the regulation of cognitive processing associated with the general switch situation and are assumed to reflect the ability to maintain three task-set instructions (e.g., action routines, such as stimulus-response mappings for search, memory, and rating tasks). Costs of the general task-switching situation (mixing costs) were estimated as the difference between repeat trials (within the mixed-task block) and single-task trials (within pure-task blocks).

Method

Participants

Undergraduates from the University of Nebraska—Lincoln participated in exchange for course credit ($N = 80$). Participants were randomly assigned to one of two groups. In one group ($N = 32$), participants completed pure-task blocks in which each viewing task was completed in a separate block, with the ordering of tasks counterbalanced across participants. In the other group ($N = 48$), participants completed a single mixed-task block in which tasks were ordered randomly from trial-to-trial. All participants had normal or corrected-to-normal vision, were naive to the purpose of the study, and were informed of their rights of participation according to the University of Nebraska—Lincoln institutional review board.

Stimuli

Stimuli were 120 real-world scenes downloaded from the Internet. Scenes were 1024×768 pixels and presented in color. Each scene was unique but all depicted highly cluttered scenes from a variety of scene categories with several background and foreground elements. Scenes consisted of internal (e.g., bedrooms) and external (e.g., buildings) locations, none of which contained people. For the search task, participants determined whether the letter *N* or *Z* was present. Given that the purpose of the search task was to have participants search for the entire duration of the trial, a target was present in only five of the scenes such that it could be relatively easily found. The purpose of the five target-present trials was to ensure that participants believed a target was present in all trials (participants were also informed prior to the start of the experiment that the target was intentionally difficult to find and that most people find only 5–10 in total; they were assured, however, that the target was in fact present). For the memory task, a test display consisting of two side-by-side scenes (each 512×384

pixels) was presented at the end of each trial. Test displays contained the same scene as presented during the trial and a slightly modified version of that same scene. Modifications were either feature substitutions, object substitutions, mirror reversals, or magnitude changes, and were intended to be unpredictable and difficult to detect so as to encourage effortful memorization; modifications were made using Adobe Photoshop 5.0.

Apparatus

Eye-movements were recorded with an SR Research EyeLink 1000 (Mississauga, Ontario, Canada). Viewing was binocular but only the right eye was recorded. Thresholds for detecting the onset of saccadic movements were accelerations of $8000^\circ/s^2$, velocities of $30^\circ/s$, and a minimum amplitude of 0.5° . Movement offset was detected when velocity fell below $30^\circ/s$ and remained at that level for 10 consecutive samples. Calibration entailed a nine-point accuracy test followed by a nine-point validity test and was repeated if any point was in error by more than 1° or if the average error for all points was greater than 0.5° . Stimuli were displayed on a Pentium 4 PC with 19-inch VGA monitor (85 Hz) at a viewing distance of 90 cm. Testing took place in a dimly lit, sound attenuated testing room.

Procedure

There were 120 trials, five of which were the target-present trials on the search task (described above) and were not submitted to analysis. To initiate a trial, participants were required to fixate a central fixation cross and press the spacebar. A trial began with the onset of a task cue, which was either “search for *N* or *Z*,” “memorize the scene,” or “rate the pleasantness of the scene.” Cues were presented for 1 s and were immediately followed by onset of the imperative scene stimulus. In the search task, participants searched for a small *N* or *Z* (subtending 1° of visual angle). In the memory task, participants memorized the scene for a memory test that was given at the end of the trial. In the rating task, participants rated the pleasantness of the scene on a seven-point scale ranging from *like the scene very much* to *dislike the scene very much*. Cues preceded each trial, both for the pure-task and mixed-task blocks. Scenes were presented for a total of eight seconds.¹ At the end of each trial, participants used the mouse to indicate whether they had found an *N* or a *Z* (they were instructed

¹ For half of participants, a probe (red circle subtending 1° of visual angle) was presented on 75% of trials approximately 6 s into the viewing period and remained visible for the remainder of the trial. Participants were instructed that the probe was part of a trial-to-trial calibration procedure and that they should fixate the probe as quickly as possible when detected. Probes appeared at either a previous fixation location (either two or four fixations back) or at a randomly determined novel location. The purpose of the probes was to measure IOR along the lines of Klein and MacInnes (1999) and Dodd et al. (2009). However, because participants failed to detect probes on 17.9% of trials and failed to fixate probes within one saccade on 41.3% of trials, this measure was severely hampered by low statistical power. As such, we do not present this data. In the analyses presented here, only saccades commencing within the first 6 s of the trial (i.e., prior to probe presentation) were analyzed and participants were collapsed across the probe presentation factor (there were no significant differences in the timing of saccades or effects of predictors between groups that did or did not receive probes).

to guess if they did not find either), to indicate which of two scenes had been seen on that trial, or to indicate their rating of the scene. The test phase of the trial was self-paced. The intertrial interval was also self-paced given that participants initiated each trial. Experimental sessions lasted 45–60 min. The experiment was programmed in Python using PyGaze (Dalmaijer, Mathôt, & Van der Stigchel, 2015) and PsychoPy (Peirce, 2007).

Calculation of Relative Saccade Metrics

To measure the delay effect, we computed, for every fixation, the direction and amplitude of the ensuing saccade relative to either the immediately previous fixation location (1-back) or the one before that (2-back). Figure 1 illustrates the method for calculating relative saccade direction and amplitude. The logic of the method is the same as in previous work (Bays & Husain, 2012; Hooge, Over, van Wezel, & Frens, 2005; Klein & MacInnes, 1999; Luke, Schmidt, & Henderson, 2013; MacInnes & Klein, 2003; Smith & Henderson, 2009, 2011a, 2011b; Wilming, Harst, Schmidt, & König, 2013). Relative saccade direction (“ Δ Angle”) was calculated as the angular difference between the current saccade and the n -back saccade. A value of 0° indicates that the current saccade was directed toward the n -back location. Relative saccade amplitude (“ Δ Amplitude”) was calculated as the difference between the distance covered by the current saccade and the distance between the n -back and current fixation locations. Positive values indicate that the current saccade was larger than the distance to the n -back location (overshooting saccade), whereas negative values indicate it was smaller (undershooting saccade). Therefore, a saccade returning to the exact location of a previous fixation corresponds to Δ Angle = 0° and Δ Amplitude = 0° , whereas a forward saccade in the exact opposite direction corresponds to Δ Angle = 180° and Δ Amplitude = 0° . Accordingly, deviation from zero indicates the degree to which a saccade vector deviated away from the n -back location. As the delay effect is delayed return to a recent fixation location, we would therefore expect a reduction in fixation duration with increasing deviation from the n -back location (i.e., as Δ Angle and/or $|\Delta$ Amplitude| increases). Supplementary detail is provided in the Appendix.

Data Analysis

Saccades commencing within the first 6 s of a trial were considered for analysis. Additionally, all saccades with amplitudes less than 1° were removed to exclude corrective and microsac-

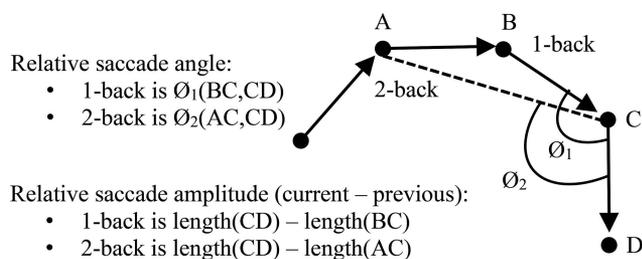


Figure 1. Method for calculating relative saccade direction (Δ Angle) and relative saccade amplitude (Δ Amplitude). Exact return saccades are defined as Δ Angle = 0° and Δ Amplitude = 0° .

ades, and only saccades with Δ Amplitude greater than -8° and less than 8° were included to exclude outliers (e.g., Smith & Henderson, 2009). Finally, all saccades with amplitudes greater than the distance to any one of the four edges of the scene were removed to exclude any possibility that changes in saccade direction were caused by scene boundaries (e.g., Bays & Husain, 2012). After all exclusions, 34,482 (pure-task blocks) and 49,576 (mixed-task block) saccades remained for 1-back analyses, and 32,455 (pure-task blocks) and 46,301 (mixed-task block) saccades remained for 2-back analyses.

