Context-dependent sequential effects of target selection for action

Jeff Moher

Cognitive, Linguistic & Psychological Sciences,
Brown University, Providence, RI, USA

Cognitive, Linguistic & Psychological Sciences,
Brown University, Providence, RI, USA
Brown Institute for Brain Sciences, Brown University,
Providence, RI, USA

Joo-Hyun Song

Humans exhibit variation in behavior from moment to moment even when performing a simple, repetitive task. Errors are typically followed by cautious responses, minimizing subsequent distractor interference. However, less is known about how variation in the execution of an ultimately correct response affects subsequent behavior. We asked participants to reach toward a uniquely colored target presented among distractors and created two categories to describe participants' responses in correct trials based on analyses of movement trajectories; *partial errors* referred to trials in which observers initially selected a nontarget for action before redirecting the movement and accurately pointing to the target, and *direct movements* referred to trials in which the target was directly selected for action. We found that latency to initiate a hand movement was shorter in trials following partial errors compared to trials following direct movements. Furthermore, when the target and distractor colors were repeated, movement time and reach movement curvature toward distractors were greater following partial errors compared to direct movements. Finally, when the colors were repeated, partial errors were more frequent than direct movements following partial-error trials, and direct movements were more frequent following direct-movement trials. The dependence of these latter effects on repeated-task context indicates the involvement of higher-level cognitive mechanisms in an integrated attention-action system in which execution of a partial-error or direct-movement response affects memory representations that bias performance in subsequent trials. Altogether, these results demonstrate that whether a nontarget is selected for action or not has a measurable impact on subsequent behavior.

Introduction

Everyday human behavior involves frequent interactions with multiple objects in complex visual environments. Selection of an individual object for action requires deployment of limited attentional resources to that object. Because attention and action systems are linked, the motor system does not merely reflect the output of higher-level cognitive processes; instead, attention and action operate concurrently with motor programs being initiated before attention and decision processes are necessarily finalized (e.g., Cisek, 2007; Song & Nakayama, 2009; Spivey & Dale, 2006). Thus, reach trajectories can reveal the temporal evolution of the selection process, providing the potential for insights into the nature of selection for action.

Song and Nakayama (2006; see also Song & Nakayama, 2008) examined target selection in a visually guided reaching task by asking observers to reach toward a uniquely colored target stimulus. When the target and distractor colors were repeated over consecutive trials, reach movements toward the target were faster, reflecting a "priming of pop-out" (POP) effect (e.g., Maljkovic & Nakayama, 1994). This result expands on previous POP studies in button-press and eye-movement tasks (Bichot & Schall, 1999; Maljkovic & Nakayama, 1994, 1996; McPeek, Maljkovic, & Nakayama, 1999), demonstrating that selection can be biased by recent experience (e.g., Chun & Jiang, 1998; Chun & Nakayama, 2000; Desimone & Duncan, 1995; Downing, 2000; Maljkovic & Nakayama, 1994, 1996, 2000; Pashler & Shiu, 1999). In addition, Song and Nakayama (2006) found that reach curvature was reduced when the colors were repeated. This suggests that when the colors switched, observers were more

likely to select a nontarget object for action and initially direct their movement toward that nontarget, thus committing a "partial error."

Other studies have demonstrated a similar variation in the execution of responses from trial to trial (e.g., Anderson & Folk, 2010; Yantis, Meyer, & Smith, 1991), and reach trajectories in particular have proven to be a useful tool for categorizing response variation (e.g., Song & Nakayama, 2006, 2007, 2008; Spivey, Grosjean, & Knoblich, 2005; Welsh & Elliott, 2005; Wood et al., 2011). However, it is unknown whether the process of selecting a nontarget object for action and thus committing a partial error has any effect on ensuing performance.

There is a precedent to suggest that an observer's performance on a single trial can affect subsequent behavior. Observers respond more slowly and more cautiously following trials in which they committed an error relative to trials in which they executed the correct response (e.g., Dutilh et al., 2011; Kerns et al., 2004; Rabbitt, 1966). These post-error adjustments are thought to be initiated by a performance monitoring system (e.g., Gehring, Goss, Coles, Meyer, & Donchin, 1993; Hester, Foxe, Molholm, Shpaner, & Garavan, 2005; Kerns et al., 2004; van Veen & Carter, 2005) and reflect an adaptive mechanism through which higher-level cognitive mechanisms (e.g., attention) are recruited to minimize distractor interference and error responses in subsequent trials.

While the effect of discrete behavioral outcomes (error vs. correct response) on subsequent behavior is relatively well studied, little is known about how variation in the execution of a correct response affects subsequent behavior. Some researchers have examined muscle twitches in the incorrect response hand using electromyograms, classifying "partial errors" as trials in which muscle activation was recorded from the incorrect response finger prior to correct response execution (e.g., Allain, Burle, Hasbroucq, & Vidal, 2009; Burle, Allain, Vidal, & Hasbroucq, 2005; Coles, Scheffers, & Fournier, 1995). These studies found evidence for post-partial error slowing although this was accompanied by *increased* compatibility effects from distracting stimuli (Burle et al., 2005), making it unclear whether these effects reflect the same mechanisms as post-error slowing.

In real-world situations, observers often select the wrong object for action and initiate a movement toward that object in space. For example, a driver might reach toward the radio volume when his or her goal is to turn on the air conditioning. For this type of "partial error," an observer physically moves toward the wrong object before making a correction and ultimately ending up with the correct action. Variation in reach movement trajectories on an individual trial basis has been studied (e.g., Song & Nakayama, 2008),

and task context has been shown to play a key role in producing variation (i.e., repetition of target colors, e.g., Song & Nakayama, 2006). However, it is unclear whether and how this variation (e.g., whether or not a nontarget was initially selected for action) affects subsequent behavior. If an observer selects a nontarget object for action, resulting in an initial movement toward that nontarget object or a "partial error," do observers engage similar adaptive mechanisms to prevent distractor interference on subsequent trials as they do following full errors?

The present study

The goal of the present study is to determine whether selection of a nontarget object for action, even when that action is corrected and no error is committed, elicits adaptive changes in behavior compared to when the target is directly selected for action. If selection of a nontarget object for action is treated by a performance-monitoring system as an event similar to an error, we would expect cautious responses and reduced distractor interference following trials in which a hand movement was aimed initially toward a nontarget object (i.e., partial errors). Alternatively, partial errors might not trigger this adaptive mechanism, but might impact subsequent behavior in other ways. For instance, if partial errors affect subsequent responses via representations in memory tied to a specific task context, such as target color, repetition of that feature might activate a similar partial-error response. Another possibility is that partial errors might create a weaker representation of the target feature than direct movements. In this case, subsequent target selection would be facilitated only when features associated with direct movements are repeated, leading to a POP effect. Both of these reflect distinct mechanisms to explain sequential effects of target selection for action that differ from the performance-monitoring system associated with post-error slowing.

