Reach tracking reveals dissociable processes underlying cognitive control

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ABSTRACT

The current study uses reach tracking to investigate how cognitive control is implemented during online performance of the Stroop task (Experiment 1) and the Eriksen flanker task (Experiment 2). We demonstrate that two of the measures afforded by reach tracking, initiation time and reach curvature, capture distinct patterns of effects that have been linked to dissociable processes underlying cognitive control in electrophysiology and functional neuroimaging research. Our results suggest that initiation time reflects a response threshold adjustment process involving the inhibition of motor output, while reach curvature reflects the degree of co-activation between response alternatives registered by a monitoring process over the course of a trial. In addition to shedding new light on fundamental questions concerning how these processes contribute to the cognitive control of behavior, these results present a framework for future research to investigate how these processes function across different tasks, develop across the lifespan, and differ among individuals.

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1. Introduction

Cognitive control refers to the capacity to align one's ongoing thoughts and actions with one's current goals and context. Individual differences in this capacity have been linked to a host of important outcomes, including mental and physical health, quality of life, and success in school and at work (for a review, see Diamond, 2013). Consequently, a growing body of research has focused on identifying the cognitive and neural mechanisms that underlie this capacity (e.g., Badre, 2008; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Casey, Durston, & Fossella, 2001; Miller & Cohen, 2001; Shenhav, Botvinick, & Cohen, 2013). Our understanding of these mechanisms has benefited greatly from congruency tasks such as the Stroop task (Stroop, 1935) and the Eriksen flanker task (Eriksen & Eriksen, 1974), which have served a central role in developing and refining models of cognitive control (e.g., Botvinick et al., 2001; Cohen, Dunbar, & McClelland, 1990; Cohen & Huston, 1994; Shenhav et al., 2013).

In the Stroop task, participants indicate what color of text (e.g., green or blue) a color word (e.g., "GREEN" or "BLUE") is written in.

On congruent trials, both the color and the meaning of the word cue the same response (e.g., "GREEN" written in green text). On incongruent trials, the color and the meaning of the word cue different responses (e.g., "GREEN" written in blue text), requiring participants to override a strong prepotent tendency to classify the word based on its meaning in favor of a more controlled classification based upon the color of its text. Similarly, in the flanker task participants identify the centermost stimulus (e.g., a letter) in a stimulus array (e.g., five letters in a row). On congruent trials, all of the stimuli cue the same response (e.g., "AAAAA"). On incongruent trials, the stimuli cue competing responses (e.g., "AABAA"), requiring participants to override a prepotent tendency to respond according to the "flanker" stimuli. In these tasks, a *congruency effect* is standardly observed such that response times and error rates are elevated on incongruent relative to congruent trials (e.g., MacLeod, 1991; Nieuwenhuis et al., 2006).

Performance on congruency tasks has been proposed to reflect two distinct processing pathways (Botvinick et al., 2001; Cohen & Huston, 1994; Cohen et al., 1990; De Jong, Liang, & Lauber, 1994; Ridderinkhof, van der Molen, & Bashore, 1995): a *direct* pathway that automatically generates response activations in favor of the prepotent response (e.g., the response cued by word meaning in the Stroop task), and an *indirect* pathway that requires control to map task-relevant stimulus features (e.g., text color in the Stroop

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task) to the appropriate response. According to one prominent model of cognitive control, three key processes are set in motion when these pathways generate competing response activations (Shenhav et al., 2013). First, a *monitoring process* registers conflict between the competing response activations generated by the direct and indirect pathways (Botvinick et al., 2001; Yeung, Botvinick, & Cohen, 2004). Next, a *response threshold adjustment process* temporarily inhibits motor output in response to the conflict (Cavanagh et al., 2011; Frank, 2006; Munakata et al., 2011; Wiecki & Frank, 2013). This process is thought to help balance speed-accuracy trade-off effects by effectively putting the brake on behavior, thereby allowing additional time for the third key process to intervene before a response is generated. Finally, a *controlled response selection process* is recruited to resolve conflict between the coactive responses by providing strong top-down support in favor of the indirect pathway (Botvinick et al., 2001; Shenhav et al., 2013).

In addition to being functionally dissociable, a growing body of research indicates that different neuroanatomical regions support these key processes. Specifically, the dorsal anterior cingulate cortex (dACC) has been implicated in supporting the monitoring and response threshold adjustment processes, while the lateral prefrontal cortex (LPFC) has been implicated in supporting the controlled response selection process (Botvinick, Cohen, & Carter, 2004; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Casey et al., 2001; Frank, 2006; Miller & Cohen, 2001; Shenhav et al., 2013).

1.1. Trial sequence effects

In the context of the model described above, elevated response times and error rates on incongruent trials can be understood to reflect performance costs associated with detecting conflict, inhibiting motor output, and recruiting top-down support in favor of the appropriate response. Beyond standard congruency effects, this model also provides a framework for interpreting *trial sequence effects* (*TSEs*) in which qualities of a previous trial influence performance on the current trial (for a review, see Egner, 2007). For example, early research on TSEs in the flanker task (Gratton, Coles, & Donchin, 1992) revealed descriptively faster response times on incongruent trials preceded by an incongruent trial (*iI trials*, where the lowercase letter denotes previous trial congruency and the uppercase letter denotes current trial congruency) than on incongruent trials preceded by a congruent trial (*cI trials*). Subsequent research indicates that response times are faster on iI relative to cI trials, but only on the subset of trials that feature a repeat of the previous trial's response (iI-r < cI-r, where "-r" denotes a response repeat) (Mayr, Awh, & Laurey, 2003; Nieuwenhuis et al., 2006).

The response time difference observed between iI-r and cI-r trials in the flanker task has been interpreted to reflect a feature integration effect in which transient stimulus-response (S-R) pairs are formed from one trial to the next (Hommel, 2004). On cI-r trials (e.g., "BBABB" preceded by "AAAAA"), the S-R pair from the previous trial (e.g., stimulus = "AAAAA" and response = Left) must be broken before the current trial's stimulus ("BBABB") can be paired with the appropriate response (Left), resulting in an S-R binding conflict. In the context of the model introduced above, S-R binding conflict can be understood to impede controlled response selection, as the appropriate S-R pair must be formed along the indirect pathway before top-down support from the controlled response selection process can swing activation in favor of the correct response. Consequently, S-R binding conflict results in higher response times on cI-r trials (Mayr et al., 2003; Nieuwenhuis et al., 2006).

Stimulus-Response binding conflict cannot account for faster response times on iI relative to cI trials in all instances, however. Kerns et al. (2004) controlled for S-R binding conflict in an fMRI investigation of the Stroop task by developing a three-response version of the task that enabled the researchers to exclude from analysis all trials that featured a repeat of the target (i.e., text color) or distractor (i.e., word) from the preceding trial. Even after controlling for S-R binding conflict, the researchers observed faster response times and lower levels of dACC activity on iI relative to cI trials. Response times and dACC activity on congruent trials were uniformly low regardless of whether the previous trial was congruent (*cC trials*) or incongruent (*iC trials*). Thus, both measures presented the same overall pattern of effects: cC = iC < iI < cI.

Kerns et al. (2004) interpreted the difference between iI and cI trials to reflect a *conflict adaptation effect*. According to this account, the recent recruitment of top-down support on one incongruent trial serves to facilitate conflict resolution on the next incongruent trial by, for example, increasing attention to task-relevant stimulus features (e.g., Botvinick et al., 2001; Ullsperger, Bylsma, & Botvinick, 2005). In addition to faster response times on iI relative to cI trials, facilitated conflict resolution is proposed to result in less dACC activity on iI trials because the monitoring process registers less co-activation between the competing responses over the course of the trial.

Although the three-response version of the task used by Kerns et al. (2004) enabled the researchers to control for S-R binding conflict, it also introduced a potential contingency learning effect (e.g., Jacoby, Lindsay, & Hessels, 2003; Schmidt, 2013; Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007). In order to maintain an equal number of congruent and incongruent trials, each congruent stimulus (e.g., the word "GREEN" in green text) appeared more frequently than each of the incongruent stimuli featuring the same word (e.g., the word "GREEN" in red or blue text). This resulted in a higher contingency between word meaning and text color on congruent trials than incongruent trials. Consequently, participants may have learned that a particular word (e.g., "GREEN") was more likely to correspond to one response (e.g., the response for green) than the other two responses.

In light of previous work indicating that response times and error rates are lower on high contingency trials than low contingency trials (Schmidt et al., 2007), Schmidt and De Houwer (2011) proposed that the contingency of the previous trial—rather than its congruency—may have led to higher response times on cI relative to iI trials in the study by Kerns et al. (2004). Given that word meaning cued the correct response on high contingency (congruent) trials in the task used by Kerns and colleagues, participants may have increased their attention to word meaning following a congruent trial. On cI trials, this would have impeded the controlled response selection process, as word meaning cued the wrong response on incongruent trials. Similarly, participants may have decreased their attention to word meaning following a low contingency (incongruent) trial, leading to better controlled response selection on iI trials (see Schmidt, 2013, or Schmidt & De Houwer, 2011, for alternative accounts of how sequential contingency effects may contribute to TSEs). Consistent with the contingency learning account, Schmidt and De Houwer observed no response time difference between iI and cI trials in the Stroop task when contingency effects were controlled for.

