



Associative priming and conflict differentially affect two processes underlying cognitive control: Evidence from reaching behavior

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Abstract

Previous research has indicated that two components of reaching behavior, initiation time and reach curvature, exhibit distinct patterns of trial sequence effects in congruency tasks. The observed patterns have been proposed to reflect two dissociable processes underlying decision behavior, with initiation times capturing the functioning of a threshold adjustment process involving the temporary inhibition of motor output, and reach curvatures reflecting a controlled selection process that supports goal-driven stimulus–response translation. The tasks used in previous studies, however, did not control for a range of associative-priming confounds commonly featured in congruency tasks. Consequently, the extent to which the observed patterns reflected the proposed processes or associative-priming confounds remained unclear. We therefore presented 45 adult participants with a reach-tracking version of the Stroop task that featured both confound-minimized and confound-laden trials. Initiation times revealed main effects of previous and current congruency on both confound-minimized and confound-laden trials, consistent with the claim that initiation times can be used to target the functioning of the threshold adjustment process. Conversely, reach curvatures exhibited a clear sensitivity to associative-priming effects, revealing a congruency sequence effect on confound-laden but not on confound-minimized trials. This finding is consistent with the claim that reach curvatures can be used to target the functioning of the controlled selection process. Thus, by directly evaluating the influence of associative-priming confounds, the present study revealed the strongest evidence to date that decision behavior in tasks involving conflict is fundamentally structured by the functioning of two dissociable processes.

Keywords Associative priming · Cognitive control · Congruency sequence effect · Decision making

For over 150 years, psychological scientists have investigated the workings of the human mind by measuring response times (Helmholtz, 1850). Although response times have contributed substantially to our current understanding of the mind, discrete behavioral responses (e.g., button presses) present limited insight into how different cognitive processes unfold over time. Consequently, researchers have developed sophisticated behavioral, neural, and computational methods to shed light

on the cognitive dynamics underlying decision behavior. In the last 15 years, particular emphasis has been placed on using hand-tracking techniques, such as *mouse tracking* and *reach tracking*, to investigate how unfolding cognitive processes are reflected in the spatial and temporal dynamics of hand movements (for reviews, see Erb, 2018; Freeman & Johnson, 2016; Song & Nakayama, 2009). In addition to accuracy and response time, recording the path that a participant's hand travels to reach a response target provides multiple measures that offer a more detailed view of how cognitive processes unfold over time, including the *initiation time* (i.e., the time elapsed between stimulus onset and movement onset) and *curvature* (a measure of the extent to which a hand movement deviates from a direct path to the selected response target).

In a series of recent studies, Erb and colleagues (Erb & Marcovitch, 2018a, 2018b; Erb, Moher, Sobel, & Song, 2016; Erb, Moher, Song, & Sobel, 2017, 2018b) presented evidence that initiation time and curvature can be used to target two processes underlying decision behavior: a *threshold adjustment process* that temporarily puts the “brake” on

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behavior when signals of conflict are detected, and a *controlled selection process* that “steers” top-down resources in favor of goal-relevant or contextually appropriate responses (e.g., Cavanagh et al., 2011; Frank, 2006; Shenhav, Botvinick, & Cohen, 2013). To illustrate how these processes are proposed to function, consider the Stroop (1935) task. In the task, participants are instructed to respond according to the color of the text that a word is presented in (e.g., red or green), regardless of the word’s meaning (e.g., “RED” or “GREEN”). On incongruent trials, the text color and word meaning cue competing responses (e.g., “RED” presented in green text). The conflict occurring on incongruent trials is proposed to result in heightened response thresholds and, consequently, in longer periods of motoric stopping on incongruent trials than on congruent trials (e.g., Frank, 2006). Given that the temporary inhibition of motor output is insufficient to ensure that the appropriate response is ultimately provided, the controlled selection process is also engaged to direct attention to the goal-relevant stimulus dimension (i.e., text color, in the Stroop task) when signals of conflict are detected. Thus, elevated response times on incongruent trials can be understood to reflect, among other factors, heightened response thresholds and the speed with which the controlled selection process sways response activations in favor of the appropriate response.

Erb et al. (2016) proposed that initiation times could be used to target the functioning of the threshold adjustment process in congruency tasks such as the Stroop task by indexing the degree of motoric stopping experienced before a movement is initiated, with higher thresholds resulting in longer periods of motoric stopping and, consequently, slower initiation times. This logic predicts a main effect of current congruency on initiation times, with slower initiation times on incongruent than on congruent trials. In light of previous electrophysiology research suggesting that heightened response thresholds are carried over into the subsequent trial (Sheth et al., 2012), the researchers also predicted that initiation times would be slower on trials preceded by an incongruent trial than on those preceded by a congruent trial. Consistent with these predictions, initiation times in a three-response version of the Stroop task presented main effects of current congruency (i.e., $C < I$, where uppercase letters denote the congruency of the current trial) and previous congruency (i.e., $c < i$, where lowercase letters denote the congruency of the previous trial), resulting in the following pattern of effects: $cC < iC < cI < iI$ (see Fig. 1A).