We presented participants with a visually guided reaching task in which they were required to search for a uniquely colored target stimulus presented among distractors and reach toward that target. Reach trajectories provide a continuous, real-time measurement of internal decision processes, allowing us to better understand the temporal dynamics of behavior within an integrated attention-action system. Trajectory curvature from reaches and eye movements has been shown to reflect the magnitude of competition from nontarget items during the selection process; for example, trajectories are typically curved toward a distractor that is selected for action (e.g., Godijn & Theeuwes, 2002b; Minken, Opstal, & Gisbergen, 1993;

Song & Nakayama, 2008; Tipper, Howard, & Houghton, 1999; Welsh & Elliott, 2004). Thus, even in trials in which the participant correctly reached toward the target, we can observe variation in response execution.

We classified two types of responses in correct trials: *partial errors*, in which the observer initially selected a nontarget object for action before correcting the movement and touching the target object, and *direct movements*, in which the observer directly selected the target for action (i.e., he or she did not initiate a reach movement toward any nontarget objects). We then examined whether and how behavior in subsequent trials varied depending on whether the preceding trial was a partial-error or direct-movement response. In order to determine whether sequential effects were implemented only at the level of motor output, we also included target color repetition as a factor in our analysis. If sequential effects of target selection for action are context-dependent, meaning that the movement in one trial predicts behavior in a subsequent trial only when the target and distractor colors are repeated, it would indicate a role for higher-level integrated attention-memory-action mechanisms. If color repetition does not interact with sequential effects of target selection for action, it would suggest that sequential effects of target selection for action might reflect a purely lower-level, motoric mechanism (e.g., Diedrichsen, White, Newman, & Lally, 2010).

Method

Participants

Sixteen Brown University undergraduate students (seven male, mean age = 19.4 years) participated for course credit. All participants were right-handed with normal or corrected-to-normal color vision. The protocol was approved by the Brown University Institutional Review Board. All procedures reported in this manuscript followed the guidelines of the Declaration of Helsinki.

Apparatus

Stimuli were projected from behind a Plexiglas display that was arranged upright on a table perpendicular to the observer's line of vision, facing the seated observer at a distance of approximately 48 cm. Three-dimensional hand position was recorded at a rate of approximately 160 Hz using an electromagnetic position and orientation recording system (Liberty, Polhemus) with a measuring error of .03 cm root mean

square. A motion-tracking marker was secured with a Velcro strap near the tip of each observer's right index finger. The observer's index finger was rested on a Styrofoam block placed in front of him or her on the table, located 27 cm from the screen along the z-dimension (i.e., the axis that is bounded by the observer and the display). The finger was aligned with the bottom of the display along the y-dimension (i.e., the axis that is bounded by the top and bottom of the display) and the horizontal midline of the display along the x-dimension (i.e., the axis that is bounded by the left and right sides of the display). Stimulus presentation was conducted using custom software designed with MATLAB (Mathworks) and Psychtoolbox (Brainard, 1997).

Stimuli

All stimuli appeared on a black background. A fixation cross appeared at the center of the screen at the beginning of each trial with a width and length of 0.7 cm. Diamonds also appeared on the screen during each trial; in order to maximize competition for selection, we used the minimum possible number of objects (three) necessary for a pop-out search task (e.g., Bravo & Nakayama, 1992; Song & Nakayama, 2006). The diameter of each diamond was 3 cm. The three diamonds were equally spaced and placed at 4, 8, and 12 o'clock on an imaginary circle surrounding fixation with a radius of 11 cm and with an interitem distance of 18.9 cm (measured from center to center). The diamonds were rendered in either red (CIE chromaticity coordinates: x = .534, y = .321) or green (CIE chromaticity coordinates: x = .348, y = .508). The two colors were equiluminant using photometer calibration (approximately 14 cd/m^2). In each trial, one diamond appeared in the randomly selected target color, and the remaining diamonds were rendered in the other color. The target diamond was randomly selected to one of the three locations described above in each trial, and the distractor diamonds were placed at the remaining two locations.

Procedure

For calibration of the hand-tracking system at the beginning of the session, each participant was asked to sequentially touch nine equally spaced points on the screen. Participants were instructed to keep their finger in the starting position until the target stimuli appeared and to touch the uniquely colored shape on every trial. Each trial began with the presentation of a fixation cross for either 500 or 750 ms (randomly selected for each trial). To discourage hand movements from
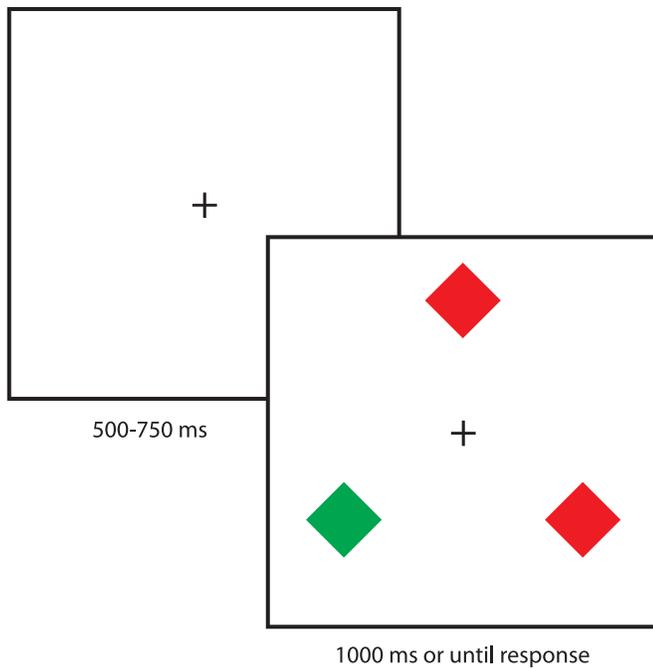
Figure 1. A typical trial in Experiment 1. Participants were required to touch the uniquely colored diamond.

occurring before the target stimuli appeared, if the participants moved their finger during the presentation of the fixation cross, they had to wait for an additional 500–750 ms after returning their finger to the starting position. Following fixation, the three diamonds appeared (Figure 1). If the participant did not touch one of the three diamonds within 1 s, the trial was counted as incorrect, and a tone was played to indicate to the participant that time ran out. The display remained on the screen for an additional 200 ms after the participant's response to encourage participants to rest briefly on the target. This resulted in more consistent deceleration at the end of reach movements, allowing us to effectively use maximum and minimum speed thresholds to analyze movement trajectories. Following every trial, participants were given an auditory feedback tone to indicate whether their response was accurate (high-pitch beep) or inaccurate (low-pitch beep). There was a 1 s intertrial interval.