Results

The findings are presented in four parts. To begin, we plot the observed distribution of relative saccade metrics and mean pattern of change in fixation duration for each n -back location. Next, for each n -back location, we report the omnibus effects of relative saccade metrics on fixation duration for each n -back location, marginalizing across task, block, and trial. We then report the effects of task, block, and trial for the 1-back location and then for the 2-back location. Finally, we perform an additional test to dissociate IOR and SM.

Observed Data

Figure 2 plots observed mean fixation duration as a function of Δ Angle (10° bins) for the 1-back (top panel) and 2-back (bottom panel) locations. For the 1-back location, there was a reduction in fixation duration with increasing Δ Angle that appeared mostly linear but which tapered-off at larger values of Δ Angle. For the 2-back location, there was a slight reduction in fixation duration with increasing Δ Angle at small values of Δ Angle but an increase in fixation duration with increasing Δ Angle at larger values. As the spatial extent of IOR decreases with increasing Δ Angle (e.g., Bennett & Pratt, 2001), a positive effect of Δ Angle² (combined with a negative effect of Δ Angle) may be interpreted as reflecting SM supplemented by IOR. Moreover, as the temporal cost of changing the direction of saccade is inversely proportional to Δ Angle (Smith & Henderson, 2009), a negative effect of Δ Angle (in the absence of an effect of Δ Angle²) may be interpreted as reflecting SM. Figure 3 plots observed mean fixation duration as a function of Δ Amplitude (2° bins) for the 1-back (left panel) and 2-back (right panel) locations. For both n -back locations, there was a peak in fixation duration at Δ Amplitude = 0° , indicating that fixations preceding saccades with the same amplitude as the n -back saccade tended to be longer than those preceding saccades that differed in amplitude from the n -back saccade. Thus, informal inspection of observed means suggested quadratic trends for the effects of Δ Angle and Δ Amplitude on fixation duration.

Effects of Relative Saccade Metrics

Model description. To confirm these observations statistically, a three-level linear mixed model in which individual saccades (Level 1) were nested within trials (Level 2) and within scenes (Level 3) and persons (Level 3) and in which scenes and persons were crossed (given that each person viewed each scene) was used to estimate quadratic effects of relative saccade metrics (estimated separately for each n -back location). We started with a

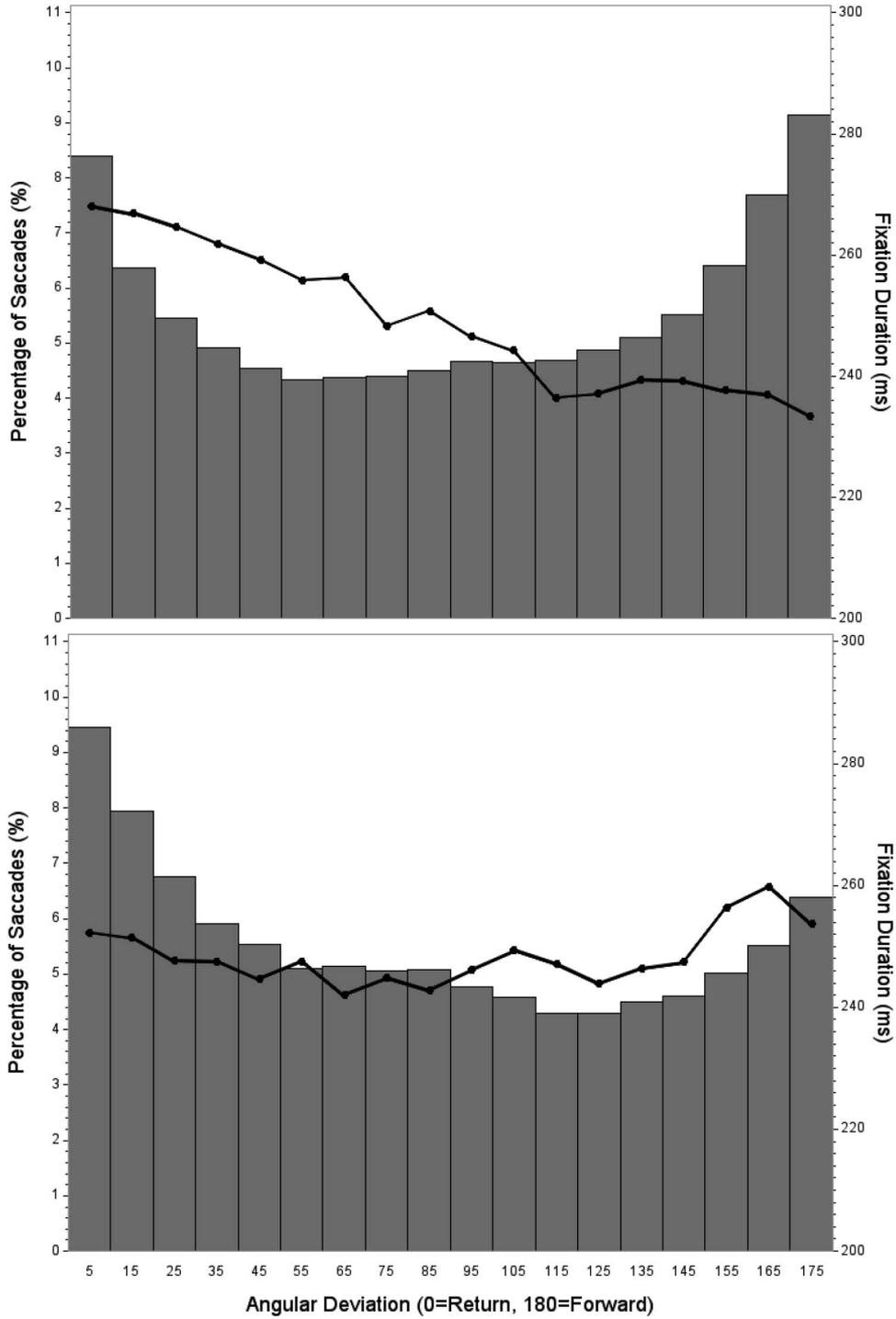


Figure 2. Observed mean fixation duration as a function of Δ Angle (10° bins) for the 1-back (top panel) and 2-back (bottom panel) locations (regression line), overlaid atop a density plot (bars) for the observed distribution of relative angles.

model including all main effects and interactions among the terms Δ Angle (centered at 0°), Δ Amplitude (centered at 0°), Δ Angle², Δ Amplitude², task (search, memory, rating), block (pure or mixed), and trial (repeat or switch), with block specified as a between-persons

factor, task as a within-person factor, and trial as a within-person contrast nested within the mixed-task block. Nonsignificant higher order interactions were removed from the model. Table 1 shows the parameter estimates and standard errors for the 1-back and 2-back