1.2. A recent puzzle

While the pattern of TSEs observed by Kerns et al. (2004) in response times and dACC activation has been interpreted to reflect the functioning of the controlled response selection process, recent electrophysiology work has revealed a different pattern of TSEs in dACC activation (Sheth et al., 2012). Sheth and colleagues used

single-unit recordings to measure dACC activation while human participants performed a Stroop-like task. As in Kerns et al., response times were faster on iI trials than cI trials (iI < cI). However, dACC activations were *elevated* on iI trials relative to cI trials (cI < iI). Moreover, Sheth and colleagues found greater dACC activations on iC trials than cC trials (cC < iC), whereas Kerns and colleagues observed no such difference with fMRI. Thus, single-unit recordings of the dACC presented a different pattern of TSEs (cC < iC < cI < iI) than that observed in fMRI (cC = iC < iI < cI).

Why might single-unit recordings and fMRI present seemingly incompatible patterns of TSEs in dACC activation? One explanation is that the pattern of effects observed in fMRI reflects the dACC's role in supporting the monitoring process, while the pattern observed in single-unit recordings reflects the region's role in supporting the response threshold adjustment process (Shenhav et al., 2013). On this interpretation, response thresholds are adjusted on a trial-by-trial basis in light of the congruency of the current trial, with congruent trials lowering one's response threshold and incongruent trials raising it (C < I). Given that the congruency of the previous trial influences the response threshold's recent position, trials preceded by a congruent trial will tend to have lower response thresholds than those preceded by an incongruent trial (c < i). Thus, the main effects of both current and previous trial type will produce the pattern of effects observed by Sheth and colleagues (cC < iC < cI < iI), assuming that the effect of current trial congruency is larger than that of previous trial congruency.

While this account of the two patterns of TSEs observed in dACC activation is consistent with the model of cognitive control introduced above, the account has not been tested directly. Ideally, such a test would use separate measures to target the response threshold adjustment process and the controlled response selection process within the same task and participants. This presents a number of significant methodological difficulties. For example, it is exceedingly rare to have the opportunity to obtain single-unit recordings of the dACC in alert humans. Further, traditional response time measures reflect both the response threshold adjustment process and the controlled response selection process, making it difficult to isolate the relative contribution of each process to performance. To address these methodological limitations, the current study uses reach tracking to target these processes behaviorally.

1.3. Reach tracking

In addition to response time and accuracy, measuring the path that a participant's hand travels to a response target affords a number of discrete and continuous measures that offer insight into the temporal and spatial characteristics of decision behavior over time. Of particular relevance are the measures of initiation time (the time elapsed between stimulus onset and movement onset) and curvature (the degree to which a response deviated from a direct path to the selected target). Previous reach tracking research indicates (a) that participants often initiate a movement (i.e., exceed a response threshold) before completely resolving conflict among response alternatives, and (b) that the degree of curvature present in a reach movement provides a sensitive measure of the extent to which competing responses are coactive over the course of a movement (Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Freeman, Nakayama, & Ambady, 2013; Song & Nakayama, 2007a).

In light of these findings, we propose that initiation time and reach curvature can be used to target the response threshold adjustment process and the controlled response selection process, respectively. If incongruent trials lead to higher response thresholds and, consequently, longer periods of motoric inhibition, then initiation times should reflect this adjustment, given that longer periods of motoric inhibition should result in longer initiation times. Similarly, if reach curvature is sensitive to the extent to which response alternatives are coactive over the course of a trial, then reach curvatures should reflect when the controlled response selection process sways activation in favor of the appropriate response. If the controlled response selection process is facilitated (e.g., by having attention directed toward task-relevant stimulus features on iI trials in the Stroop task) or the demands placed on the process are otherwise decreased, reach curvatures on incongruent trials should be relatively small, as hand movements will be less pulled toward the prepotent response. If the process is impeded (e.g., by having attention directed toward misleading stimulus features on cI trials in the Stroop task) or the demands placed on the process are increased, reach curvatures should be relatively large, as hand movements will be more pulled toward the prepotent response.

Previous reach tracking research by Song and Nakayama (2007a, Experiment 2) provides support for the proposal that initiation time can be used to target the response threshold adjustment process. The researchers presented participants with alternating sequences of five conflict and five non-conflict trials in a visual search task, and found that initiation times increased over the sequence of conflict trials and decreased over the sequence of non-conflict trials. This finding is consistent with the prediction that the congruency of the current trial influences initiation times by adjusting one's response threshold up or down from its previous position. However, the researchers did not investigate the effect of current and previous trial congruency on initiation times when congruent and incongruent trials were randomly intermixed, nor did they report the effect of the sequences on reach curvatures.

While a number of previous studies have measured response initiation times in congruency tasks (e.g., Buetti & Kerzel, 2009; Rubichi, Nicoletti, Umiltà, & Zorzi, 2000; Rubichi & Pellicano, 2004; Scorolli, Pellicano, Nicoletti, Rubichi, & Castiello, 2014), many of these studies did not report TSEs. Scorolli et al. (2014) did report TSEs in a reaching version of the Simon task, however their task design did not allow participants to change their response after a movement was initiated. Consequently, initiation times on incongruent trials likely reflected both the response threshold adjustment process and the controlled response selection process given that both processes needed to unfold before a response was initiated. Consistent with this claim, initiation times on congruent trials conformed to the pattern of effects proposed to underlie the response threshold adjustment process (cC < iC), while initiation times on incongruent trials did not, with descriptively lower initiation times on iI relative cI trials.

A similar limitation is present in a mouse tracking study by Scherbaum, Dshemuchadse, Fischer, and Goschke (2010). Scherbaum et al. (2010) had participants complete a Simon task by moving a computer cursor to one of two response boxes at the top of a computer screen. To deter participants from deciding on a response before initiating a movement, participants were required to move the cursor toward the top of the screen before the stimulus appeared. Consequently, initiation times were not measured and the pattern of TSEs observed in hand movements (cC < iC < iI < cI) likely reflected both the response threshold adjustment process and the controlled response selection process. Thus, in the present study, we attempt to isolate the response threshold adjustment process and the controlled response selection process separately using initiation time and reach curvature.

2. Experiment 1

Experiment 1 tests the proposal that initiation time and reach curvature can be used to target the response threshold adjustment process and controlled response selection process, respectively, by adapting the Stroop task used by Kerns et al. (2004) for use with

reach tracking. As in the Kerns et al. study, target and distractor repetition trials (i.e., trials featuring a repeat of the text color and/or word from the previous trial) are excluded from analysis to control for S-R binding conflict. If the pattern of TSEs observed in dACC activation with single-unit recordings (Sheth et al., 2012) reflects the region's role in supporting the response threshold adjustment process, then initiation times should conform to the same pattern of effects, revealing main effects of both current and previous trial congruency (cC < iC < cI < iI). If the pattern of TSEs observed in dACC activation with fMRI (Kerns et al., 2004) reflects the region's role in registering conflict over the course of a trial, then reach curvatures should conform to the same pattern of effects, revealing a main effect of current trial congruency and an interaction of current and previous trial congruency (cC = iC < iI < cI).

2.1. Method

2.1.1. Participants

Twenty-four right-handed adults (M = 19.6 years, SD = 1.2 years; 15 females) with normal reaching behavior and normal or corrected-to-normal vision participated in the experiment. Participants received course credit for their participation. The Institutional Review Board at Brown University approved the protocol. One additional participant was tested but excluded from the current analyses for engaging in a number of strategies to avoid attending to the semantic content of the stimuli (e.g., squinting, focusing above the cued location).

2.1.2. Apparatus

The experiment was conducted using a rear-mounted projector (Viewsonic PJD6221) to display the task on a Plexiglass screen that was arranged upright on a table approximately 48 cm in front of the participant (see Fig. 1). The Plexiglass screen was 55.7 cm wide and 43.2 cm tall and the projected image was 44 cm wide by 33 cm tall. Reach movements and response selections were measured at a rate of approximately 160 Hz with an electromagnetic position and orientation recording system (Liberty, Polhemus). The root mean square error of the tracker was 0.3 mm. In order to measure hand position, a small motion-tracking marker (2.26 cm long, 1.27 cm wide, and 1.14 high) weighing 0.13 oz was secured to participants' right index finger with a Velcro strap. The task was programmed in MATLAB (Mathworks).

2.1.3. Procedure

In the task, participants were instructed to indicate what color of text (green, red, or blue) a centrally presented word ("GREEN", "RED", or "BLUE") was written in by touching one of three response locations positioned toward the bottom left (12.3 cm from left border of the projected image, 11.5 cm from the bottom), top center (22 cm from left, 27.1 from bottom), or bottom right (31.7 cm from left, 11.5 from bottom) of the screen. Before beginning the task, participants were told the mappings for each response location multiple times (green at bottom left, red at top center, and blue at bottom right) and were asked to recall the mappings. These mappings remained constant across the experiment.

On each trial, participants rested their pointing finger on a Styrofoam starting block located 27 cm in front of the screen, aligned with the center of the display. The starting block was 2 × 2 × 2 cm. The task was designed so that a trial would not initiate until the subject's finger was resting on the starting block. Once the participant's finger was on the starting block, a crosshair appeared in the center of the projected image (22 cm from left, 16.75 from bottom) for one second, followed by the stimulus in the same location. If the participant's hand moved from the starting block before the
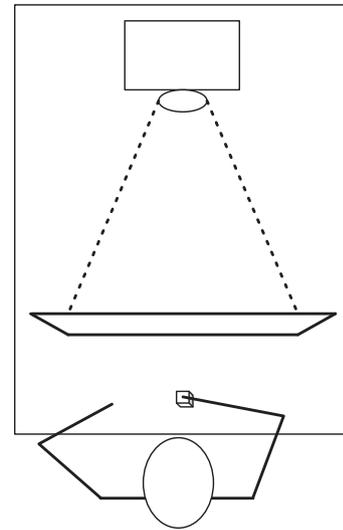

Fig. 1. Diagram of experimental setup. A rear-mounted projector was used to display the task on a Plexiglass screen mounted upright on the table in front of the participant.

stimulus appeared, the task was paused and did not resume until the participant's hand returned to the starting block for 500 ms.