The experiment began with 20 practice trials, followed by 12 blocks of 50 trials each (one participant only completed 10 blocks due to technical problems). Participants were given an opportunity to rest between each block. Each session lasted approximately one hour.

Data analysis

When the participant's finger came within approximately 0.5 cm of the display on the z-dimension and

simultaneously within approximately 2 cm of the target diamond on the x and y dimensions within the 1-s time limit, a response was considered correct. If this threshold was passed for a nontarget diamond or the participant did not cross any reaching threshold during the time limit, the trial was counted as incorrect.

Hand-movement data were analyzed offline using custom MATLAB (Mathworks) software. Three-dimensional speed scalars were created for each trial using a differentiation procedure in MATLAB. These scalars were then submitted to a Butterworth filter (second-order, 10 Hz high cutoff). *Movement onset* was calculated as the first time point in each trial after stimulus onset at which hand movement resultant speed exceeded 10 cm/s. *Resultant speed* was calculated as the three-dimensional distance traveled (i.e., the square root of the sum of the squared distance traveled along the x, y, and z axes) at each sample divided by the time elapsed since the previous sample. *Movement offset* was defined as the first subsequent measurement in each trial when resultant speed decreased to below 10 cm/s. Each individual trial was visually inspected (e.g., Song & Nakayama, 2006, 2007, 2008); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, thresholds were adjusted manually to more appropriate levels for that trial (0.6% of all trials).

Initial latency was defined as the time elapsed between stimulus onset and movement onset. *Movement time* was defined as the time elapsed between movement onset and movement offset. *Total time* was defined as the sum of movement time and initial latency.

Trajectories for calculating curvature were measured in two-dimensional XY space by calculating a line from the start to the end point of the movement and measuring the orthogonal deviation of the actual movement from that line at each sample throughout the movement. *Curvature* was defined as the maximum point of deviation (unsigned) in centimeters divided by the length of the line from the start to the end points of the movement in centimeters (see e.g., Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Song & Nakayama, 2006). We use centimeters (cm) as the measurement scale for reporting curvature throughout the rest of the manuscript although we note that the value is reported following a normalization procedure and therefore does not reflect the absolute value in centimeters of the deviation.

To classify correct responses into two categories, we resampled each trial to create 101 samples equally spaced in time along the x-dimension (e.g., Song & Nakayama, 2008; Spivey et al., 2005). We then calculated the average movement toward each diamond from all correct responses to that diamond and created a "zone" surrounding the average movement calculated
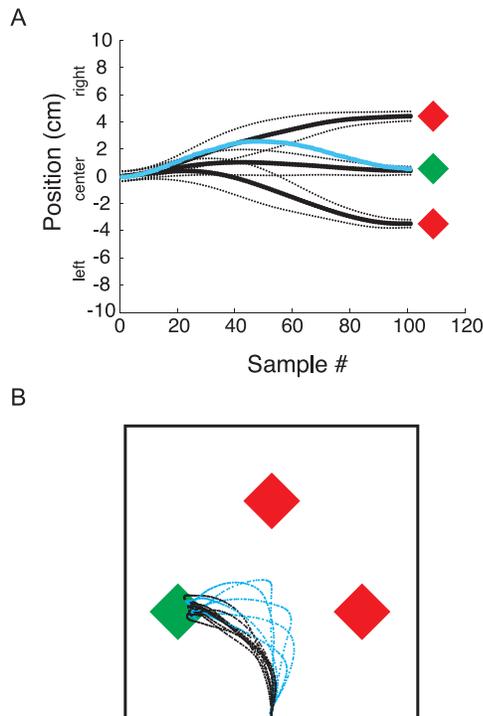
A

B

Figure 2. A) An example of one participant's average target "zones," plotted as movement along the x-dimension (y-axis) over time (x-axis). Mean movement to each target is plotted as a solid black line, and the "zone" boundaries (i.e., 1.5 standard deviations) are plotted in black dashed lines. Partial errors were defined as trials in which the hand left the target zone and entered the zone of a nontarget for a minimum of one sample (example partial error in blue). B) A sampling of movement trajectories from one participant plotted in two-dimensional space. Partial errors are colored in blue, direct movements in black. These trajectories reflect only trials in which the target appeared on the left side.

as the distance 1.5 standard deviations in each direction from each time point along the x-dimension (as in Song & Nakayama, 2008). *Partial errors* were defined as trials in which the participant's hand left the zone of the target and entered the zone of a nontarget along the x-axis for a minimum of one sample. *Direct movements* were defined as trials in which the hand did not exit the target zone at any sample (Figure 2).

It should be noted that trajectories can also be curved away from a distractor, reflecting inhibition of that distractor. However, this typically occurs only with shorter response latencies or when distractor onset precedes target onset (e.g., Godijn & Theeuwes, 2002a, 2004; Welsh & Elliott, 2004). In the present study, distractor onset was concurrent with display onset, and reaches were initiated quickly, making it unlikely that inhibition would affect reach trajectories significantly. To ensure this was the case, we examined the direction of reach trajectories to targets appearing on the left and right sides of fixation as reaches to these targets could

either be curved toward the two distractors or away from the two distractors. Only 5.6% of these reach movements were curved away from the distractors with the remaining 94.4% curved toward the distractors. Of the responses to the left and right targets that were classified as partial errors, even fewer (1.2%) were curved away from the distractors. This analysis supports the notion that trajectories deviated away from nontargets via inhibitory mechanisms were highly infrequent in the present task, and thus we used unsigned curvature as a measure of distractor interference in all data analyses presented.

Results

We removed from analysis trials in which no movement was initiated and trials in which a large number of samples were dropped from recording; for sequential analyses, we also removed trials in which either of these events occurred on the preceding trial, the first trial of each block, and trials for which the response in the preceding trial was inaccurate (5.7% of all trials).

In order to avoid large cumulative priming effects in which curvature is greatly reduced when the target and distractor features are repeated over multiple consecutive trials (e.g., Song & Nakayama, 2006), we also limited our analysis to examine either trials in which the target and distractor colors switched or trials in which the colors were repeated only once (i.e., trial N-2 was a switch).

Partial errors

We conducted one-way ANOVAs to compare performance in partial-error trials to performance in direct-movement trials. Partial errors occurred on 18.5% of all correct trials while direct movements occurred on 57.7% of all trials. As expected based on our criteria for defining partial errors, curvature was much greater in partial-error trials (.260 $\pm$ .011 cm)[1] than in direct-movement trials (.120 $\pm$ .006 cm), $F(1, 15) = 189.60$, $p < 0.001$. Initial latency was much shorter in partial-error trials (269 $\pm$ 13 ms) compared to direct-movement trials (298 $\pm$ 11 ms), $F(1, 15) = 72.48$, $p < 0.001$. However, movement time was longer in partial-error trials (468 $\pm$ 13 ms) compared to direct-movement trials (424 $\pm$ 14 ms), $F(1, 15) = 182.99$, $p < 0.001$. Overall, total time was longer in partial-error trials (737 $\pm$ 9 ms) compared to direct-movement trials (722 $\pm$ 10 ms), $F(1, 15) = 10.14$, $p < 0.01$.