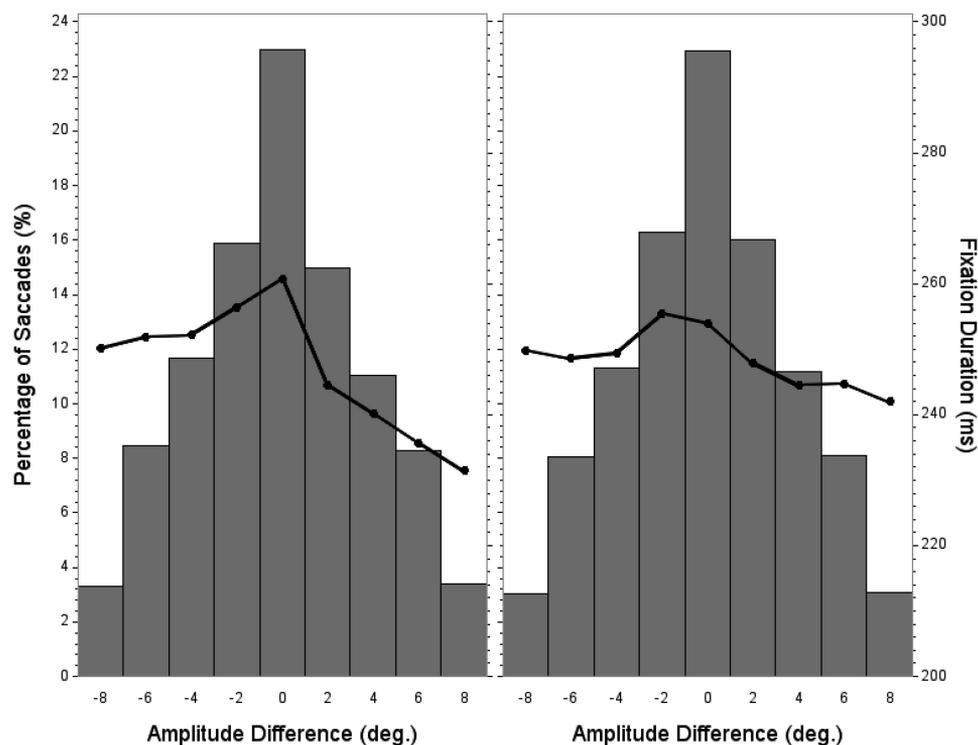


Figure 3. Observed mean fixation duration as a function of Δ Amplitude for the 1-back (left) and 2-back (right) locations (regression lines), overlaid atop a density plot for the observed distribution of relative amplitudes.

locations. Task, block, and trial were analysis-of-variance (effect) coded, so the estimates in Table 1 are for an average task, block, and trial. Bolded estimates indicate the parameter was significantly different from zero ($p < .05$). Note that unless stated otherwise, all effects reported below and presented on tables or in figures control for effects of Δ Amplitude at 0° .

Delay effect. The intercept is the predicted fixation duration (in milliseconds) when Δ Angle = 0° and Δ Amplitude = 0° , which represents the exact location of the n -back fixation. The effect of Δ Angle is the instantaneous linear rate of change in fixation duration per unit Δ Angle specifically when Δ Angle = 0° and Δ Amplitude = 0° . The coefficients were negative, indicating a significant reduction in fixation duration with increasing Δ Angle. The effect of Δ Angle² is how the effect of Δ Angle changes per unit Δ Angle specifically when Δ Amplitude = 0° . The coefficients were positive, indicating that the reduction in fixation duration at Δ Angle = 0° significantly lessened with increasing Δ Angle. The size of the overall delay effect (computed as the difference in fixation duration between return and forward saccades) is given by combining these terms, computed as, delay effect = $(\Delta$ Angle \times 180°) + $(\Delta$ Angle² \times 180° \times 180°). Negative values reflect delayed return time to the n -back location, whereas positive values reflect speeded return time. On average, the delay effect at the 1-back location was -42 ms ($SE = 2.9$, $p < .001$), whereas the delay effect at the 2-back location was 1.5 ms ($SE = 2.0$, $p = .70$). Thus, on average, saccades returning to the 1-back location were delayed relative to forward saccades whereas the timing of saccades returning to the 2-back location did not differ from forward saccades.

Interaction test for dissociating IOR and SM. If the delay effect was due to IOR, then there should be a spatially localized delay effect at the n -back location greater than that caused by simply reversing the direction of a saccade. The critical term in this regard is the Δ Angle \times Δ Amplitude interaction. The coefficients were negative indicating that when Δ Angle = 0° there was a reduction in fixation duration with larger absolute values of Δ Amplitude. That is, saccades landing exactly at the n -back location were preceded by longer fixations than saccades also directed at this location but which over- or undershot it. This can be seen in Figure 4 by the peak in fixation duration at Δ Angle = 0° / Δ Amplitude = 0° . This peak replicates previous work and is characteristic of a spatially localized IOR effect (Smith & Henderson, 2009, 2011a, 2011b). It is important that the interaction was significant at 1-back but not 2-back locations. Thus, for the average task, block, and trial, the delay effect at 1-back locations was attributable to both IOR and SM, whereas at 2-back locations the delay effect was attributable to SM alone.²

²For completeness, the Δ Amplitude and Δ Amplitude² terms indicate that saccades of the same amplitude as the previous saccade were preceded by longer fixations than saccades that were larger or smaller than the previous saccade. Moreover, smaller saccades (e.g., Δ Amplitude = -4°) were preceded by longer fixations than larger saccades (e.g., Δ Amplitude = 4°). As Δ Amplitude was centered at 0° , this is indicated statistically by a significant negative coefficient for Δ Amplitude. The Δ Angle \times Δ Amplitude² and Δ Angle² \times Δ Amplitude terms control the spatial extent of the inhibitory effect, indicating that it diminishes additively with Δ Amplitude and Δ Angle.

Table 1
Parameter Estimates (Est) and Standard Errors (SE) for Fixation Durations Preceding Saccades to the Immediately Previous Fixation Location (1-Back) and the One Before That (2-Back)

| Parameter | 1-Back | | 2-Back | |
|--|---------------|--------|---------------|--------|
| | Est | SE | Est | SE |
| Fixed effects | | | | |
| Intercept | 279 | 4.3 | 255 | 3.9 |
| ΔAngle ($0 = 0^\circ$) | -.33 | .04 | -.17 | .03 |
| ΔAngle^2 | .00041 | .00018 | .00098 | .00017 |
| $\Delta\text{Amplitude}$ ($0 = 0^\circ$) | -1.89 | 0.35 | -0.27 | 0.28 |
| $\Delta\text{Amplitude}^2$ | -.40 | .05 | -.15 | .03 |
| $\Delta\text{Angle} \times \Delta\text{Amplitude}$ | -.019 | .008 | -.002 | .002 |
| $\Delta\text{Angle}^2 \times \Delta\text{Amplitude}$ | .00011 | .00004 | | |
| $\Delta\text{Angle} \times \Delta\text{Amplitude}^2$ | .00164 | .00045 | | |
| Random effects | | | | |
| Saccade | 84.4 | 28.0 | 61.7 | 22.1 |
| ΔAngle | .0001 | .0001 | .0004 | .0005 |
| $\Delta\text{Amplitude}$ | .10 | .11 | .43 | .21 |
| Person | 965 | 162 | 808 | 134 |
| ΔAngle | .009 | .002 | .003 | .001 |
| $\Delta\text{Amplitude}$ | .90 | .31 | 1.15 | .35 |
| Trial | 16.1 | 5.0 | 16.0 | 4.8 |
| Residual | 16,454 | 79 | 15,525 | 74 |

Note. As the task, block, and trial variables were analysis-of-variance (effect) coded and as the ΔAngle and $\Delta\text{Amplitude}$ variables were centered $0^\circ/0^\circ$, the intercepts represent the predicted mean fixation duration preceding an exact return saccade on an average task, block, and trial. Reliable estimates ($p < .01$) are highlighted in bold.