The task was displayed on a white background. The response locations were identical 0.6 cm by 0.6 cm black squares. From stimulus onset, participants had up to 3 s to touch a response location. Accurate responses within the allotted time resulted in a high tone sounding at 600 Hz for 200 ms, while inaccurate responses or responses that exceeded the allotted time resulted in a low tone sounding at 300 Hz for 200 ms. The first 10 trials of the first block were presented as practice trials and were excluded from further analysis.

Before beginning the task, participants completed a nine-point calibration sequence. Participants then completed 24 baseline trials to familiarize them with the reaching procedure. The task was presented in ten blocks, each consisting of 48 trials. A block of trials consisted of 24 congruent and 24 incongruent trials, randomly intermixed. The stimuli were 1.1 cm in height and ranged from 2.7 cm to 4.7 cm in length. There were nine possible word and color combinations, three of which were congruent and six of which were incongruent. Each of the six incongruent combinations was presented four times per block, while each of the three congruent combinations was presented eight times per block. Before each block, participants were reminded to respond quickly while maintaining a high degree of accuracy.

2.1.4. Data processing

The data processing methods used in the current study were largely adapted from Moher and Song (2013). The data from each participant was analyzed offline using custom MATLAB (Mathworks) software. Three-dimensional resultant speed scalars were created for each trial using a differentiation procedure in MATLAB. These scalars were then submitted to a second order, low-pass Butterworth filter with a cutoff of 10 Hz. Movement onset was calculated as the first point on each trial after stimulus onset at which hand movement speed exceeded 25.4 cm/s. Each individual trial was visually inspected as in previous work (Song & Nakayama, 2006, 2007b, 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. Movement initiation time was defined as the time elapsed between stimulus onset and movement onset.

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 in centimeters divided by the length of the line from the starting point to the end point of the movement in centimeters (see, e.g., Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Moher & Song, 2013; Song & Nakayama, 2006).

For additional analyses, we resampled each movement to 101 points equally spaced in time for comparison (see, e.g., Moher & Song, 2013; Song & Nakayama, 2008). Resampled data were used to generate trajectory images in two-dimensional xy space. To generate *distractor attraction scores* (Moher, Anderson, & Song, 2015; Moher, Sit, & Song, 2014) for each participant (see below), we calculated the average trajectory for each combination of target color and semantic identity on all incongruent trials. For each target type, we compared the mean trajectory for movements in the presence of the two possible incompatible distractor types. For example, an incompatible trial with a red target could feature the word "BLUE" or "GREEN." At each of the 101 movement points, we calculated the distance between the positions of the hand for those two trajectories. This distance was calculated as positive if the hand was pulled closer to a particular location when the semantic content of the incompatible word matched that location, and negative if that was not the case. For example, if the position of the hand were pulled closer to the blue location when the incompatible word was "BLUE" rather than "GREEN", the score at that point would be positive.

2.2. Results

All trials featuring a repeat of the target (i.e., text color) or distractor (i.e., word) presented on the previous trial were excluded from analysis, as was the first trial of each block. Only accurate responses following an accurate response were included in the following analyses, except for the measure of error rate, which included inaccurate responses. Removing errors and trials preceded by an error resulted in the additional exclusion of 7.0% of the remaining valid trials ($SD = 5.7\%$) per participant on average. Performance was analyzed with a series of 2 (current trial congruency: C vs. I) × 2 (previous trial congruency: c vs. i) ANOVAs.

2.2.1. Initiation time

As predicted, initiation times conformed to the pattern of effects proposed to underlie the response threshold adjustment process (cC < iC < cI < iI; see Fig. 2A). Initiation times revealed a main effect of current trial congruency, with higher initiation times on incongruent relative to congruent trials, $F(1,23) = 18.95$, $p < 0.001$, $\eta_p^2 = 0.45$, and a significant main effect of previous trial congruency, $F(1,23) = 5.95$, $p = 0.023$, $\eta_p^2 = 0.21$, with higher initiation times on trials preceded by an incongruent relative to a congruent trial. No interaction between current and previous trial congruency was observed, $F(1,23) = 0.183$, $p = 0.67$.

2.2.2. Reach curvature

Consistent with our second prediction, reach curvatures conformed to the pattern of effects previously linked to the monitoring component of cognitive control in the Stroop task (cC < iC < iI < cI; see Fig. 2B). Reach curvatures revealed a main effect of current trial congruency, with larger reach curvatures on incongruent relative to congruent trials, $F(1,23) = 19.05$, $p < 0.001$, $\eta_p^2 = 0.45$. A significant main effect of previous trial congruency was also observed, $F(1,23) = 5.33$, $p = 0.03$, $\eta_p^2 = 0.19$, with larger curvatures on trials preceded by a congruent relative to an incongruent trial. Further,

a significant interaction between previous and current trial congruency was observed, $F(1,23) = 6.98$, $p = 0.015$, $\eta_p^2 = 0.23$. Follow-up tests revealed larger reach curvatures on cI than iI trials, $F(1,23) = 8.48$, $p = 0.008$, $\eta_p^2 = 0.27$. No effect of previous trial type was found on congruent trials, $F(1,23) = 0.009$, $p = 0.92$. Further, reach curvatures were significantly larger on iI than iC trials, $F(1,23) = 5.60$, $p = 0.027$, $\eta_p^2 = 0.20$.

Why did incongruent trials feature larger reach curvatures than congruent trials? One possibility is that reaches on incongruent trials were initially pulled toward the prepotent response cued by word meaning before additional top-down support was recruited in favor of the response cued by text color. On this view, increased levels of curvature can be understood to reflect conflict at the level of competing response activations. A second possibility is that increased curvature levels reflect temporary indecision resulting from conflict at the level of the stimulus (for a discussion of stimulus conflict and response conflict in congruency tasks, see Egner, 2007). On this view, participants might have initiated a movement toward the display before committing to any one response in particular.

These two possibilities were explored by further examining participants' reach trajectories. Fig. 3 presents the average reach trajectories to each of the three targets for trials preceded by either a congruent (Fig. 3A) or an incongruent (Fig. 3B) trial. The color of each line represents the semantic content of the stimulus (e.g., a dark grey line indicates the word presented was "RED"), whereas the location of the target indicates the color of the stimulus (e.g., responses to the target labeled "G" indicate the stimulus was presented in green text). The labels "G", "R", and "B" were included for clarity in this figure and were not presented to participants during the task. Solid lines indicate congruent trials, whereas dashed lines indicate incongruent trials.

To evaluate the extent to which conflict on incongruent trials resulted from the co-activation of competing responses, distractor attraction scores were calculated using participants' average reach trajectories (described above, see also Moher et al., 2014, 2015). These scores measured the degree to which participants' reaches were pulled toward the semantically cued location relative to the non-cued location over the course of the movement. Responses on cI trials were significantly more attracted to the semantically cued location from 33% to 76% of the movement, $p < 0.001$, as shown by the solid line in Fig. 4. To illustrate, consider responses to the center location shown in Fig. 3A. When the word "GREEN" was presented in red text, responses were curved toward the semantically cued location (i.e., the response associated with green) at the left of the display before ultimately being redirected toward the correct response location. This result demonstrates that conflict on cI trials did stem in part from the co-activation of the two cued responses.

Reach trajectories were not more attracted to the semantically cued location than the non-cued location on iI trials, however, as illustrated by the dashed line in Fig. 4. This does not mean that all iI trials were free of conflict. Reach trajectories in Fig. 3B are more curved on iI trials than iC trials for responses to the left or right locations but not for responses to the center location. These results are consistent with the proposal that conflict at the level of the stimulus led to a brief period of indecision. When the correct response was in the center of the screen, this delay caused no increase in curvature relative to congruent trials, as any non-systematic deviations from a straight trajectory average out. When the correct response was at the left or right of the screen, however, the effects of this conflict are visible in reach curvatures. Thus, reach tracking revealed a crucial difference between the types of conflict underlying performance on cI and iI trials in the current experiment.
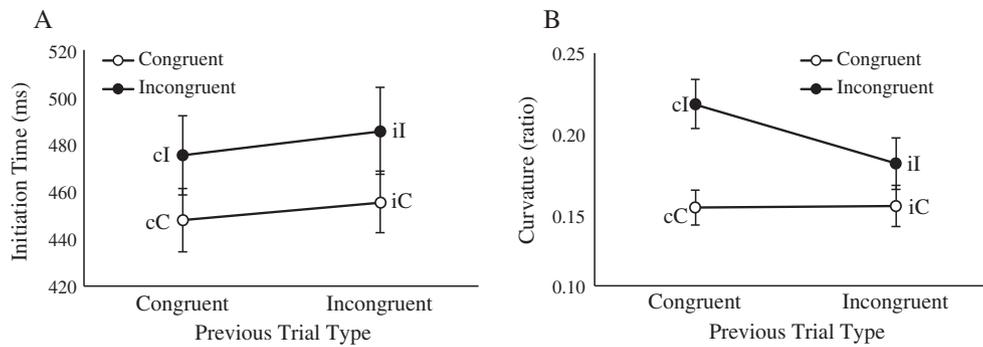
Fig. 2. Average performance on each of the four trial types (cC, iC, cI, iI) for measures of (A) initiation time and (B) curvature. Error bars indicate standard errors.
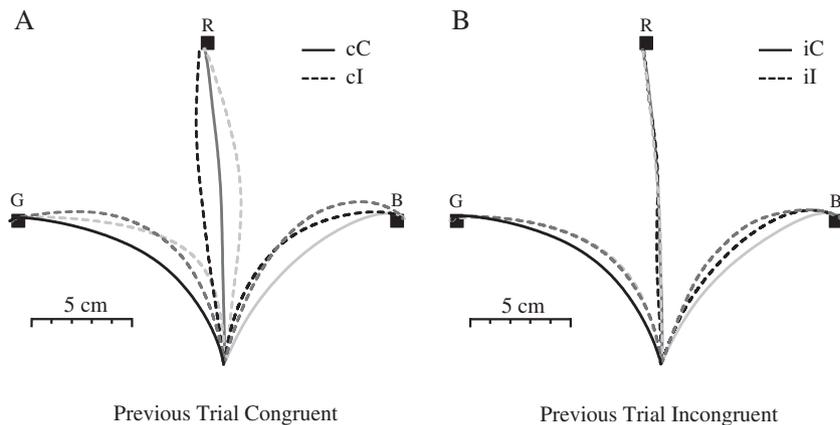