Together, these demonstrate that partial errors typically occurred when initial latency was short, and

Previous trial performance	Target color	
	Repeated	Switched
Partial error		
Initial latency (ms)	286 ± 11	286 ± 13
Curvature (cm)	.151 ± .009	.155 ± .007
Movement time (ms)	433 ± 15	436 ± 14
Error rate (%)	1.2 ± .6	.6 ± .2
Direct movement		
Initial latency (ms)	296 ± 11	293 ± 11
Curvature (cm)	.130 ± .007	.155 ± .009
Movement time (ms)	426 ± 14	438 ± 14
Error rate (%)	.9 ± .3	.9 ± .2

Table 1. Initial latency (ms), curvature (cm), movement time (ms), and error rate (%) means from a two-way ANOVA with factors of previous trial performance (partial error vs. direct movement) and target color (repeated vs. not repeated). Curvature measurement (cm) is normalized by dividing by the length between start and end points of the reach. Error terms reflect standard error of the mean (s.e.m.).

partial errors resulted in longer total time relative to direct movements.

For the remaining analyses, we examined the sequential effects of partial errors and direct movements. The goal of this analysis was to determine whether selection of a nontarget object for action has any effect on subsequent behavior. To further determine whether these sequential effects involved higher-level cognitive mechanisms that differed depending on task context, we also included target color repetition as a factor. We conducted 2×2 repeated-measures ANOVAs with factors of target color (repeated vs. switched) and previous trial performance (partial error vs. direct movement) for group mean values of curvature, initial latency, movement time, and error rate (see Table 1). No main effects or interactions were significant with respect to error rate ($ps > 0.1$). The following sections address results from the remaining three dependent measures.

Curvature

The curvature data suggest that whether a nontarget was selected for action in one trial may have impacted performance in the next trial. Specifically, we found that curvature was greater following trials in which a partial error occurred (.153 ± .007 cm) relative to trials in which a direct movement occurred (.143 ± .007 cm), an effect that approached significance, $F(1, 15) = 3.84$, $p = 0.07$.

To determine whether task context mediated the effect of previous trial performance on curvature, as might be expected if higher-level cognitive mechanisms in an integrated attention-action system were involved

in sequential effects of previous trial performance, we next examined the factor of target color repetition. First, we replicated the basic finding of Song and Nakayama (2008), finding reduced curvature when the target color was repeated (.141 ± .007 cm) relative to when the target color was switched (.155 ± .007 cm), $F(1, 15) = 8.00$, $p < 0.05$. This result confirms our assumption that repetition of the target color reduced distractor interference.

The critical analysis was to determine if the effect of previous trial performance on curvature differed depending on whether the target color was repeated or switched. To address this question, we examined the interaction between previous trial performance and target color repetition. Looking at the data (Figure 3A), we can see that the effect of previous trial performance differed depending on whether the task context was repeated, an observation confirmed by a significant interaction, $F(1, 15) = 4.59$, $p < 0.05$.

The interaction appears to be driven by an effect of previous trial performance occurring only when the target color was repeated with greater curvature following partial errors (.151 ± .009 cm) relative to direct movements (.130 ± .007 cm). Simple main effects analyses confirmed that this difference was significant, $F(1, 15) = 8.73$, $p < 0.01$. This suggests that when the task context was repeated, performance in the previous trial did affect reach curvature. Unlike the reduction in distractor interference typically seen following errors, we found increased distractor interference following trials in which a nontarget object was selected for action (i.e., partial-error trials) relative to trials in which only the target was selected for action (i.e., direct-movement trials). Curvature was not statistically different when the target color was switched whether there was a partial error on the previous trial (.155 ± .007 cm) or a direct movement (.155 ± .009 cm), $F(1, 15) < 1$. Thus, performance in the previous trial had no effect on reach curvature when the task context was not repeated.

We can also consider whether there is a benefit of target color repetition following partial errors and direct movements, respectively. In Figure 3A (black bars), we can see a reduction in curvature when the target color is repeated following direct movements. A simple main effects analysis confirms this observation with a significantly lower curvature when the target color was repeated than when it was switched, $F(1, 15) = 12.85$, $p < 0.01$. On the other hand, as shown in Figure 3A (blue bars), there appears to be no benefit to repeating the target color following a partial error. Again, a simple main effects analysis confirms this observation with no significant difference in curvature whether target color was repeated or switched following a partial error, $F(1, 15) < 1$. Together, these data demonstrate that target color repetition effects differ
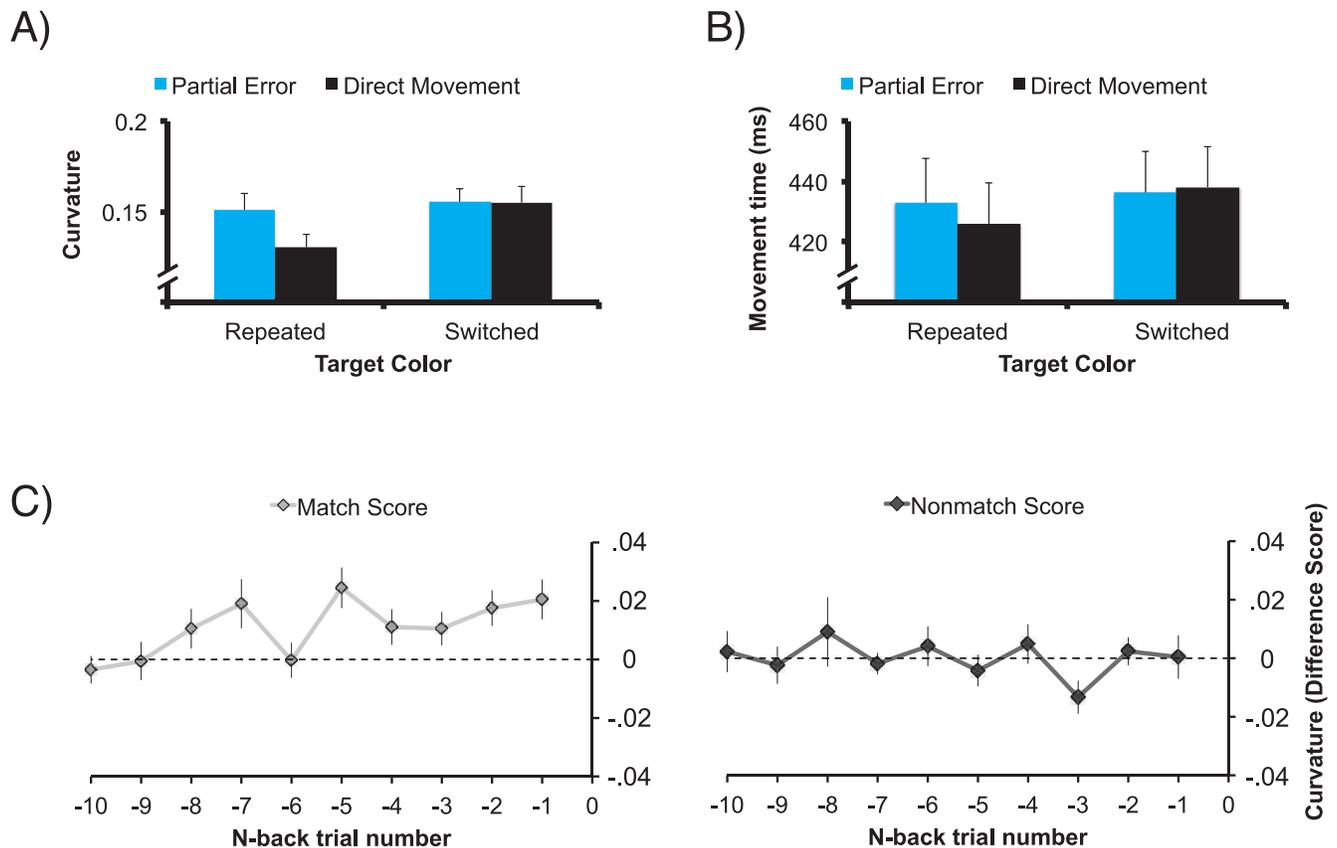
Figure 3. A) Hand-path curvature following partial errors and direct movements, according to whether the target color was repeated from the previous trial. Curvature was greater following partial errors but only when the target color was repeated. Error bars represent s.e.m. B) Movement time data following partial errors and direct movements. The same pattern of data was observed as in the curvature measure. Error bars represent s.e.m. C) Effects of partial errors up to 10 trials prior to the current trial on curvature, reflected in the *match score* (target color repeated) and *nonmatch score* (target color switched). A positive number indicates increased curvature following partial errors. There was a linear trend for match scores with a trend toward positive match scores that decreased for larger (i.e., more negative) N-back numbers. This pattern suggests that sequential effects of target selection for action survive for a longer duration than a single trial. Error bars represent s.e.m.