One-Back Location: Effects of Task

Effect of task on delay effect, but no differences between single-task, repeat, and switch trials. There were significant Task \times ΔAngle interactions ($F = 3.98, p = .05$) and Task \times ΔAngle^2 interactions ($F = 2.81, p = .06$) but no significant effects of block or trial ($ps > .20$). Estimates of the intercept, ΔAngle , ΔAngle^2 , and delay effect are presented on Table 2 for each task, as well as for the difference between each task. As can be seen in Figure 5, which plots predicted mean fixation duration as a function of ΔAngle for each task, the effect of ΔAngle was more negative and the effect of ΔAngle^2 more positive for rating than search and memory. The $\Delta\text{Angle} \times \Delta\text{Amplitude}$ interaction was not moderated by task ($F = .84, p = .43$), indicating that the spatial extent of IOR was similar across tasks.

Two-Back Location: Effects of Task, Block, and Trial

Effect of task in single-task trials, but not in repeat or switch trials. Figure 6 plots predicted mean fixation duration as a function of ΔAngle for each task within pure-task (left panel) and mixed-task (right panel) blocks. There was a significant Block \times Task \times ΔAngle^2 interaction ($F = 2.98, p = .05$) attributable to a significant Task \times ΔAngle^2 interaction in pure-task ($F = 3.77, p = .02$) but not mixed-task ($F < 1$) blocks; within the mixed-task block, the Trial \times Task \times ΔAngle^2 interaction also was not significant ($F = 1.21, p = .30$), indicating similar effects of ΔAngle^2 in switch and repeat trials. Estimates of the intercept, ΔAngle , ΔAngle^2 , and delay effect for each task within pure-task blocks, as well as for the difference between tasks, are presented on Table 3. Accordingly, the effect of ΔAngle^2 was more positive for rating and memory than search. Moreover, the effect of ΔAngle^2 was significant for memory and rating but not search.

Switching tasks changes the sign of the linear parameter.

Estimates for the intercept, ΔAngle , ΔAngle^2 , and delay effect are presented on Table 3 for single-task, repeat, and switch trials. Estimates of switch cost (difference between switch and repeat trials) and mixing cost (differences between repeat and single-task trials) are also provided. Mixing cost was observed as a reduction in the effect of ΔAngle^2 , which was significantly positive in single-task trials but absent in repeat trials. This is shown in Figure 7 by a curved line for single-task trials and a straight line for repeat trials. Switch cost was observed as oppositely signed effects of ΔAngle in repeat versus switch trials: In repeat trials, ΔAngle was negative, indicating delayed return, whereas in switch trials, ΔAngle was positive, indicating speeded return. As this pattern did not interact with task ($F = 1.48, p = .23$), these results indicate a task-unspecific effect of switching. Moreover, as these effects were independent of $\Delta\text{Amplitude}$, as indicated by the nonsignificant Trial \times $\Delta\text{Angle} \times \Delta\text{Amplitude}$ interaction ($F < 1$), these results suggest that trial moderated SM.

Two-Back Saccades: Effect of Previous Saccade Direction

Although the results of the interaction test support the SM account of the delay effect at 2-back locations, this support comes from null findings (the lack of differences between exact return saccades and return saccades that under- or overshoot the 2-back location). A stronger test would be an analysis that predicts the presence of a difference between saccade characteristics, not the lack of a difference. This can be achieved by considering the relative direction of both the current saccade (ΔAngle) and the preceding saccade (ΔAngle_{n-1}) under conditions for which the SM and IOR accounts would lead to different directional predic-

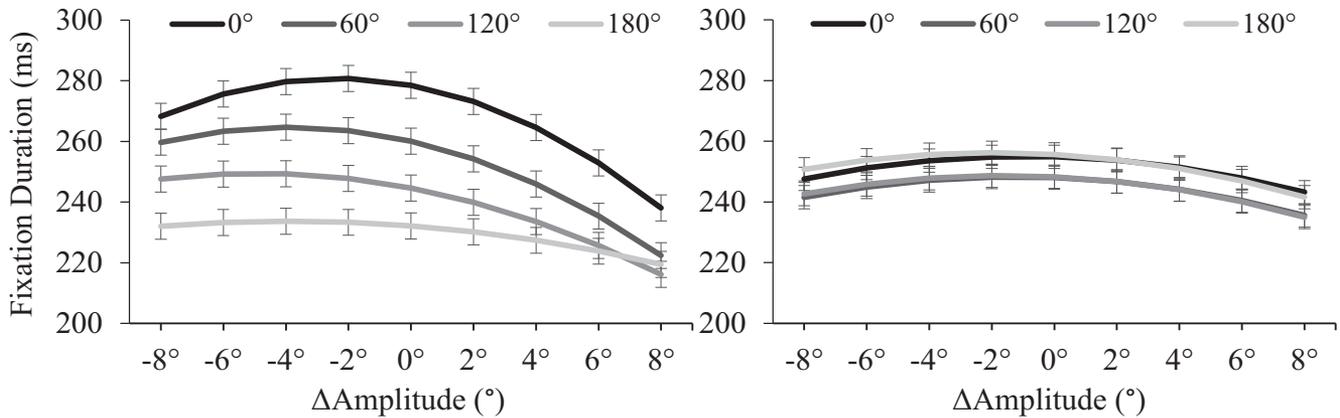


Figure 4. Predicted mean fixation duration preceding saccades of different directions relative to the 1-back (left) and 2-back (right) locations as a function of relative amplitude, averaging over task, block, and trial. The 1-back data show a peak in fixation duration preceding exact return saccades ($\Delta\text{Angle} = 0^\circ$ and $\Delta\text{Amplitude} = 0^\circ$) characteristic of a spatially localized inhibitory effect, whereas the 2-back data show no such peak. Error bars represent ± 1 standard error.

tions. Figure 8 provides a schematic illustration of one such example where different predictions are made (cf. Pratt, Spalek, & Bradshaw, 1999, Experiment 4). If the saccade preceding the current saccade is directed toward the 2-back location, SM predicts that the time taken to execute the current saccade should increase with increasing ΔAngle (speeded return). This is because a temporal cost is incurred when a saccade changes its direction relative to the previous saccade. The current saccade should be faster to return to the 2-back location than other locations, therefore, because the vector of the previous saccade is repeated.³ As ΔAngle_{n-1} increases, SM predicts that the effect of ΔAngle should gradually change sign. Thus, SM predicts a $\Delta\text{Angle}_{n-1} \times \Delta\text{Angle}$ interaction such that small values of ΔAngle_{n-1} cause speeded return whereas large values cause delayed return.⁴ The IOR account, in contrast, predicts that the time taken to execute the current saccade should decrease with increasing ΔAngle (delayed return) regardless of ΔAngle_{n-1} . This is because saccades should be inhibited from returning to a recently fixated location regardless of the direction of the previous saccade.

As can be seen in Figure 9, the pattern of results are consistent with the predictions of SM. This was evidenced by a significant $\Delta\text{Angle}_{n-1} \times \Delta\text{Angle}$ interaction ($Estimate = -.006$, $SE = .002$, $p = .02$), indicating that the effect of ΔAngle decreased with increasing ΔAngle_{n-1} and eventually changed sign. For instance, when $\Delta\text{Angle}_{n-1} = 0^\circ$, the effect of ΔAngle was positive, indicating that fixation duration increased with increasing ΔAngle (i.e., a positive delay effect, reflecting speeded return to the 2-back location). In contrast, when $\Delta\text{Angle}_{n-1} = 180^\circ$, the effect of ΔAngle was negative, indicating that fixation duration decreased with increasing ΔAngle (i.e., a negative delay effect, reflecting delayed return to the 2-back location).