Fig. 3. Average reach trajectories to each target for (A) trials preceded by a congruent trial and (B) trials preceded by an incongruent trial. The color of each line indicates the semantic content of the stimulus presented on that trial (black = "GREEN", dark grey = "RED", and light grey = "BLUE"), whereas the location of the target indicates the color of the text presented on that trial (labeled with a "G", "R", or "B" for clarity). Responses to congruent trials are presented with solid lines, while responses to incongruent trials are presented with dashed lines.
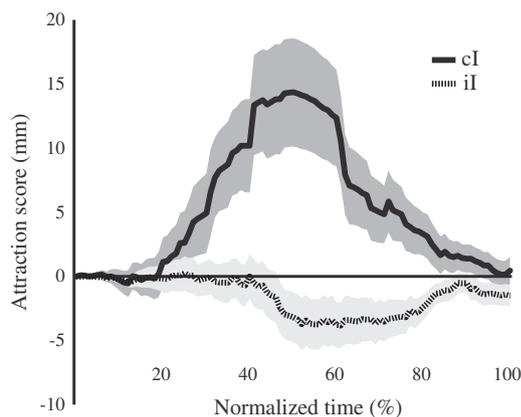

Fig. 4. Distractor attraction scores for iI trials (dashed line) and cI trials (solid line). Movement trajectories were pulled toward the location matching the semantic content of the stimulus for much of the movement on cI trials, reflecting strong competition between the text's meaning and color. However, iI trials showed no attraction, and even some repulsion away from the location corresponding to the semantic content of the stimulus. Shaded area reflects standard error of the mean.

Table 1
The average error rate, movement time, and total time on each of the four trial types (cC, iC, cI, iI). Standard deviations in parentheses.

	cC	iC	cI	iI
Error rate (%)	2.2 (3.3)	2.4 (4)	7.9 (7.8)	4.9 (5.3)
Movement time (ms)	410.8 (63.2)	411.9 (67.3)	448.0 (74.7)	439.7 (77.6)
Total time (ms)	858.6 (98)	867.5 (103)	923.3 (124.6)	925.2 (130.1)

$\eta_p^2 = 0.37$, and previous trial type, $F(1,23) = 4.81$, $p = 0.039$, $\eta_p^2 = 0.17$, were observed. The interaction of current and previous trial type approached but did not reach significance, $F(1,23) = 3.93$, $p = 0.059$, $\eta_p^2 = 0.15$. Movement times also revealed a similar pattern of results to that of curvature and error rate. A main effect of current trial type was found for movement time, $F(1,23) = 39.79$, $p < 0.001$, $\eta_p^2 = 0.63$. However, the interaction of current trial type and previous trial type did not reach significance, $F(1,23) = 3.60$, $p = 0.071$, $\eta_p^2 = 0.14$. Finally, total times revealed a main effect of current trial type alone, $F(1,23) = 40.81$, $p < 0.001$, $\eta_p^2 = 0.64$.

2.2.3. Error rate, movement time, and total time

In addition to initiation time and curvature, measures of error rate, movement time (the time elapsed between movement onset and target selection), and total time (the sum of initiation time and movement time) were collected. Error rates revealed a pattern of effects similar to that of curvature, as illustrated in Table 1. A main effect of current trial type, $F(1,23) = 13.58$, $p = 0.001$,

2.3. Discussion

As predicted, initiation times and reach curvatures presented two distinct patterns of TSEs. Initiation times conformed to the same pattern of effects previously observed in single-unit recordings of the dACC (cC < iC < cI < iI) (Sheth et al., 2012), while reach curvatures conformed to the pattern of effects previously observed

with fMRI (cC = iC < iI < cI) ([Kerns et al., 2004](#)). These findings provide support for the claim that initiation time and reach curvature can be used to target the response threshold adjustment process and controlled response selection process, respectively. On this interpretation of the data, conflict detected at the outset of a trial generated higher response thresholds with longer periods of motoric inhibition and, consequently, longer initiation times on incongruent relative to congruent trials (C < I). This effect carried over into the subsequent trial, resulting in higher response thresholds and longer initiation times on trials preceded by an incongruent relative to a congruent trial (c < i).

Reach curvatures, on the other hand, reflected the relative co-activation of the response alternatives. On congruent trials, both text color and word meaning cued the same response and, consequently, reach curvatures were uniformly low. On cI trials, reach movements were initially biased toward the response cued by word meaning. This resulted in relatively large curvatures, as reach movements were pulled toward the incorrect response until the controlled response selection process swayed activation in favor of the response cued by text color. Although continuous reach trajectories on iI trials revealed no evidence of co-activation between the responses cued by word meaning and text color, reach curvatures on these trials were elevated relative to congruent trials. This finding indicates that conflict at the level of the stimulus delayed the controlled response selection process on iI trials. Consequently, participants initiated movements toward the display on iI trials without any systematic bias in response activations. Without measuring the spatial characteristics of decision behavior inherent in the motor response, we would have been unable to explore this important distinction between the different types of conflict underlying iI and cI trials.

The ability to disentangle the behavioral effects of the response threshold adjustment process and controlled response selection process presents new opportunities for investigating how these processes function across different tasks. For example, at present it is unclear whether contingency learning effects influence the controlled response selection process in the flanker task in the same manner as the Stroop task. Several studies have found that performance on the flanker task is not enhanced on iI relative to cI trials when feature integration effects such as S-R binding conflict are controlled for (e.g., [Mayr et al., 2003; Nieuwenhuis et al., 2006](#)). However, these studies did not allow for contingency learning effects to occur. This raises the question of whether contingency learning effects will influence performance in the flanker task in the same manner as the Stroop. Experiment 2 builds on the findings of the current experiment to address this question directly.

3. Experiment 2

Experiment 2 investigates the extent to which the dissociable patterns of effects observed in initiation time and reach curvature in the Stroop task are also present in the flanker task. To compare performance between the two tasks, we developed a three-response version of the flanker task analogous to the Stroop task used in Experiment 1. In the task, participants identified the centermost letter in an array of five letters by reaching to touch one of three response locations on a digital display.

As in Experiment 1, all trials featuring a repeat of the target (i.e., center letter) or distractor (i.e., flanker letter) presented on the previous trial were excluded from analysis to control for feature integration effects such as S-R binding conflict. Given that the response threshold adjustment process can be expected to function similarly across both the flanker and Stroop tasks, initiation times in the current experiment should conform to the same pattern observed in

Experiment 1: cC < iC < cI < iI. If contingency learning effects influence the controlled response selection process similarly in both tasks, then reach curvatures in the flanker task should conform to the same pattern observed in Experiment 1: cC = iC < iI < cI. If contingency learning effects do not influence flanker task performance, then no effect of previous trial congruency should be observed in reach curvatures: cC = iC < iI = cI.

3.1. Method

3.1.1. Participants

Forty right-handed adults (M = 19.5 years, SD = 1.2 years; 29 females) with normal reaching behavior and normal or corrected-to-normal vision participated in the experiment. Participants received course credit for their participation. The protocol was approved by the Institutional Review Board at Brown University.

3.1.2. Apparatus

The same reach tracking system described in Experiment 1 was used in the current experiment.

3.1.3. Procedure

Participants completed a three-response version of the flanker task modeled on the task used in Experiment 1. In the task, participants were presented with an array of five letters and were instructed to identify the centermost letter in the array by reaching to touch one of three response locations positioned toward the bottom left, top center, or bottom right of a digital display while wearing a small tracking device on their index finger. The letters presented in the task were "B", "A", and "K". On congruent trials, all of the letters cued the same response (e.g., "BBBBB"). On incongruent trials, the centermost letter and the flanker letters cued competing responses (e.g., "AAKAA"). Before beginning the task, participants were told the mappings for each response locations multiple times ("B" at top center, "A" at bottom left, and "K" at bottom right) and were asked to recall the mappings. These mappings remained constant across the task. The letters in the stimulus array appeared in black text. The background of the display was white. The response locations were identical 0.6 cm by 0.6 cm black squares. The arrays of letters were 4.2 cm wide and 1 cm tall.

Before beginning the task, participants completed a nine-point calibration sequence followed by 24 trials in which a solo target appeared on the screen at each of the target locations from the main task. These trials provided a baseline of participant's reaching behavior and familiarized participants with the procedure. Participants then completed 12 practice trials of the experimental task, followed by six blocks of 48 trials. Trial procedure was otherwise identical to Experiment 1.