depending on whether the preceding movement was a partial error or direct movement. We discuss the implications of this analysis in detail in the Discussion.

Initial latency

Next, we examined initial latency to determine whether observers delayed their responses following partial errors as they typically do following a full error. We found no evidence for this type of cautious responding following partial errors. Instead, initial latency was *shorter* in trials following a partial error (286 ± 12 ms) relative to trials following a direct movement (294 ± 11 ms), $F(1, 15) = 16.75$, $p < 0.05$. These data again demonstrate that whether a nontarget object is selected for action in the previous trial affects performance in the current trial. Selection of a nontarget object for action did not elicit the same

adaptive changes as a full error in which observers respond cautiously in subsequent trials. Instead, latency to initiate a response was shorter following trials in which observers initially selected a nontarget object for action.

Unlike the curvature measure, initial latency was unaffected by whether the target color was repeated or switched, $F(1, 15) < 1$. This suggests that task context did not impact initial latency. There was also no significant interaction between target color and previous trial performance, $F(1, 15) < 1$. Thus, the shorter latencies observed following partial errors are not dependent on task context. Perhaps this is not surprising, considering that repeated task context did not have any effect on initial latency measures. Regardless, the data provide additional evidence that whether an observer selects a nontarget object for action affects performance in subsequent trials.

Movement time

Unlike the results for curvature and initial latency, there was no effect of previous trial performance on movement time, $F(1, 15) = 1.5$, $p > 0.1$. Thus, selection of a nontarget object for action in the previous trial had no overall effect on movement time.

We did find a benefit to repeating the target color with shorter movement times when the target color was repeated (429 ± 14 ms) than when it was switched (437 ± 14 ms), $F(1, 15) = 13.16$, $p < 0.01$. As with the curvature measure and the results from Song and Nakayama (2006), this suggests that distractor interference is reduced when the target color is repeated in consecutive trials. Furthermore, because this demonstrates that task context did affect movement time, we might expect that previous trial performance also had an effect on movement time that was contingent on repeated task context as in the curvature measure.

In Figure 3B, we see that the movement time data do indeed reflect the same pattern as the curvature data with the effect of previous trial performance on movement time differing depending on whether the target color was repeated or switched. This interaction approached significance, $F(1, 15) = 4.09$, $p = 0.06$. We conducted simple main effects analyses to parse this interaction. Although interpretation of these analyses is mitigated by the fact that they follow a nonsignificant interaction, the pattern of results is entirely consistent with the curvature data. As with the curvature measure, we found that responses were longer following partial-error trials (433 ± 15 ms) relative to direct-movement trials (426 ± 14 ms) when the target color was repeated, $F(1, 15) = 5.37$, $p < 0.05$. Again, this suggests that whether a nontarget is selected for action or not in the preceding trial affected movement time in the current trial but only when the task context was repeated, with longer movement times following partial errors relative to direct movements. The comparison when the target color was switched (436 ± 14 ms vs. 438 ± 14 ms) was not significant, $F(1, 15) < 1$, suggesting that whether or not a nontarget was selected for action in the previous trial had no effect on movement time when the task context was not repeated.

As with the curvature data, there appears to be a reduction in movement time when the target color is repeated following direct movements (Figure 3B, black bars), $F(1, 15) = 15.46$, $p < 0.01$. Simultaneously, there appears to be no change in movement time when the target color is repeated following partial errors, $F(1, 15) < 1$. We discuss this analysis in more detail in the Discussion.

Decay of partial error influence

Maljkovic and Nakayama (1994) found that responses were facilitated when the target color up to five trials prior matched the target color in the current trial, regardless of intervening events, suggesting that the memory trace associated with the target color lasted beyond a single trial.

We used a similar approach to investigate the time course of sequential effects of target selection for action on curvature in the context of target color repetition. We examined whether a partial error in a single prior trial (up to 10 trials prior to the current trial) affected performance in the current trial. For each N-back, we first sorted trials according to whether the target color in the N-back trial matched the target in the current trial. Then, we determined whether the response in the N-back trial was a direct movement or a partial error. We calculated the *match score* for each N-back that matched the current target color as the curvature in trial N when the response in the N-back trial was a partial error minus the curvature in trial N when the response in the N-back trial was a direct movement. The *nonmatch score* was calculated the same way for trials in which the N-back target color did not match the current target color.