Discussion

The present study investigated task-set control of gaze behavior using the delay effect (temporal delay in the initiation of saccades directed toward a previous fixation location relative to other loca-

tions) as a measure of task performance. We used a pure/mixed design in which three different tasks were performed in isolation (pure-task blocks) or intermixed across trials (mixed-task blocks) to decompose two aspects of control processes involved in changing tasks: mixing cost (difference in task performance between repeat and pure trials) and switching costs (difference in task performance between switch and repeat trials). We expected the requirement to change tasks to reduce, eliminate, or otherwise alter the expression of the delay effect. The major finding was substantial switch and mixing costs on the delay effect at the 2-back location. From the considerations that follow, our principal conclusion is that saccade- and fixation-relevant parameters that vary by task may be represented and switched as part of a task-set. Before discussing the mixing and switching costs, we first consider the overall effects of relative saccade metrics, followed by effects of task on the delay effect.

The Delay Effect

The delay effect was represented by the effect of relative saccade direction on the timing of the saccade. As in previous work (Bays & Husain, 2012; Dodd et al., 2009; Hooge et al., 2005; Klein & MacInnes, 1999; Luke et al., 2013; MacInnes & Klein, 2003; Smith & Henderson, 2009, 2011a, 2011b; Wilming et al., 2013), there was a general tendency for fixations preceding saccades directed toward a recent fixation location to be prolonged relative

³ This could actually result in two possible outcomes, either of which are consistent with SM. One possibility is the one outlined in the text. The other is that the direction of the previous saccade could simply disrupt the momentum of the current saccade such that there would be no effect at all of ΔAngle (cf. Pratt et al., 1999, Experiment 4).

⁴ Note that the predictions of SM are most directly observed when the previous saccade is an undershooting saccade. This is because an undershooting previous saccade allows for both the previous and current saccades to be unambiguously directed at the 2-back location, which is the feature that permits the present test. Therefore, we included only previous saccades that undershot the 2-back location by more than 1° .

Table 2
One-Back Model Parameter Estimates (Est) and Standard Errors (SE)

| Parameter | Intercept | | ΔAngle | | ΔAngle^2 | | Delay | |
|---------------|--------------|-----|----------------------|-----|------------------------|--------|--------------|-----|
| | Est | SE | Est | SE | Est | SE | Est | SE |
| Task | | | | | | | | |
| Memory | 270 | 4.6 | -.30 | .05 | .00032 | .00030 | -43.4 | 3.3 |
| Rating | 287 | 4.7 | -.47 | .06 | .00074 | .00031 | -60.7 | 3.4 |
| Search | 279 | 4.7 | -.23 | .06 | .00018 | .00031 | -35.0 | 3.4 |
| Difference | | | | | | | | |
| Search-memory | 9.2 | 1.7 | .07 | .05 | -.00014 | .00022 | 8.4 | 6.1 |
| Search-rating | -8.7 | 1.8 | .24 | .05 | -.00056 | .00023 | 25.7 | 6.3 |
| Memory-rating | -17.9 | 1.8 | .17 | .05 | -.00043 | .00022 | 17.3 | 6.2 |

Note. Parameter estimates and standard errors for each task and the difference between them. Estimates of the delay effect are also provided, computed as $\text{Delay} = (\Delta\text{Angle} \times 180^\circ) + (\Delta\text{Angle}^2 \times 180^\circ \times 180^\circ)$, where negative values reflect delayed return to the 1-back location. Reliable estimates ($p < .05$) are highlighted in bold.

to fixations preceding saccades in other directions. This was evidenced by significant linear effects of relative direction at both the 1-back and 2-back locations. To identify the source of this delay—namely, whether it was due to SM (the tendency for the eyes to move in the same direction as the previous saccade) or IOR (the avoidance of a previously fixated location)—we assessed the spatial specificity of the delay in two ways. First, we tested a quadratic parameter for the effect of relative direction. Deviations from linearity in this effect would suggest that an extra process contributed to the delay effect above and beyond that associated with changing saccade direction (cf. Wilming et al., 2013). Overall, the quadratic parameter was significant for both the 1-back and 2-back locations. Thus, SM alone was insufficient to account for the delay effect.

Second, we tested for an interaction of relative direction and relative amplitude (Smith & Henderson, 2009). If the delay effect was due in part to spatially localized inhibition at the previous fixation location, then saccades landing exactly at this location should be preceded by longer fixations than saccades also directed at this location but which over- or undershot it. The interaction was significant at the 1-back location, indicating that IOR and SM both contributed to the delay effect. In contrast, the interaction was not significant at the 2-back location, indicating that IOR at the 2-back

locations did not contribute to the delay effect. On the one hand, this might be taken as evidence that SM alone accounted for the delay effect at 2-back locations (Smith & Henderson, 2009, 2011a, 2011b). On the other hand, the significant quadratic parameter implies an additional process. For instance, Wilming et al. (2013) estimated a latent change point model with two slopes (a model conceptually similar to the present quadratic model) and also found a breakpoint in the linear effect that could not be attributed to IOR. They hypothesized that their two linear parameters might be due to two mechanisms that contribute to eliciting saccades with different dependencies on relative direction. It should be noted, however, that although the intervening saccade in our 2-back analysis could have been in any direction relative to the 2-back location, most were either toward or away (see Figure 2). Consequently, the direction of the intervening saccade should figure prominently into the directional bias of the current saccade. Specifically, if the delay effect at the 2-back location was due to SM, then a negative effect of relative direction (i.e., delayed return) should be observed when the previous saccade was directed away from the 2-back location whereas a positive effect (i.e., speeded return) should be observed when it was directed toward. This prediction was confirmed: speeded return was observed when the previous saccade was directed toward the 2-back location, whereas delayed return was observed when it was directed away. This supports the conclusion that the delay effect at 2-back locations was attributable to SM. We refer to this speeding-up of return saccades as “reverse” saccadic momentum (rSM) in recognition of the fact that it was caused by repetition of the previous saccade program just as SM, but whereas SM is a general benefit at forward locations, rSM is a contextual benefit at return locations.

These findings have two important implications regarding the currently controversial issue of oculomotor IOR in scene viewing. First, there is mixed evidence on the temporal properties of the delay effect. The preponderant suggestion in the literature is that the delay effect reflects the operation of an inhibitory mechanism (i.e., IOR) responsible for directing attention to novel locations in support of optimal foraging strategies. The dominant finding of SM in the present study and the repeated finding of SM across multiple studies (Luke et al., 2013; Smith & Henderson, 2009, 2011a, 2011b; Wilming et al., 2013), however, indicates that the delay effect cannot be attributed entirely to IOR.

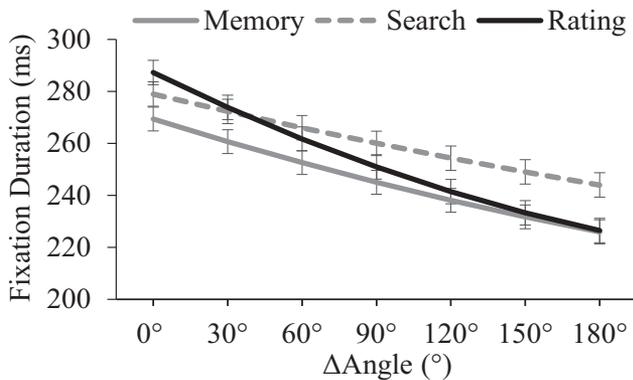


Figure 5. One-back model. Predicted mean fixation duration as a function of relative saccade direction for each task, averaging across block and trial. Error bars represent ± 1 standard error.