There were nine possible center letter and flanker letter combinations, three of which were congruent and six of which were incongruent. Each of the six incongruent combinations was presented four times per block, while each of the three congruent combinations was presented eight times per block. Trial types were randomly intermixed. Before each block, participants were reminded to respond quickly while maintaining a high degree of accuracy.

3.1.4. Data processing

Data were processed in the same manner as in Experiment 1.

3.2. Results

All trials featuring a repeat of the center letter or flanker letters presented on the previous trial were excluded from analysis, as was the first trial of each block. Only accurate responses following

an accurate response were included in the following analyses, except for the measure of error rate, which included inaccurate responses. Removing errors and trials preceded by an error resulted in the additional exclusion of less than 1.0% of the remaining valid trials (SD = 1.2%) per participant on average. Performance was analyzed with a series of 2 (current trial congruency: C vs. I) × 2 (previous trial congruency: c vs. i) ANOVAs.

3.2.1. Initiation time

As predicted, initiation times conformed to the pattern of TSEs proposed to underlie the response threshold adjustment process (cC < iC < cI < iI; see Fig. 5A). Initiation times revealed a significant main effect of current trial congruency, with higher initiation times on incongruent relative to congruent trials, $F(1,39)$ = 45.45, $p < 0.001$, η_p^2 = 0.54, and a significant main effect of previous trial congruency, $F(1,39)$ = 5.30, p = 0.027, η_p^2 = 0.12, with higher initiation times on trials preceded by an incongruent relative to a congruent trial. No interaction between current and previous trial congruency was observed, $F(1,39)$ = 0.56, p = 0.46.

3.2.2. Reach curvature

Reach curvatures revealed a significant main effect of current trial congruency, with larger curvatures on incongruent relative to congruent trials, $F(1,39)$ = 60.00, $p < 0.001$, η_p^2 = 0.61 (see Fig. 5B). In contrast to the results of Experiment 1, the effect of previous trial congruency was not significant, $F(1,39)$ = 1.02, p = 0.32, nor was the interaction between current and previous trial congruency, $F(1,39)$ = 0.006, p = 0.94.

As in Experiment 1, distractor attraction scores were computed to determine the degree to which hand movements on incongruent trials were pulled toward the location cued by the identity of the flankers (see Fig. 6). Unlike in Experiment 1, continuous reach trajectories revealed significant attraction toward the location cued by the distractor for both cI trials (15% through 69% of the movement) and iI trials (31% through 80% of the movement). These effects can be seen in Fig. 7. For example, examining responses to the center target, there is more rightward pull for "K" flankers and more leftward pull for "A" flankers in both cases. There was significantly greater pull on cI trials than iI trials for a brief, early portion of the movement (16% through 18% of the movement).

These data suggest that while there might be modest differences in the degree to which the hand is pulled toward the location cued by the distractor on cI relative to iI trials, there is clear pull in that direction in both cases. This is in contrast to the iI condition of Experiment 1, which revealed no evidence that the hand was pulled toward the location cued by the semantic content of the stimulus. However, it is also worth noting that the magnitude of pull toward the cued location in both cI and iI trials appears to be smaller than the pull toward the cued location on cI trials in Experiment 1. For example, the maximum pull in the combined
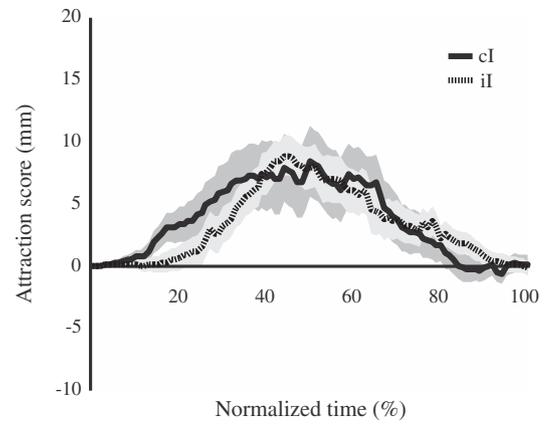

Fig. 6. Distractor attraction scores for iI trials (dashed line) and cI trials (solid line) in the flanker task. Movement trajectories for both iI and cI trials were pulled toward the response cued by the misleading flanker letters, indicating strong competition between the two cued responses. However, iI trials showed significantly less attraction to the response cued by the flanker letters than cI trials from 16% to 18% of the movement.

attraction scores across all participants in Experiment 1 is 14.4 mm, whereas the maximum in Experiment 2 is 8.4 mm in the cI condition and 8.9 mm in the iI condition. To directly compare these measures, the distractor attraction scores from cI and iI trials from Experiment 2 were collapsed (since they were largely similar). Although the difference between the attraction scores from the two experiments did not reach significance at α = 0.05, a more liberal threshold of α = 0.1 revealed greater pull in the cI condition of Experiment 1 relative to the pull from the combined conditions in Experiment 2 from 54% through 59% of the movement.

3.2.3. Error rate, movement time, and total time

Average error rate, movement time, and total time for each of the trial types are shown in Table 2. Error rates were at floor and were not analyzed further. Movement times were significantly higher on incongruent than congruent trials, $F(1,39)$ = 48.00, $p < 0.001$, η_p^2 = 0.55. Total times were significantly higher on incongruent than congruent trials, $F(1,39)$ = 117.80, $p < 0.001$, η_p^2 = 0.75, and on trials preceded by an incongruent relative to a congruent trial, $F(1,39)$ = 4.29, p = 0.045, η_p^2 = 0.10.

3.2.4. Target and distractor repetition trials included

The reach curvature results presented above indicate that contingency learning effects play a limited role in the flanker task relative to the Stroop task. The results are consistent with previous research demonstrating that performance on the flanker task is not enhanced on cI relative to iI trials when trials featuring S-R
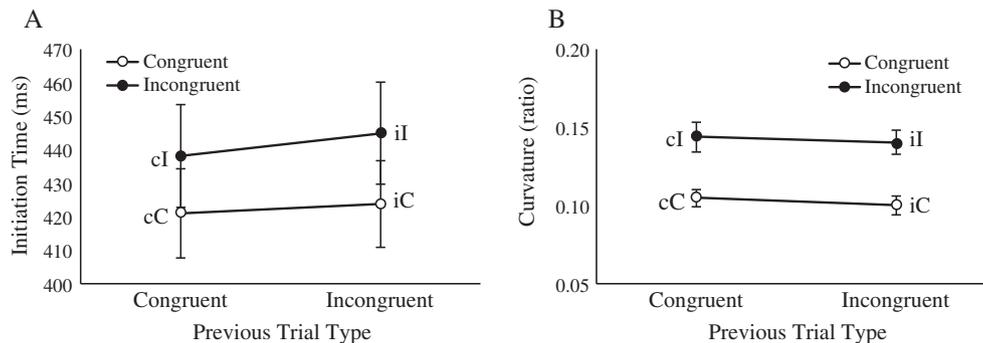

Fig. 5. Average performance on each of the four trial types (cC, iC, cI, iI) for measures of (A) initiation time and (B) curvature. Error bars indicate standard errors.
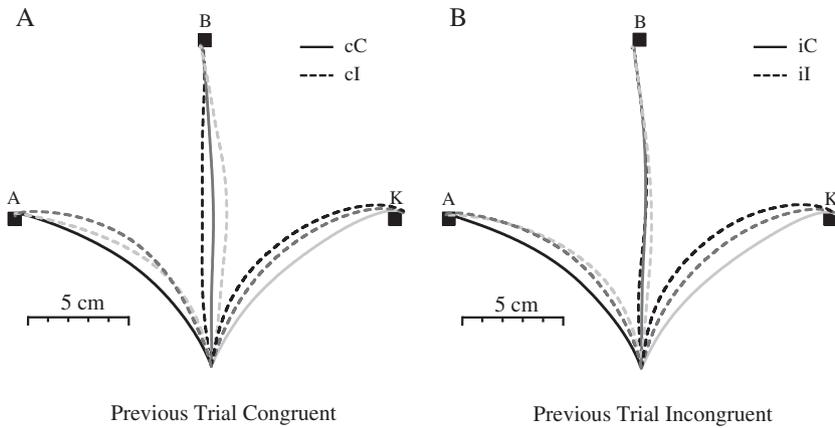
Fig. 7. Average reach trajectories to each target for (A) trials preceded by a congruent trial and (B) trials preceded by an incongruent trial. The color of each line indicates the identity of the flanker letters presented on that trial (black = A's, dark grey = B's, and light grey = K's), while the location of the target indicates the identity of the center letter presented on that trial (labeled with a "A", "B", or "K" for clarity). Responses to congruent trials are presented with solid lines, while responses to incongruent trials are presented with dashed lines.

Table 2
The average error rate, movement time, and total time on each of the four trial types (cC, iC, cI, iI) with standard deviations in parentheses.

	cC	iC	cI	iI
Error rate (%)	0.4 (0.9)	0.3 (1.3)	0.7 (1.6)	0.6 (1.2)
Movement time (ms)	405.9 (52.6)	408.4 (56.9)	425.7 (54.9)	422.7 (54.8)
Total time (ms)	826.9 (118.2)	832.2 (120)	863.7 (129.3)	867.5 (129.6)

binding conflict are excluded from analysis (e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). In these studies, the inclusion of feature integration effects such as S-R binding conflict results in faster response times on iI relative to cI trials. This raises the question of how the inclusion of these trials may alter the patterns of TSEs reported above.