Earlier, we reported that trials following partial errors exhibited higher curvature than trials following direct movement only when the target color matched. If this same effect carries over multiple intervening trials, we would expect the *match score* to be positive, reflecting high curvature following partial errors in the N-back trial relative to direct movements in the N-back trial when the colors of the N-back trial and the current trial matched. We would also expect the *nonmatch score* to be near zero as previous trial performance would not affect performance in the current trial if the colors switched.

We conducted a 2×10 repeated-measures ANOVA with factors of score (match vs. nonmatch) and N-back (1–10). As expected, mean match score ($.0109 \pm .0025$) was larger than mean nonmatch score ($.0001 \pm .0023$), $F(1, 15) = 8.32$, $p < 0.01$. There was no main effect of N-back, $F(9, 135) = 1.37$, $p > 0.1$, but the interaction between score and N-back was marginally significant, $F(9, 135) = 1.68$, $p = 0.1$. We conducted separate one-way ANOVAs to determine the effect of N-back on match scores and nonmatch scores separately. There was a significant effect of N-back for match scores, $F(9, 135) = 2,4$, $p < 0.01.$, with a significant linear trend, $F(1, 15) = 12.86$, $p < 0.01$, suggesting that match scores were decreasing in magnitude as the N-back got larger. There was no effect of N-back for nonmatch scores, $F(9, 135) < 1$.

A clear trend can be seen of a positive *match score* that diminishes slowly over time in Figure 3C,

confirmed by the linear trend reported above. The match score is positive for the first five N-back trials while the nonmatch score is near zero (or negative) for the first five N-back trials. These data are suggestive of the notion that performance in a previous trial can affect performance in the current trial, even if there are several intervening trials, as long as the target-defining feature is shared between the two trials. Thus, the effect of selecting a nontarget object for action on subsequent behavior may be long-lasting, diminishing slowly over time.

Response type in the previous and current trial

The data reported above indicate that when the target color was repeated in consecutive trials, distractor interference was greater following partial errors relative to direct movements. Thus, it seems likely that categorical distinctions in response type would also be affected by the preceding response type; that is, partial errors would be more likely to occur following partial errors than following direct movements and vice versa when the target color is repeated.

To first confirm that the effect of previous response type on current response type was dependent on target color repetition, we conducted a $2 \times 2 \times 2$ ANOVA with factors of previous response type (partial error vs. direct movement), current response type (partial error vs. direct movement), and target color (repeated vs. switched). We found a significant three-way interaction, $F(1, 15) = 9.93$, $p < 0.01$, indicating that whether the target color was repeated affected the relationship between the previous and current response types.

Separate 2×2 ANOVAs for the color-repeated and color-switched cases demonstrated that the interaction between response type in the previous trial and response type in the current trial was significant when the target color was repeated, $F(1, 15) = 5.44$, $p < 0.05$, but not when the target color was switched, $F(1, 15) < 1$. Subsequent simple main effects analyses also revealed that when the target color was repeated, partial errors were more frequent following partial errors ($15.1 \pm 5.8\%$) relative to direct movements ($11.7 \pm 3.1\%$), $F(1, 15) = 8.24$, $p < 0.05$. Furthermore, direct movements were more frequent following direct movements ($62.5 \pm 5.0\%$) than following partial errors ($56.7 \pm 9.6\%$), $F(1, 15) = 23.85$, $p < 0.001$.

These data suggest that both partial errors and direct movements have a tendency to occur in clusters, such that executing either of these response types in one trial predicts that a similar response type is more likely to occur in a subsequent trial when the target color is repeated. In other words, when the task context is repeated, partial errors beget partial errors, and direct movements beget direct movements.

This pattern is evocative of patterns seen in post-error slowing studies in which errors are typically preceded by faster and faster responses, a cycle that is only broken once the error occurs (e.g., Dutilh et al., 2011). Thus, one might predict that partial errors continue occurring until a full selection error occurs and triggers some type of strategic adjustment. However, in the present study the overall error rate was very low (0.98%), precluding this type of analysis and suggesting that the cycle of partial errors or direct movements may be interrupted instead by other events. Further research is needed to fully understand the nature of these cycles and what types of events (including error responses) might trigger and/or interrupt them.

Discussion

In a simple visually guided reaching task, we observed significant variation in performance on correct responses. In a subset of trials, observers selected a nontarget object for action, resulting in a partial error. In another subset of trials, observers directly selected the target for action, resulting in a direct movement. Initial latency was shorter in trials following partial-error trials relative to trials following direct movements. Movement time and curvature were also greater following partial-error trials relative to direct-movement trials, reflecting stronger competition for action from nontarget distractors. Finally, partial errors were more frequent following partial-error responses, and direct movements were more frequent following direct-movement responses. However, these sequential effects, along with movement time and curvature effects, were only observed when the target color was repeated, suggesting that sequential effects of target selection for action cannot be explained solely by the repetition of the previous movement by the motor system. Instead, higher-level cognitive processes in which the task context is represented were involved. Specifically, the data indicate that initial selection of a nontarget for action and/or direct selection of the target for action affected representations in memory that biased subsequent responses.

Together, these data suggest that whether a nontarget object is selected for action, even if selection of a nontarget does not lead to an error, has an effect on subsequent behavior. However, distractor interference was increased rather than decreased following partial errors, suggesting that the sequential effects of target selection for action observed in the present study and typical post-error effects (e.g., Rabbitt, 1966) arise from distinct mechanisms. In the following section, we

discuss possible mechanisms that may explain the sequential effects of target selection for action observed in the present study.

Mechanisms: Partial errors versus direct movements

We demonstrated that when the target color and distractor colors were switched across trials, whether the observer selected a nontarget object for action (i.e., committed a partial error) or not (i.e., made a direct movement) in the previous trial had no effect on distractor interference in the current trial. However, when the target and distractor colors were repeated, we observed greater distractor interference following partial errors relative to direct movements (Figure 3). This suggests that action outcomes affect memory representations, which then bias performance in subsequent encounters with similar task contexts. However, there are multiple ways in which this interactive attention-memory-action mechanism might be implemented.

One interpretation of this outcome is that there was a reduction in distractor interference following a trial in which the observer selected only the target object for action (i.e., a direct movement).[2] In other words, efficient selection of the target in one trial resulted in decreased distractor interference in the next trial when the target color was repeated. Efficient selection of the target object might, for example, produce a strong bias toward selection of targets matching that color in future trials. Because the distractor color is also repeated when the target color is repeated, it is possible that there is creation of an inhibitory code that biases selection against the repeated distractor color. When a nontarget object is selected for action, resulting in a partial error, this process might interfere with (or reduce the strength) of one or both of these biases. For example, selection of a nontarget for action might create a bias *toward* objects matching the distractor color, thus competing with the bias for selecting target-colored objects. Thus, there would be no benefit to repeating target and distractor colors (i.e., no reduced distractor interference) following partial errors because those two biases would cancel each other out.