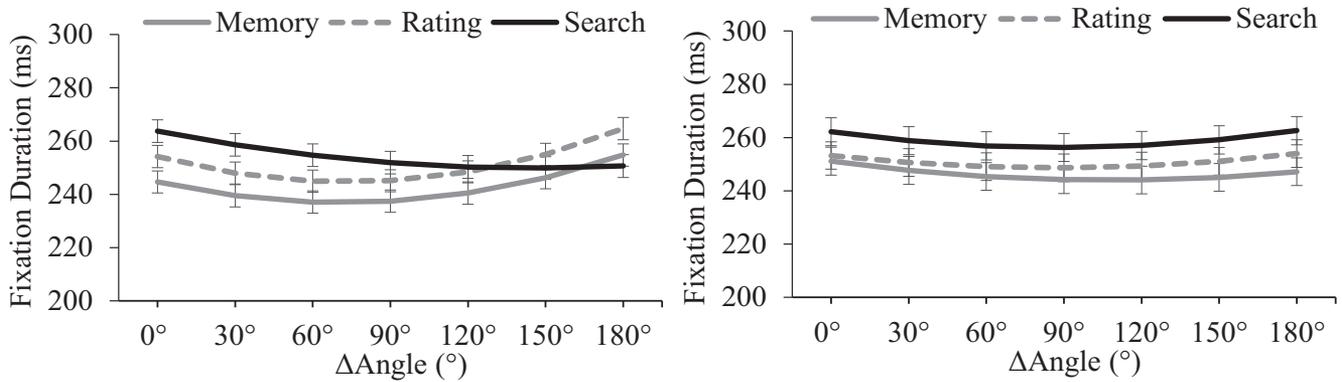


Figure 6. Two-back model. Predicted mean fixation duration as a function of relative saccade direction for each Task within pure-task (left) and mixed-task (right) blocks. Error bars represent +/- 1 standard error.

Second, the finding that particular characteristics of individual saccades within a sequence of saccades is a critical factor in predicting whether the delay effect manifests as speeded or delayed return brings order to inconsistencies in the literature on the expression oculomotor delay in scene viewing. The pattern of results from the directionally specific test of SM replicate the noncorroborating results of Dodd et al. (2009) and Smith and Henderson (2009) regarding the temporal-FOR effect. Dodd et al. reported IOR during a search task but temporal-FOR during memory, rating, and free-view tasks. Using a similar memory task and similar scenes, Smith and Henderson (2009) reported null effects in their memory task (however, the direction of the effect was consistent with a delay effect). The present study showed that when the direction of the previous saccade relative to the 2-back location is included as a predictor that temporal-FOR, temporal-delay, and null effects are all predicted depending on the current saccade's direction relative to the 2-back location and the previous saccade's direction relative to the 2-back location (see Figure 8). Moreover, the pattern of results is predicted by SM. Thus, the

interaction confirms the existence of temporal-FOR and showed that temporal-FOR is "reversed" SM that occurs when preceding and current saccades are both directed toward the 2-back location. Accordingly, the reason temporal-FOR may not be observed is because it depends on characteristics of the previous saccade.

Task-Dependent Delay

The magnitude of delay effect at the 1-back location differed by task, regardless of block or trial. More specifically, tasks differed on the quadratic parameter. This suggests that the IOR component of the delay differed between tasks, which was confirmed by the interaction test described above (i.e., the significant Direction × Amplitude interaction did not differ by task). This result extends the task-dependent nature of IOR experienced by saccades executed in response to onsets (Dodd et al., 2009) to freely executed saccades as well as to 1-back locations. Consistent with the idea that the delay effect represents a task-dependent fixation selection strategy (Castel, Pratt, Chasteen, & Scialfa, 2005; Dodd et al.,

Table 3
Two-Back Model Parameter Estimates (Est) and Standard Errors (SE)

| Parameter | Intercept | | ΔAngle | | ΔAngle ² | | Delay | |
|--------------------|--------------|-----|-------------|-----|---------------------|--------|--------------|-----|
| | Est | SE | Est | SE | Est | SE | Est | SE |
| Single-task trials | 254 | 5.6 | -.22 | .05 | .00133 | .00026 | 2.5 | 2.9 |
| Memory | 245 | 6.1 | -.22 | .08 | .00152 | .00044 | 10.2 | 4.2 |
| Rating | 254 | 6.1 | -.26 | .08 | .00177 | .00045 | 10.5 | 4.3 |
| Search | 264 | 6.2 | -.19 | .08 | .00065 | .00046 | -13.2 | 4.4 |
| Search-memory | 19.2 | 6.7 | .03 | .08 | -.00087 | .00042 | -23.4 | 7.1 |
| Search-rating | 10.7 | 6.8 | .07 | .09 | -.00112 | .00054 | -23.7 | 7.3 |
| Memory-rating | -9.9 | 6.8 | .04 | .09 | -.00025 | .00056 | -0.3 | 7.3 |
| Mixed-task trials | | | | | | | | |
| Repeat | 270 | 6.0 | -.24 | .11 | .00012 | .00058 | -37.6 | 5.2 |
| Switch | 241 | 5.3 | .02 | .08 | .00119 | .00043 | 35.7 | 4.0 |
| Costs | | | | | | | | |
| MC (repeat-single) | 16.1 | 7.8 | -.01 | .12 | -.00122 | .00060 | -40.1 | 5.8 |
| SC (switch-repeat) | -29.7 | 6.3 | .27 | .13 | .00107 | .00092 | 73.3 | 7.7 |

Note. As parameters did not differ by task on repeat or switch trials, marginal values are reported for these trials. Also shown are estimates for (a) delay effect (Delay = ΔAngle × 180° + ΔAngle² × 180° × 180°), where negative values reflect delayed return to the 2-back location and positive values reflect speeded return, (b) mixing cost (MC = repeat - single), and (c) switching cost (SC = switch - repeat). Reliable estimates (p < .05) are highlighted in bold.

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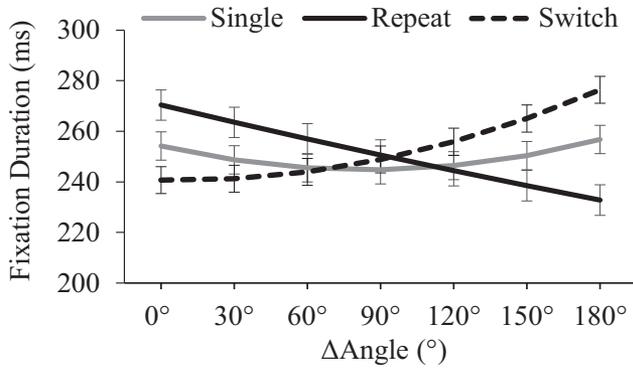


Figure 7. Two-back model. Predicted mean fixation duration as a function of relative saccade direction for single-task, repeat, and switch trials. Error bars represent ± 1 standard error.

2009; Lupiáñez, Milliken, Solano, Weaver, & Tipper, 2001), the dependency on task suggests that IOR is under control of task-set and/or moment-to-moment processing requirements.