To address this question, we evaluated performance across all of the trials, including those featuring a repeat of the target (i.e., center letter) or distractor (i.e., flanker letter) presented on the preceding trial. As in the preceding analyses, the first trial of each block was excluded, and only accurate responses following an accurate response were included in the following analyses, except for the measure of error rate, which included inaccurate responses. Removing errors and trials preceded by an error resulted in the additional exclusion of less than 1.0% of the remaining valid trials (SD = 1.1%) per participant on average. Performance was then analyzed with a series of 2 (current trial congruency: C vs. I) × 2 (previous trial congruency: c vs. i) ANOVAs.

3.2.4.1. Initiation time. As in the preceding analyses, initiation times conformed to the pattern of TSEs proposed to underlie the response threshold adjustment process (cC < iC < cI < iI; see Fig. 8A). Initiation times revealed a main effect of current trial congruency, $F(1,39) = 56.83$, $p < 0.001$, $\eta_p^2 = 0.59$, with longer initiation times on incongruent relative to congruent trials, and a main effect of previous trial congruency, $F(1,39) = 18.38$, $p < 0.001$, $\eta_p^2 = 0.32$, with longer initiation times on trials preceded by an incongruent relative to a congruent trial. The interaction between current and previous trial congruency did not approach significance, $F(1,39) = 0.01$, $p = 0.92$.

3.2.4.2. Reach curvature. As in the previous analyses, reach curvatures revealed a main effect of current trial congruency, $F(1,39) = 56.47$, $p < 0.001$, $\eta_p^2 = 0.59$, with larger reach curvatures on incongruent relative to congruent trials (see Fig. 8B). In contrast to the previous analyses, reach curvatures also revealed a main effect of previous trial congruency, $F(1,39) = 4.55$, $p = 0.039$, $\eta_p^2 = 0.10$, with higher reach curvatures on trials preceded by a congruent as opposed to an incongruent trial, and a significant interaction between current and previous trial congruency, $F(1,39) = 13.89$, $p < 0.001$, $\eta_p^2 = 0.26$. Follow-up tests revealed a significant effect of previous trial congruency on incongruent trials, $F(1,39) = 12.74$, $p < 0.001$, $\eta_p^2 = 0.25$, but not on congruent trials, $F(1,39) = 1.72$, $p = 0.20$.

3.2.4.3. Error rate, movement time, and total time. Average error rate, movement time, and total time for each of the trial types
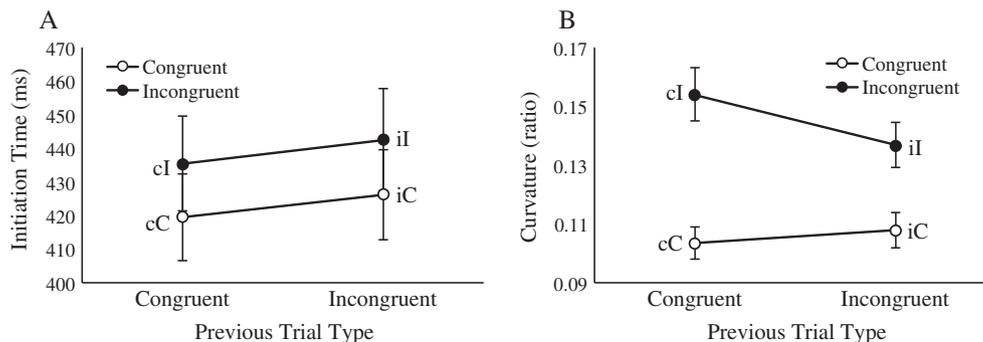

Fig. 8. Average performance on each of the four trial types (cC, iC, cI, iI) for measures of (A) initiation time and (B) curvature. Error bars indicate standard errors. Target and distractor repetition trials included in analysis.

Table 3
The average error rate, movement time, and total time on each of the four trial types (cC, iC, cI, iI), with standard deviations in parentheses. Target and distractor repetition trials included in analysis.

	cC	iC	cI	iI
Error rate (%)	0.3 (0.7)	0.3 (0.8)	0.6 (1.0)	0.5 (0.8)
Movement time (ms)	405 (53.7)	410.1 (58.8)	427 (53.5)	421.1 (55.5)
Total time (ms)	824.5 (116.7)	836.2 (123.7)	862.4 (120)	863.5 (130.4)

are displayed in Table 3. Error rates were at floor and were not analyzed further. Movement times were significantly higher on incongruent trials than congruent trials, $F(1, 39) = 75.17$, $p < 0.001$, $\eta_p^2 = 0.66$. A significant interaction between current and previous trial congruency was also observed in movement times, $F(1, 39) = 17.74$, $p < 0.001$, $\eta_p^2 = 0.31$, with lower movement times on trials that featured a repeat of the previous trial's congruency. Finally, total times revealed a significant effect of current trial congruency, $F(1, 39) = 225.67$, $p < 0.001$, $\eta_p^2 = 0.85$, and previous trial congruency, $F(1, 39) = 6.84$, $p = 0.013$, $\eta_p^2 = 0.15$. A significant interaction between current and previous trial type was also observed in total times, $F(1, 39) = 8.10$, $p < 0.01$, $\eta_p^2 = 0.17$. Follow-up tests revealed a significant effect of previous trial congruency on congruent trials, $F(1, 39) = 33.04$, $p < 0.001$, $\eta_p^2 = 0.46$, but not on incongruent trials, $F(1, 39) = 0.08$, $p = 0.78$.

3.3. Discussion

Experiment 2 provides further evidence that initiation time and curvature are sensitive to two dissociable processes underlying cognitive control. As in Experiment 1, initiation times conformed to the same pattern of TSEs observed in single-unit recordings of the dACC (cC < iC < cI < iI) by Sheth et al. (2012), regardless of whether target and distractor repetition trials were excluded from analysis. In contrast to Experiment 1, no evidence of larger reach curvatures on cI relative to iI trials was observed when target and distractor repetition trials were excluded from analysis (cC = iC < iI = cI), suggesting that contingency learning effects do not influence flanker task performance in the same manner as the Stroop task. While previous research has demonstrated that controlling for both feature integration and contingency learning effects eliminates response time differences between cI and iI trials in the Stroop and flanker tasks (Schmidt & De Houwer, 2011), this work did not determine the relative impact of contingency learning effects on each of the tasks. Thus, the results of the current study serve to clarify the nature of the similarities and differences existing between these two prominent tasks.

Although reach curvatures on iI and cI trials did not differ when target and distractor repetitions were excluded from analysis, continuous reach trajectories did reveal slightly less pull toward the response cued by the flanker letters on iI relative to cI trials from 16% to 18% of the movement. This suggests that contingency learning effects may have played a limited role in flanker task performance. For example, attention to the flanker letters may have been slightly greater on cI trials and, consequently, the pull of the flanker letters emerged earlier in the movement.

When feature integration effects such as S-R binding conflict were included in the analyses, reach curvatures were significantly larger on cI relative to iI trials (cC = iC < iI < cI). These findings are consistent with previous research indicating that performance on the flanker task is enhanced on iI relative to cI trials when S-R binding conflict and stimulus repetitions are included in analysis, but not when these effects are excluded (e.g., Gratton et al., 1992; Mayr et al., 2003; Nieuwenhuis et al., 2006). It is worth noting that the results of Experiment 1 did not substantially change when target and distractor repetition trials were included in the analyses. Initiation times and reach curvatures in the Stroop task

revealed the same pattern of TSEs regardless of whether repetition trials were included in the analyses. We explore this and other differences between the Stroop and flanker performance further in Section 4.

4. General discussion

Research investigating the neural underpinnings of trial sequence effects in congruency tasks has revealed two different patterns of effects in dACC activity, one with single-unit recordings (cC < iC < cI < iI) (Sheth et al., 2012) and the other with fMRI (cC = iC < iI < cI) (Kerns et al., 2004). To account for these seemingly inconsistent findings, it was proposed that each pattern of effects reflected a different process supported by the dACC (Shenhav et al., 2013). On this view, the pattern of TSEs observed in single-unit recordings reflected the region's role in supporting a response threshold adjustment process, while the pattern observed in fMRI reflected its role in supporting a monitoring process which, in turn, reflected how rapidly conflict was resolved by a controlled response selection process. The current study tested this proposal by using two measures afforded by reach tracking, initiation time and curvature, to target these dissociable processes.

In light of previous research suggesting a link between the response threshold adjustment process and motoric inhibition (e.g., Cavanagh et al., 2011; Frank, 2006; Wiecki & Frank, 2013), we hypothesized that higher response thresholds would lead to longer periods of motoric inhibition and, consequently, longer initiation times. If the pattern of TSEs observed by Sheth et al. (2012) reflected the dACC's role in supporting the response threshold adjustment process, then initiation times in the current study would conform to the same pattern of effects (cC < iC < cI < iI). The results of Experiments 1 and 2 supported this prediction, revealing significant main effects of current and previous trial congruency.

Drawing on previous reach tracking research (e.g., Farmer et al., 2007; Freeman et al., 2013; Song & Nakayama, 2007a), we hypothesized that reach curvatures would reflect the relative activation of competing responses over the course of a trial. If the pattern of effects observed with fMRI by Kerns et al. (2004) reflected the dACC's role in monitoring conflict, then reach curvatures in the Stroop task would conform to the same pattern of effects (cC = iC < iI < cI). The results of Experiment 1 supported this prediction, revealing significantly larger reach curvatures on cI than iI trials and no difference between cC and iC trials. In contrast to Experiment 1, reach curvatures in Experiment 2 revealed no difference between cI and iI trials when target and distractor repetition trials were excluded from analysis (cC = iC < iI = cI), indicating that contingency learning effects play a limited role in the flanker task relative to the Stroop.