According to this framework, the present results can be summarized as follows: POP is dependent upon efficient target selection. This argument is supported by evidence of a significant reduction in curvature and movement time when the target color was repeated compared to when it was switched following direct movements but no effect of target color repetition following partial errors. In other words, there is only

evidence for POP following direct movements and not following partial errors.

However, an alternative interpretation is that the interactions depicted in Figure 3 are driven by costs associated with selection of a nontarget object for action in repeated contexts that are offset by POP benefits. For example, recent studies have demonstrated neural mechanisms reflecting fluctuations in cognitive control and distractibility that shift gradually over time (e.g., Esterman, Noonan, Rosenberg, & DeGutis, 2012; Leber, 2010). In the present experiment, it could be the case that a nontarget object is more likely to be selected for action when the observer is in a state of high distractibility and/or reduced cognitive control. Therefore, selection of a nontarget object for action resulting in a partial-error response may be attributable to an underlying distractible state. It is possible that this type of attentional state might be associated with a specific context, such as target and/or distractor color. Thus, when the target and distractor colors are repeated following a partial error, observers are more likely to initially select the wrong object for action again because they are still in that distractible state. POP effects could operate independently from this distractibility mechanism; for example, POP can speed perceptual processing and response selection (e.g., Kristjánsson & Campana, 2010). If this were the case, costs associated with the selection of a nontarget object for action in the previous trial would be offset by the benefits from POP, consistent with the results presented in Figure 3.

The role of the motor system

The mechanisms proposed thus far have been focused on the target-selection process. However, in an integrated attention-memory-action system, it is also important to consider the role of the motor system. For example, sequential effects of target selection for action reported in the present study could be driven in part by a binding between a specific motor plan and a target and/or distractor color. Jax, Rosenbaum and colleagues (e.g., Jax & Rosenbaum, 2007, 2009; van der Wel, Fleckenstein, Jax, & Rosenbaum, 2007) demonstrated that repeated hand movements tend to take similar trajectories even when an obstacle present during the first movement is removed, an effect known as "hand-path priming." Jax and Rosenbaum (2007) argued that one potential mechanism for hand-path priming effects is that a single parameter from the first trial—the length of the axis orthogonal to the movement path (similar to our measure of curvature in the present experiment)—is represented in memory and biases future movements. In the present experiment, a

representation of this parameter could be bound to a task context that includes the target color, the distractor color, or both. Thus, when one or both of those features is repeated a short time later, the representation is recalled and that type of movement is "reused" (e.g., Diedrichsen et al., 2010; Jax & Rosenbaum, 2007) whether it was a direct movement or an indirect, partial-error movement.

This is similar to the notion of "event files" (Hommel, 2004, 2005). Hommel proposed that when an observer encounters a perceptual event and responds with a specific action, a transient "event file" is created in which a representation of the perceptual event, task context, and associated action are bound. These files can be retrieved during future encounters with that same perceptual event and task context, thereby reducing the demand on limited cognitive resources required for action selection. However, it is unknown whether action responses within event files are stored in the form of action outcome goals (e.g., reach toward the green diamond, independent of a particular path of motion) or in more specific movement trajectories. The present data suggest that the latter may be the case; specific task contexts, such as the target color or distractor color, can be associated with specific hand-movement trajectories from the previous trial. Thus when a nontarget object was selected for action in the previous trial, a curved movement trajectory is stored in an event file with that task context whereas when the target was directly selected in the previous trial a more direct movement is stored in the event file. In subsequent encounters with that same task context (i.e., the same target and distractor color), that representation is activated, and a similar movement is executed.

The data from the present studies represent clear evidence that variation in the execution of an ultimately correct response affects performance in subsequent trials via an integrated attention-memory-action system. More specifically, the data show that whether a nontarget object is initially selected for action in one trial affects behavior in subsequent trials, and these effects are largely dependent on repeated task context. Although we propose several mechanisms that may drive these effects above, we cannot yet distinguish among these mechanisms. Future studies, however, may be able to shed further light on the mechanisms involved. For example, recent studies (e.g., Kristjánsson & Driver, 2008; Lamy, Antebi, Aviani, & Carmel, 2008) have implemented clever designs to disentangle the contributions of target repetition and distractor repetition to POP benefits. An adaptation of these designs to a visually guided reaching task might provide valuable insight into the mechanisms involved in the effects reported in the present paper.

Conclusions

Distractor interference and partial-error frequency was increased following partial errors relative to direct movements when the task context was repeated. These data suggest that whether or not an observer selects a nontarget object for action, even if the correct action is ultimately executed in the case in which an observer initially selects a nontarget, affects subsequent behavior. This underscores a strong link between memory, attention, and action and highlights a role for sequential effects driven by an observer's own behavior that are distinct from traditional post-error slowing mechanisms.

Keywords: visually guided reaching, selection for action, partial errors, priming of pop-out, trial history

Commercial relationships: none.
Corresponding author: Jeff Moher.
Email: jeff_moher@brown.edu.
Address: Department of Cognitive, Linguistic & Psychological Sciences, Brown University, Providence, RI, USA.

Footnotes

[1] This and all subsequent error terms reported reflect the standard error of the mean (s.e.m.). Also, note that we use "cm" as the unit of measurement for curvature although the reported numbers reflect a ratio rather than an absolute value.

[2] We thank Timothy Welsh for this suggestion.

References

Allain, S., Burle, B., Hasbroucq, T., & Vidal, F. (2009). Sequential adjustments before and after partial errors. *Psychonomic Bulletin & Review*, *16*(2), 356–362.

Anderson, B. A., & Folk, C. L. (2010). Variations in the magnitude of attentional capture: Testing a

two-process model. *Attention, Perception & Psychophysics*, *72*(2), 342–352.

Bichot, N. P., & Schall, J. D. (1999). Effects of similarity and history on neural mechanisms of visual selection. *Nature Neuroscience, 2,* 549–554.

Brainard, D. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*(4), 433–436.

Bravo, M., & Nakayama, K. (1992). The role of attention in different visual search tasks. *Perception and Psychophysics, 51*(5), 465–472.

Burle, B., Allain, S., Vidal, F., & Hasbroucq, T. (2005). Sequential compatibility effects and cognitive control: Does conflict really matter? *Journal of Experimental Psychology: Human Perception & Performance, 31*(4), 831–837.

Chun, M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition, 7,* 65–81.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71.

Cisek, P. (2007). Cortical mechanisms of action selection: The affordance competition hypothesis. *Philosophical Transactions of the Royal Society B: Biological Sciences, 362*(1485), 1585–1599.