At the 2-back location, the quadratic parameter of the delay effect also differed by task (however, this effect was restricted to single-task trials). Calculating the overall size of this delay as the difference in preceding fixation duration between exact return and exact forward saccades showed that return was delayed in search but speeded in memory and return. This pattern replicates Dodd et al.'s (2009) 2-back and 4-back findings, which they interpreted as IOR in search and temporal-FOR in memory and rating. However, it does not seem that the quadratic parameter should be interpreted as IOR. First, calculating the size of the delay in this way obscures the fact that, in memory and rating, there was in fact a negative effect of relative direction (i.e., delayed return) for larger changes in direction (i.e., $\Delta\text{Angle} < 90^\circ$). A positive effect, presumably reflecting temporal-FOR, was observed only for smaller changes (i.e., $\Delta\text{Angle} > 90^\circ$). Second, the quadratic parameter was not

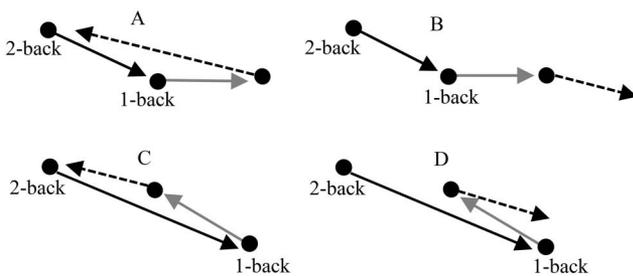


Figure 8. Diagram illustrating a test for dissociating IOR and SM accounts of the delay effect at the 2-back location. Dashed arrows represent the current saccade and gray arrows represent the saccade that preceded it. When the previous saccade is directed away from the 2-back location (A and B), IOR and SM accounts both predict that the time taken to execute the current saccade will be longer for return (A) versus forward (B) saccades. Critically, however, when the previous saccade is directed toward the 2-back location (C and D), IOR and SM accounts make opposite predictions: whereas the IOR account predicts that the time taken to execute the current saccade will be *longer* for return (C) versus forward (D) saccades, the SM account predicts that the time taken to execute the current saccade will be *shorter* for return (C) versus forward (D) saccades.

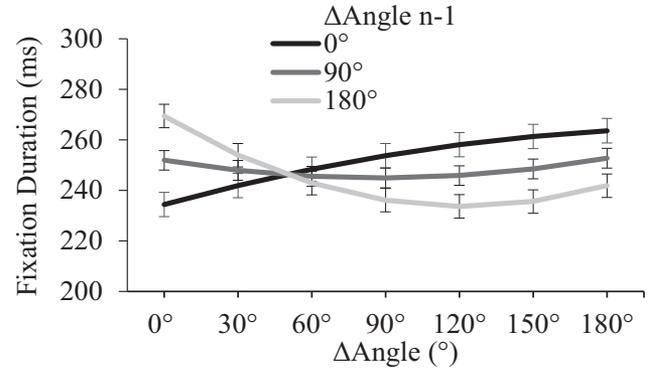


Figure 9. Two-back model: Effect of previous saccade direction. Predicted mean fixation duration as a function of relative saccade direction for saccades preceded by a return saccade ($\Delta\text{Angle}_{n-1} = 0^\circ$), a perpendicular saccade ($\Delta\text{Angle}_{n-1} = 90^\circ$), or a forward saccade ($\Delta\text{Angle}_{n-1} = 180^\circ$), averaging over task, block, and trial. Error bars represent ± 1 standard error.

significant in the search task. Moreover, the interaction test was not significant overall (indicating the absence of IOR) and did not differ by task. Thus, there was no evidence of IOR in search or for saccades of large changes in direction in memory and rating. Finally, as the name implies, temporal-FOR should be observed as a spatially specific effect of relative direction on the return location. This was not the case, however, as a positive effect of relative direction was observed only for smaller changes in direction. In other words, it was not the case that return saccades were speeded (due to temporal-FOR) but rather that forward saccades were delayed (due to rSM).

The present effect of task on the delay effect at 1-back and 2-back locations agrees with the findings of Dodd et al. (2009), as well as with Bays and Husain's (2012) finding that the magnitude of IOR at 1-back locations differed by task. Moreover, our finding that SM and IOR both contribute to the delay effect at 1-back locations regardless of task also agrees with a number of studies (Luke et al., 2013; Smith & Henderson, 2009, 2011a, 2011b; see Table 4 for a summary of existing findings for SM, IOR, and temporal-FOR in scene viewing tasks). In disagreement with our results, Bays and Husain (2012) found no evidence at all for SM; Wilming et al. (2013) found no evidence at all for IOR; and although Smith and Henderson (2009) did not examine effects of task on the delay effect, they used a similar memory task and found a null delay effect at the 2-back location (as opposed to the speeded return observed here).

Although rSM offers a potentially simple account for discrepancies between studies in the expression of the delay effect at 2-back locations, discrepancies in the source of the delay effect are harder to reconcile. Our finding that effects of task were restricted to single-task trials, however, may hint that context is crucial in determining the nature of the delay effect: That the same task on the same stimuli elicited different gaze behavior in pure- versus mixed-task blocks suggests that global control processes (e.g., reallocation of working memory resources) may prove critical. As an example, IOR may be the preferred mechanism for driving gaze through a scene whenever capacity is available to "tag" locations, whereas SM may be preferred whenever capacity is unavailable.

Table 4
 Summary Table of Existing Findings for SM, IOR, and Temporal-FOR

| Source | Method | <i>n</i> -back | Task | Delay (ms) | Account |
|---------------------------|--------|----------------|----------------|----------------|----------|
| Klein & MacInnes (1999) | Probe | 1 | Search | -20 | Unclear |
| | Probe | 2 | Search | -57 | IOR |
| MacInnes & Klein (2003) | Probe | 1 | Search | -47 | IOR |
| | Probe | 2, 4, 6 | Search | -70 -82 -2 | IOR |
| Dodd et al. (2009) | Probe | 2, 4, 6 | Memory | 32 13 4 | FOR |
| | Probe | 2, 4, 6 | Rating | 60 60 68 | FOR |
| | Probe | 2, 4, 6 | Free-view | 43 32 -4 | FOR |
| | Probe | 1 | Memory | -33 | SM + IOR |
| Smith & Henderson (2009) | Free | 1 | Memory | -78 | SM + IOR |
| | Probe | 2 | Memory | -30 | SM |
| | Free | 2 | Memory | -46 | SM |
| | Probe | 1 | Search | -28 | SM + IOR |
| Smith & Henderson (2011a) | Free | 1 | Search | -28 | SM + IOR |
| | Probe | 1 | Search | -36 | SM + IOR |
| Smith & Henderson (2011b) | Probe | 2 | Search | -19 | SM |
| | Free | 1 | Free-view | -64 | IOR |
| | Free | 1 | Preview search | -27 | IOR |
| Luke et al. (2013) | Free | 1 | Memory | -13 | SM + IOR |
| Wilming et al. (2013) | Free | 1 | Variety | -45 | SM |

Note. For the size of the delay, negative values indicate delayed return and positive value indicate speeded return. SM = saccadic momentum; IOR = inhibition of return; Temporal-FOR = temporal facilitation of return.

This could explain why Bays and Husain (2012) found evidence for IOR-only in free-view and preview search tasks (tasks with relatively minimal demands on memory), whereas Wilming et al. (2013) found evidence for SM-only in a delayed patch recognition task (a task requiring memory for where in a sample image the target patch was selected). More research is needed to test this claim but at present we use it to illustrate the more general point that the “choice of mechanism” for driving gaze through a scene may be strategic, and contextual factors may weigh heavily on strategy selection.

Trial-Dependent Delay

The main finding was that switching tasks flipped the pattern of the delay effect at 2-back locations such that delayed return was observed on repeat trials whereas speeded return was observed on switch trials. It is important to note that the present design allowed us to separate the cost for switching tasks from the cost for other processes. It could be that differences in working memory load (number of task rules stored), task-uncertainty (the degree to which participants can anticipate the identity of the task in each upcoming trial), or decision strategy cause the difference in the delay effect between repeat and switch trials rather than switching task sets. For instance, working memory load is greater in mixed-task versus pure-task blocks, which could contribute to differences in the delay effect (Los, 1996; Rogers & Monsell, 1995). In pure-task trials, the task is perfectly predictable on each trial, whereas in a mixed-task trials the identity of the next task is uncertain until cued at the beginning of each trial; this uncertainty may restrain participants from preparing as effectively in mixed-task versus pure-task trials, which could contribute to differences in the delay effect (Braver et al., 2003; Los, 1996). Decision strategies might differ in the face of mixed-task versus pure-task blocks, which could also contribute to differences in the delay effect.