Given the difficulties associated with linking behavioral and neurophysiological results across different studies, our proposal that the patterns of effects observed in initiation time and curvature correspond to the patterns of effects observed in dACC activation should be interpreted with care. Ideally, the link between initiation times and dACC activation would be evaluated by measuring reaching behavior and dACC activation simultaneously. However, it is rare to have the opportunity to obtain single-unit

recordings of the dACC in alert humans. While further research is needed to more fully evaluate our proposal, it should be noted that the predictions of the current study were developed in direct response to previous neurophysiology findings and were not generated post hoc to account for the observed behavioral data. Thus, an important strength of our proposal is that it generated original predictions that gained empirical support.

4.1. Comparing Stroop and flanker task performance

One of the advantages of reach tracking illustrated in the current study is that the method provides the opportunity to compare and contrast how key processes underlying cognitive control unfold across different tasks. Initiation times in the Stroop and flanker tasks conformed to the same pattern of TSEs, suggesting that response thresholds are adjusted in a similar manner in both tasks. Reach tracking also revealed a number of clear differences between the tasks. First, reach curvatures in the Stroop task were larger on cI relative to iI trials, while reach curvatures in the flanker task were only larger on cI relative to iI trials when repetition trials were included in the analyses. Second, continuous reach trajectories in the Stroop task were pulled toward the response cued by the distractor on cI trials but not iI trials, while reach trajectories in the flanker task were pulled toward the response cued by the distractor on both trial types. Finally, the Stroop task featured higher error rates, initiation times, reach curvatures, and movement times than the flanker task, indicating a general difference in task difficulty.

What might account for these differences in task performance? One potential explanation focuses on the nature of the conflict involved in each task. In the Stroop task, different dimensions of the same stimulus cue two competing responses on incongruent trials, whereas separate stimuli cue competing responses in the flanker task. Previous research comparing the standard or *integrated* version of the Stroop task to *separated* versions of the task involving multiple stimuli (e.g., the word "RED" in black text surrounded by colored asterisks) has found that response times and congruency effects are substantially larger in the integrated than the separated version of the task (MacLeod, 1998). This finding indicates that the within-stimulus conflict of the Stroop task and the between-stimulus conflict of the flanker task place different demands on attention and inhibitory control. Continuous reach trajectories in the current study provide further insight into the nature of this difference, indicating that iI trials in the flanker task but not the Stroop task feature strong response-level conflict. This suggests that distractor inhibition differs greatly when the distractor and target are presented as different dimensions of a single stimulus as opposed to separate stimuli.

4.2. The role of repetition priming effects

Given that the curvature predictions of Experiment 1 were based on the fMRI results of Kerns et al. (2004), the tasks used in the current study were intentionally modeled on that of Kerns and colleagues. This task design had two primary strengths. First, it allowed contingency learning effects to occur, which enabled us to capture distinctly different patterns of TSEs in initiation time (cC < iC < cI < iI) and reach curvature (cC = iC < iI < cI) in Experiment 1, and compare the role of contingency learning effects between the Stroop and flanker tasks. Second, the task design enabled us to control for feature integration effects such as S-R binding conflict by removing target and distractor repetition trials from analysis.

The design, however, did not allow us to control for other potential repetition priming effects. Even after target and distractor repetition trials were excluded from analysis, iI trials featured

cases in which the distractor of the previous trial became the target on the current trial (e.g., the word "RED" in blue text followed by "GREEN" in red text, or "BBABB" followed by "KKBKK") and cases in which the target of the previous trial became the distractor on the current trial (e.g., the word "RED" in blue text followed by "BLUE" in green text, or "BBABB" followed by "AAKAA"). Given that both the target and distractor prompted the same response on congruent trials, no such repetitions occurred on cC, iC, or cI trials (e.g., the word "RED" in red text followed by "GREEN" in blue text, or "BBKBB" followed by "AAAAA"). One potential limitation of the current study concerns the extent to which our results were driven by repetition priming effects on iI trials.

It is unclear how these potential repetition priming effects could account for the results observed in the current study. These effects are generally reported to impede performance, as in the case of negative priming (e.g., Tipper, 1985). Yet, reach curvatures were *more* direct on iI than cI trials in Experiment 1, and no difference was observed between these trial types in Experiment 2 when target and distractor repetition trials were excluded from analysis. While initiation times were elevated on iI trials, repetition priming alone cannot account for the overall pattern of TSEs observed in initiation times (cC < iC < cI < iI). Further, the inclusion of target and distractor repetition trials did not influence the pattern of TSEs observed in initiation times in Experiments 1 and 2, suggesting that repetition priming effects do not substantially alter how the response threshold adjustment process functions. Taken together, these observations indicate that the repetition priming effects outlined above cannot account for the patterns of results observed across Experiments 1 and 2.

4.3. Implications for previous research

How might the effects observed in the current study be reflected in response times in traditional button-press tasks? One clear difference between reach tracking and button-press tasks is that reach tracking allows participants to engage in online adjustments, while button-press tasks encourage ballistic responses. Consequently, error rates in the current study were low relative to previous research with the Stroop task (e.g., Kerns et al., 2004) or the flanker task (e.g., Nieuwenhuis et al., 2006). Participants in the current study were able to adjust the speed of their movements online, leading to slight differences between the patterns of effects observed in curvature and movement time. For example, the interaction between current and previous trial congruency in Experiment 1 was more pronounced in curvature than movement time, indicating that participants increased their movement speed to offset large reach curvatures on cI trials. Given that these types of adjustments are less likely to occur on button-press tasks, total times in reach tracking tasks can be expected to differ in certain circumstances from response times in button-press tasks.

Despite these differences, there is some evidence to suggest that response times in button-press tasks reflect a combination of the patterns of effects observed in initiation time and curvature in reach tracking tasks. For instance, one experiment reported by Nieuwenhuis et al. (2006, Experiment 5) tested over 600 adults on a two-response version of the flanker task. On the subset of trials that featured a response change (i.e., that did not allow for S-R binding conflict), Nieuwenhuis et al. observed a large main effect of current trial congruency (C < I) and a small but significant main effect of previous trial congruency (c < i), resulting in the following pattern of effects: cC < iC < cI < iI.[1] The same pattern emerges when the TSEs observed in initiation time (cC < iC < cI < iI) and curvature

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[1] The effect of previous trial congruency on response change trials was not reported in the article, but the presence of a significant effect was confirmed by the first author (Nieuwenhuis, personal communication, September 24th, 2014).

(cC = iC < iI = cI) in the first set of analyses in Experiment 2 are combined (i.e., a particularly large effect of current trial congruency and a relatively small effect of previous trial congruency).

On the subset of trials that featured a response repetition (i.e., that allowed for S-R binding conflict), Nieuwenhuis et al. (2006) observed the following pattern of effects, known as the *Gratton effect*: cC < iC < iI < cI. This same pattern emerges when the patterns of effects observed in initiation time (cC < iC < cI < iI) and reach curvature (cC = iC < iI < cI) in the second set of analyses in Experiment 2 are combined, assuming that the large effect of previous trial congruency observed in reach curvatures on incongruent trials (iI < cI) outweighs the smaller effect of previous trial congruency observed in initiation times (cI < iI). Thus, our findings indicate that previous reports of TSEs in response times on congruency tasks likely reflect a combination of effects stemming from the response threshold adjustment process and controlled response selection process, although further research is necessary to evaluate the relative contribution of these processes to response times in different tasks and conditions.

5. General conclusions

The results of the current study indicate that the different patterns of trial sequence effects previously observed in dACC activation with single-unit recordings (Sheth et al., 2012) and fMRI (Kerns et al., 2004) reflect the region's role in supporting two dissociable processes underlying cognitive control: a response threshold adjustment process involving the temporary inhibition of motor output and a monitoring process that registers the relative co-activation of competing responses over the course of a trial. Our findings also offer new insights into the similarities and differences existing between the Stroop and flanker task, particularly with relation to the roles of response-level conflict and contingency learning effects in each task. More generally, our findings contribute to a growing body of research highlighting the promise of using continuous measures of behavior to study how processes across perception, cognition, and action interact to support flexible, online behavior (e.g., Freeman et al., 2013; Resulaj, Kiani, Wolpert, & Shadlen, 2009; Song & Nakayama, 2009; Spivey, 2008; Welsh, Neyedli, & Tremblay, 2013). By targeting different processes implicated in the cognitive control of behavior with distinct measures, reach tracking presents new opportunities for investigating how these processes function across different tasks, differ among individuals, and change across development.

Author contributions

C. D. Erb designed and conducted both experiments under the guidance of J.-H. Song and D. M. Sobel. C. D. Erb and J. Moher developed the computerized tasks used in each experiment and performed the data analyses. C. D. Erb wrote the majority of the manuscript, with J. Moher contributing to the result sections. J. Moher, J.-H. Song, and D. M. Sobel provided critical revisions to the manuscript. All authors approved the final version of the manuscript for submission.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found at http://dx.doi.org/10.1016/j.cognition.2016.03.015.

References

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends in Cognitive Sciences, 12*(5), 193–200. http://dx.doi.org/10.1016/j.tics.2008.02.004.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652. http://dx.doi.org/10.1037/0033-295X.108.3.624.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences, 8*(12), 539–546. http://dx.doi.org/10.1016/j.tics.2004.10.003.

Botvinick, M. M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402*(6758), 179–181. http://dx.doi.org/10.1038/46035.

Buetti, S., & Kerzel, D. (2009). Conflicts during response selection affect response programming: Reactions toward the source of stimulation. *Journal of Experimental Psychology: Human Perception and Performance, 35*(3), 816–834. http://dx.doi.org/10.1037/a0011092.