Coles, M., Scheffers, M., & Fournier, L. (1995). Where did you go wrong? Errors, partial errors, and the nature of human information processing. *Acta Psychologica, 90,* 129–144.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Desmurget, M., Jordan, M., Prablanc, C., & Jeannerod, M. (1997). Constrained and unconstrained movements involve different control strategies. *Journal of Neurophysiology, 77*(3), 1644–1650.

Diedrichsen, J., White, O., Newman, D., & Lally, N. (2010). Use-dependent and error-based learning of motor behaviors. *Journal of Neuroscience, 30*(15), 5159–5166.

Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science, 11*(6), 467–473.

Dutilh, G., Vandekerckhove, J., Forstmann, B. U., Keuleers, E., Brysbaert, M., & Wagenmakers, E.-J. (2011). Testing theories of post-error slowing. *Attention, Perception & Psychophysics, 74*(2), 454–465.

Esterman, M., Noonan, S. K., Rosenberg, M., & DeGutis, J. (2012). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, published online August 31, 2012, doi:10.1093/cercor/bhs261.

Gehring, W. J., Goss, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4*(6), 385–390.

Godijn, R., & Theeuwes, J. (2002a). Oculomotor capture and inhibition of return: Evidence for an oculomotor suppression account of IOR. *Psychological Research, 66*(4), 234–246.

Godijn, R., & Theeuwes, J. (2002b). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology Human Perception & Performance, 28*(5), 1039–1054.

Godijn, R., & Theeuwes, J. (2004). The relationship between inhibition of return and saccade trajectory deviations. *Journal of Experimental Psychology: Human Perception & Performance, 30*(3), 538–554.

Hester, R., Foxe, J. J., Molholm, S., Shpaner, M., & Garavan, H. (2005). Neural mechanisms involved in error processing: A comparison of errors made with and without awareness. *NeuroImage, 27*(3), 602–608.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494–500.

Hommel, B. (2005). Feature integration across perception and action: Event files affect response choice. *Psychological Research, 71*(1), 42–63.

Jax, S. A., & Rosenbaum, D. A. (2007). Hand path priming in manual obstacle avoidance: Evidence that the dorsal stream does not only control visually guided actions in real time. *Journal of Experimental Psychology: Human Perception & Performance, 33*(2), 425–441.

Jax, S. A., & Rosenbaum, D. A. (2009). Hand path priming in manual obstacle avoidance: Rapid decay of dorsal stream information. *Neuropsychologia, 47*(6), 1573–1577.

Kerns, J. G., Cohen, J. D., MacDonald, II, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023–1026.

Kristjánsson, Á., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception & Psychophysics, 72*(1), 5–18.

Kristjánsson, Á., & Driver, J. (2008). Priming in visual search: Separating the effects of target repetition,

distractor repetition and role-reversal. *Vision Research*, *48*(10), 1217–1232.

Lamy, D., Antebi, C., Aviani, N., & Carmel, T. (2008). Priming of pop-out provides reliable measures of target activation and distractor inhibition in selective attention. *Vision Research, 48*(1), 30–41.

Leber, A. B. (2010). Neural predictors of within-subject fluctuations in attentional control. *Journal of Neuroscience*, *30*(34), 11458–11465.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, *22*(6), 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception & Psychophysics*, *58*(7), 977–991.

Maljkovic, V., & Nakayama, K. (2000). Priming of popout: III. A short-term implicit memory system beneficial for rapid target selection. *Visual Cognition, 7*(5), 571–595.

McPeek, R., Maljkovic, V., & Nakayama, K. (1999). Saccades require focal attention and are facilitated by a short-term memory system. *Vision Research*, *39*(8), 1555–1566.

Minken, A., Opstal, A. J., & Gisbergen, J. (1993). Three-dimensional analysis of strongly curved saccades elicited by double-step stimuli. *Experimental Brain Research*, *93*(3), 521–533.

Pashler, H., & Shiu, L. (1999). Do images involuntarily trigger search? A test of Pillsbury's hypothesis. *Psychonomic Bulletin & Review*, *6*(3), 445–448.

Rabbitt, P. M. (1966). Errors and error correction in choice-response tasks. *Journal of Experimental Psychology*, *71*(2), 264–272.

Song, J., & Nakayama, K. (2008). Target selection in visual search as revealed by movement trajectories. *Vision Research, 48*(7), 853–861.

Song, J., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Sciences, 13*(8), 360–366.

Song, J. H., & Nakayama, K. (2006). Role of focal attention on latencies and trajectories of visually guided manual pointing. *Journal of Vision, 6*(9):11, 982–995, http://www.journalofvision.org/content/6/9/11, doi:10.1167/6.9.11. [PubMed] [Article]

Song, J. H., & Nakayama, K. (2007). Automatic adjustment of visuomotor readiness. *Journal of Vision*, *7*(5):2, 1–9, http://www.journalofvision.org/content/7/5/2, doi:10.1167/7.5.2. [PubMed] [Article]

Spivey, M. J., & Dale, R. (2006). Continuous dynamics in real-time cognition. *Current Directions in Psychological Science*, *15*(5), 207–211.

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences, USA, 102*(29), 10393–10398.

Tipper, S. P., Howard, L. A., & Houghton, G. (1999). Behavioral consequences of selection form neural population codes. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII* (pp. 223–245). Cambridge, MA: MIT Press.

van der Wel, R. P. R. D., Fleckenstein, R. M., Jax, S. A., & Rosenbaum, D. A. (2007). Hand path priming in manual obstacle avoidance: Evidence for abstract spatiotemporal forms in human motor control. *Journal of Experimental Psychology: Human Perception & Performance*, *33*(5), 1117–1126.

van Veen, V., & Carter, C. S. (2005). Separating semantic conflict and response conflict in the Stroop task: A functional MRI study. *NeuroImage*, *27*(3), 497–504.

Welsh, T., & Elliott, D. (2005). The effects of response priming on the planning and execution of goal-directed movements in the presence of a distracting stimulus. *Acta Psychologica, 119*(2), 123–142.

Welsh, T. N., & Elliott, D. (2004). Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. *The Quarterly Journal of Experimental Psychology*, *57A*(6), 1031–1057.

Wood, D. K., Gallivan, J. P., Chapman, C. S., Milne, J. L., Culham, J. C., & Goodale, M. A. (2011). Visual salience dominates early visuomotor competition in reaching behavior. *Journal of Vision*, *11*(10):16, 1–11, http://www.journalofvision.org/content/11/10/16, doi:10.1167/11.10.16. [PubMed] [Article]

Yantis, S., Meyer, D. E., & Smith, J. K. (1991). Analyses of multinomial mixture distributions: New tests for stochastic models of cognition and action. *Psychological Bulletin, 110*(2), 350.