Costs of these global processes are contained in mixing cost, which contrasts single-task and repeat trials and reflects the extra effort involved in potentially (but not actually) having to switch to another task. Although there was a substantial mixing cost (observed as a reduction in the quadratic parameter of the delay effect such that the positive quadratic in pure-task blocks was reduced to zero in repeat trials), the paradigm of distinguishing mixing and switch costs allowed us to capture the effects of these processes on the delay effect while keeping switch cost unaffected by them. Accordingly, the difference in the delay effect between repeat and switch trials represents the cost of local processes involved in switching task sets rather than the cost of global processes. We conclude that saccade- and fixation-relevant parameters that vary by task may be represented and switched as part of a task-set.

There are two general accounts of switching costs. Reconfiguration accounts (De Jong, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001) assume that switching tasks requires a process that operates on an abstract, hierarchically higher level than that of specific tasks. Such processes may involve retrieving task rules from long-term memory into working memory (Logan & Gordon, 2001; Mayr & Kliegl, 2000, 2003; Monsell & Mizon, 2006), or inhibiting a no-longer relevant task-set (Mayr & Keele, 2000). Carryover accounts suggest switching costs reflect inertia in (Allport et al., 1994) or associative reactivation of (Waszak, Hommel, & Allport, 2003) task-specific attentional settings, not just the stimulus-response mappings.

Although the nature of the local control processes and their eliciting conditions as it relates to switch costs in gaze behavior remains to be determined, the general idea that gaze control parameters are represented in task sets is conceivably compatible with either a reconfiguration or carryover account. For example, if return saccades serve as a rehearsal function (e.g., Zelinsky, Loschky, & Dickinson, 2011), then tasks requiring more rehearsal (e.g., memorization) would need a mechanism for making trial-to-

trial adjustments to gaze control settings, raising and lowering the criterion to execute a return saccade as warranted by task goals. Implementing such adjustments, however, may be effortful or time consuming and, thus, may have deleterious effects on performance in switch trials. As the relevant return rate may need to be represented and switched as part of a task-set, however, these representations may be susceptible to carryover effects associated with characteristics of the previous task, response, or stimulus and, thus, may have deleterious effects on performance in switch trials but beneficial effects in repeat trials.

Many open questions remain. One particularly relevant issue is whether the mixing and switching costs observed here with complex tasks are due to the same sorts of mechanisms that have been proposed to explain the mixing and switching costs observed in traditional paradigms with simple tasks. Multistep tasks are more complex and may require additional layers of control (e.g., subgoals need to be established and prioritized, triggers need to be set in prospective memory to initiate subtasks when the conditions for them become ripe, transitions between subtasks need to be managed to avoid capture of behavior by habitual transitions). It may be the management of these subgoals that requires control processes in complex tasks. A related issue is whether traditionally critical variables such as cue-stimulus-interval (i.e., preparation time) carry the same significance in the study of oculomotor control processes. In addition to possible differential effects that some variables might have in complex versus simple tasks, it is also possible that complex tasks may be sensitive to variables that are not particularly relevant for simple skills. For example, attentional focus seems to mainly influence complex tasks (Wulf & Shea, 2002). More sophisticated experiments are needed to elucidate these questions. It is possible, however, that task-switching methods offer particularly favorable conditions in which these questions can be investigated.

In conclusion, task-switching methods have long been used to study cognitive control processes but only recently have attempts been made to extend these methods to the study of oculomotor control processes. The present results provide preliminary evidence of mixing and switching costs on gaze control parameters, thus demonstrating the sensitivity of oculomotor control processes to general task contexts and changing situational demands.

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(Appendix follows)

Appendix

Method for Computing Saccade Characteristics

For every fixation, the direction and distance of the ensuing saccade was computed relative to the immediately previous fixation (1-back) and the one before that (2-back). The schematic in Figure 2 shows how the angle between two vectors, \emptyset , was used to compute relative direction (ΔAngle) and how vector length was used to compute relative distance ($\Delta\text{Amplitude}$). Relative to the 1-back fixation location, B, the direction of the saccade launching from the current fixation location C is given by $\emptyset_1(\text{BC}, \text{CD})$; i.e., the angle formed by vectors BC and CD). For example, had the direction of the saccade launching from C perfectly repeated the direction of the immediately previous saccade that launched from B, then \emptyset_1 would equal 180° , which would indicate no change in saccade direction (i.e., that the vectors formed a straight line, defined as $\Delta\text{Angle} = 180^\circ$). Similarly, relative to the 2-back fixation location, A, the direction of the saccade launching from C is given by $\emptyset_2(\text{AC}, \text{CD})$, where segment AC is simply a straight line connecting the 2-back and current fixation location derived from the x, y coordinates at those locations. Thus, had the saccade launching from C been directed toward the 2-back fixation location, then \emptyset_2 would equal 0° , which would indicate a reversal in saccade direction (i.e., that the current saccade was directed back toward the location of the 2-back fixation, defined as $\Delta\text{Angle} = 0^\circ$).

Notice that the relative direction of a saccade does not contain information about where the saccade actually landed. This means that a saccade may be directed back toward a previous fixation location (i.e., $\Delta\text{Angle} = 0^\circ$) without actually landing there (i.e., the saccade may over- or undershoot that location). As such, any assessment of a spatially localized effect such as IOR requires a measure that indexes relative distance (i.e., the difference between the distance separating the n -back and current fixation locations

and the distance traversed by the saccade launched from the current fixation location). This measure was provided by relative saccade amplitude ($\Delta\text{Amplitude}$). Accordingly, the distance of a saccade relative to the 1-back location was computed as the difference in amplitude between the current and previous saccade (current - previous). In Figure 2, this is represented as the difference between the length of CD and the length of BC. Similarly, the distance of a saccade relative to the 2-back location was computed as the difference between the amplitude of the current saccade and the distance separating the 2-back and current fixation locations—that is, $\text{length}(\text{CD}) - \text{length}(\text{AC})$. Thus, when $\Delta\text{Amplitude} = 0^\circ$, this means that the amplitude of the current saccade was equivalent to the distance separating the current and previous fixation locations—for example, $\text{length}(\text{CD}) = \text{length}(\text{AC})$. When $\Delta\text{Amplitude} > 0^\circ$, this means that the amplitude of the current saccade exceeded the distance separating the current and previous fixation locations—for example, $\text{length}(\text{CD}) > \text{length}(\text{AC})$. When $\Delta\text{Amplitude} < 0^\circ$, this means that the amplitude of the current saccade was less than this distance—for example, $\text{length}(\text{CD}) < \text{length}(\text{AC})$. Taken together, when $\Delta\text{Angle} = 0^\circ$ (indicating that the current saccade was directed back toward the n -back location) and $\Delta\text{Amplitude} \neq 0^\circ$, this means that although the current saccade was directed at the n -back location, it did not land there; rather, it either overshoot ($\Delta\text{Amplitude} > 0^\circ$) or undershot ($\Delta\text{Amplitude} < 0^\circ$) the n -back location. Only when $\Delta\text{Angle} = 0^\circ$ and $\Delta\text{Amplitude} = 0^\circ$ would a saccade land exactly at the n -back fixation location.

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