Casey, B. J., Durston, S., & Fossella, J. A. (2001). Evidence for a mechanistic model of cognitive control. *Clinical Neuroscience Research, 1*(4), 267–282. http://dx.doi.org/10.1016/S1566-2772(01)00013-5.

Cavanagh, J. F., Wiecki, T. V., Cohen, M. X., Figueroa, C. M., Samanta, J., Sherman, S. J., & Frank, M. J. (2011). Subthalamic nucleus stimulation reverses mediofrontal influence over decision threshold. *Nature Neuroscience, 14*(11), 1462–1467. http://dx.doi.org/10.1038/nn.2925.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97*(3), 332–361. http://dx.doi.org/10.1037/0033-295X.97.3.332.

Cohen, J. D., & Huston, T. A. (1994). Progress in the use of interactive models for understanding attention and performance. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 453–476). Cambridge, MA: MIT Press.

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance, 20*(4), 731–750. http://dx.doi.org/10.1037/0096-1523.20.4.731.

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

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. http://dx.doi.org/10.1146/annurev-psych-113011-143750.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience, 7*(4), 380–390. http://dx.doi.org/10.3758/CABN.7.4.380.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149. http://dx.doi.org/10.3758/BF03203267.

Farmer, T. A., Cargill, S. A., Hindy, N. C., Dale, R., & Spivey, M. J. (2007). Tracking the continuity of language comprehension: Computer mouse trajectories suggest parallel syntactic processing. *Cognitive Science, 31*(5), 889–909. http://dx.doi.org/10.1080/03640210701530797.

Frank, M. J. (2006). Hold your horses: A dynamic computational role for the subthalamic nucleus in decision making. *Neural Networks, 19*(8), 1120–1136. http://dx.doi.org/10.1016/j.neunet.2006.03.006.

Freeman, J. B., Nakayama, K., & Ambady, N. (2013). Finger in flight reveals parallel categorization across multiple social dimensions. *Social Cognition, 31*(6), 792–805. http://dx.doi.org/10.1521/soco.2013.31.6.792.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121*(4), 480–506. http://dx.doi.org/10.1037/0096-3445.121.4.480.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494–500. http://dx.doi.org/10.1016/j.tics.2004.08.007.

Jacoby, L. L., Lindsay, D. S., & Hessels, S. (2003). Item-specific control of automatic processes: Stroop process dissociations. *Psychonomic Bulletin & Review, 10*(3), 638–644. http://dx.doi.org/10.3758/BF03196526.

Kerns, J. G., Cohen, J. D., MacDonald, 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. http://dx.doi.org/10.1126/science.1089910.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*(2), 163–203. http://dx.doi.org/10.1037/0033-2909.109.2.163.

MacLeod, C. M. (1998). Training on integrated versus separated Stroop tasks: The progression of interference and facilitation. *Memory & Cognition, 26*(2), 201–211. http://dx.doi.org/10.3758/BF03201133.

Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience, 6*(5), 450–452. http://dx.doi.org/10.1038/nn1051.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*(1), 167–202. http://dx.doi.org/10.1146/annurev.neuro.24.1.167.

Moher, J., Anderson, B. A., & Song, J.-H. (2015). Dissociable effects of salience on attention and goal-directed action. *Current Biology, 25*(15), 2040–2046. http://dx.doi.org/10.1016/j.cub.2015.06.029.

Moher, J., Sit, J., & Song, J.-H. (2014). Goal-directed action is automatically biased towards looming motion. *Vision Research, 113*, 188–197. http://dx.doi.org/10.1016/j.visres.2014.08.005.

Moher, J., & Song, J.-H. (2013). Context-dependent sequential effects of target selection for action. *Journal of Vision, 13*(8), 1–13. http://dx.doi.org/10.1167/13.8.10. 10.

Munakata, Y., Herd, S. A., Chatham, C. H., Depue, B. E., Banich, M. T., & O'Reilly, R. C. (2011). A unified framework for inhibitory control. *Trends in Cognitive Sciences, 15*(10), 453–459. http://dx.doi.org/10.1016/j.tics.2011.07.011.

Nieuwenhuis, S., Stins, J. F., Posthuma, D., Polderman, T. J., Boomsma, D. I., & de Geus, E. J. (2006). Accounting for sequential trial effects in the flanker task: Conflict adaptation or associative priming? *Memory & Cognition, 34*(6), 1260–1272. http://dx.doi.org/10.3758/BF03193270.

Resulaj, A., Kiani, R., Wolpert, D. M., & Shadlen, M. N. (2009). Changes of mind in decision-making. *Nature, 461*(7261), 263–266. http://dx.doi.org/10.1038/nature08275.

Ridderinkhof, K. R., van der Molen, M. W., & Bashore, T. R. (1995). Limits on the application of additive factors logic: Violations of stage robustness suggest a dual-process architecture to explain flanker effects on target processing. *Acta Psychologica, 90*(1), 29–48. http://dx.doi.org/10.1016/0001-6918(95)00031-O.

Rubichi, S., Nicoletti, R., Umiltà, C., & Zorzi, M. (2000). Response strategies and the Simon effect. *Psychological Research Psychologische Forschung, 63*(2), 129–136. http://dx.doi.org/10.1007/PL00008171.

Rubichi, S., & Pellicano, A. (2004). Does the Simon effect affect movement execution? *European Journal of Cognitive Psychology, 16*(6), 825–840. http://dx.doi.org/10.1080/09541440340000367.

Scherbaum, S., Dshemuchadse, M., Fischer, R., & Goschke, T. (2010). How decisions evolve: The temporal dynamics of action selection. *Cognition, 115*(3), 407–416. http://dx.doi.org/10.1016/j.cognition.2010.02.004.

Schmidt, J. R. (2013). The Parallel Episodic Processing (PEP) model: Dissociating contingency and conflict adaptation in the item-specific proportion congruent paradigm. *Acta Psychologica, 142*(1), 119–126. http://dx.doi.org/10.1016/j.actpsy.2012.11.004.

Schmidt, J. R., & Besner, D. (2008). The Stroop effect: Why proportion congruent has nothing to do with congruency and everything to do with contingency. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*(3), 514–523. http://dx.doi.org/10.1037/0278-7393.34.3.514.

Schmidt, J. R., Crump, M. J., Cheesman, J., & Besner, D. (2007). Contingency learning without awareness: Evidence for implicit control. *Consciousness and Cognition, 16*(2), 421–435. http://dx.doi.org/10.1016/j.concog.2006.06.010.

Schmidt, J. R., & De Houwer, J. (2011). Now you see it, now you don't: Controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica, 138*(1), 176–186. http://dx.doi.org/10.1016/j.actpsy.2011.06.002.

Scorolli, C., Pellicano, A., Nicoletti, R., Rubichi, S., & Castiello, U. (2014). The Simon effect in action: Planning and/or on-line control effects? *Cognitive Science, 39*(5), 972–991. http://dx.doi.org/10.1111/cogs.12188.

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: An integrative theory of anterior cingulate cortex function. *Neuron, 79*(2), 217–240. http://dx.doi.org/10.1016/j.neuron.2013.07.007.

Sheth, S. A., Mian, M. K., Patel, S. R., Asaad, W. F., Williams, Z. M., Dougherty, D. D., Bush, G., & Eskandar, E. N. (2012). Human dorsal anterior cingulate cortex neurons mediate ongoing behavioural adaptation. *Nature, 488*(7410), 218–221. http://dx.doi.org/10.1038/nature11239.

Song, J.-H., & Nakayama, K. (2006). Role of focal attention on latencies and trajectories of visually guided manual pointing. *Journal of Vision, 6*(9), 982–995. http://dx.doi.org/10.1167/6.9.11.

Song, J.-H., & Nakayama, K. (2007a). Automatic adjustment of visuomotor readiness. *Journal of Vision, 7*(5), 1–9. http://dx.doi.org/10.1167/7.5.2. 2.

Song, J.-H., & Nakayama, K. (2007b). Fixation offset facilitates saccades and manual reaching for single but not multiple target displays. *Experimental Brain Research, 177*(2), 223–232. http://dx.doi.org/10.1007/s00221-006-0667-4.

Song, J.-H., & Nakayama, K. (2008). Target selection in visual search as revealed by movement trajectories. *Vision Research, 48*(7), 853–861. http://dx.doi.org/10.1016/j.visres.2007.12.015.

Song, J.-H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Sciences, 13*(8), 360–366. http://dx.doi.org/10.1016/j.tics.2009.04.009.

Spivey, M. (2008). *The continuity of mind*. Oxford University Press.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. http://dx.doi.org/10.1037/h0054651.

Tipper, S. P. (1985). The negative priming effect: Inhibitory priming by ignored objects. *The Quarterly Journal of Experimental Psychology, 37*(4), 571–590. http://dx.doi.org/10.1080/14640748508400920.

Ullsperger, M., Bylsma, L. M., & Botvinick, M. M. (2005). The conflict adaptation effect: It's not just priming. *Cognitive, Affective, & Behavioral Neuroscience, 5*(4), 467–472. http://dx.doi.org/10.3758/CABN.5.4.467.

Welsh, T. N., Neyedli, H., & Tremblay, L. (2013). Refining the time course of facilitation and inhibition in attention and action. *Neuroscience Letters, 554*, 6–10. http://dx.doi.org/10.1016/j.neulet.2013.08.055.

Wiecki, T. V., & Frank, M. J. (2013). A computational model of inhibitory control in frontal cortex and basal ganglia. *Psychological Review, 120*(2), 329–355. http://dx.doi.org/10.1037/a0031542.

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review, 111*(4), 931–959. http://dx.doi.org/10.1037/0033-295X.111.4.931.