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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.

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