Erb et al. (2016) further proposed that reach curvatures could be used to target the functioning of the controlled selection process, by indexing the degree of coactivation between competing responses over the course of a trial, with larger curvatures indicating greater activation of the competing response or indecision stemming from conflict at the level of the stimulus (for a discussion of stimulus-level and response-level

conflict, see the Future Directions section of the Discussion).¹ The researchers predicted that reach curvatures in the Stroop task would conform to the same pattern of effects previously linked to the controlled selection process in a functional magnetic resonance imaging (fMRI) study by Kerns et al. (2004) that had used the same three-response version of the Stroop task: $cC = iC < iI < cI$. Consistent with this prediction, Erb et al. (2016) observed main effects of current congruency and previous congruency, as well as an interaction between current and previous congruency, resulting in the same pattern of effects observed by Kerns et al. (see Fig. 1B). This pattern of effects is often referred to as the *congruency sequence effect* (CSE), because the size of the congruency effect (the performance difference between congruent and incongruent trials) is smaller on trials preceded by an incongruent trial (iC and iI trials) than on trials preceded by a congruent trial (cC and cI trials).²

The CSE has been at the center of recent debates surrounding the cognitive and neural mechanisms underlying cognitive control and has been attributed to a range of factors, including *conflict adaptation* and *associative priming* (for reviews, see Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007, 2017; Schmidt & De Houwer, 2011). According to the conflict-adaptation account, the CSE occurs because top-down control is up-regulated following an incongruent (i.e., control-demanding) trial (Botvinick et al., 2001; Ullsperger, Bylsma, & Botvinick, 2005). In the Stroop task, this up-regulation of control results in increased attention to text color on trials following incongruent trials and, consequently, enhanced performance on iI relative to cI trials.

According to the associative-priming account (Hommel, 2004; Hommel, Proctor, & Vu, 2004), the CSE is driven by the degree to which the stimulus and response features of the current trial overlap with those of the previous trial. For example, if the current trial features the same stimulus and response as the previous trial (e.g., a LEFT response to the word “RED” in green text on two consecutive trials), performance can be facilitated because the appropriate stimulus–response pair was formed on the previous trial. Importantly, exact

¹ According to this view, curvature can be interpreted to reflect how rapidly evidence is accumulated in favor of the correct response. This interpretation of reach curvatures is therefore compatible with various perspectives proposing that the congruency effect observed in response times is attributable in part to slower evidence accumulation on incongruent trials (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Liu, Holmes, & Cohen, 2008; Scherbaum, Dshemuchadse, Ruge, & Goschke, 2012).

² The CSE is generally associated with a reduced congruency effect on trials following an incongruent trial, relative to trials following a congruent trial. However, the precise pattern of effects can differ from task to task. For example, the pattern observed by Kerns et al. (2004) and Erb et al. (2016) did not reveal a significant difference between cC and iC trials, whereas other studies have observed differences between these trial types (e.g., Erb & Marcovitch, 2018b). We discuss the different patterns associated with the CSE in greater detail in the Relation to Previous Hand-Tracking Studies section of the Discussion.

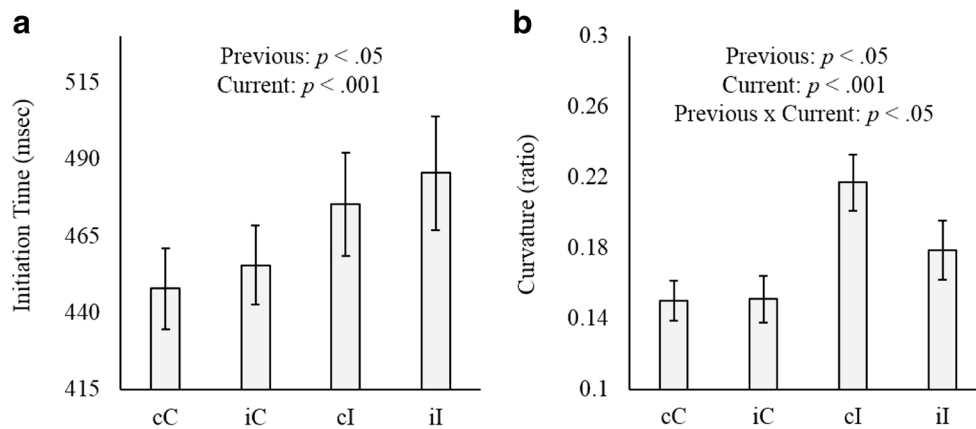


Fig. 1 The (a) initiation time and (b) curvature results observed by Erb et al. (2016, Exp. 1), in a version of the Stroop task that featured three response options. Lowercase and uppercase letters denote the congruency (congruent vs. incongruent) of the previous and current trials,

repetitions of the stimulus–response pair from the previous trial only occur on congruency repeat trials in the Stroop task (i.e., cC and iI trials). If the current trial features some—but not all—of the stimulus and response features of the previous trial, performance can be impaired, because the stimulus–response pair formed on the previous trial can interfere with the formation of the appropriate stimulus–response pair on the current trial. This type of partial overlap between the stimulus–response pairs of the current and previous trials occurs more frequently on congruency switch trials (i.e., iC and cI trials) than on congruency repeat trials in the Stroop task. Thus, according to this view, the CSE reflects both facilitated performance on congruency repeat trials and impaired performance on congruency switch trials.

Unresolved challenges

Although the results of Erb and colleagues (Erb & Marcovitch, 2018a, 2018b; Erb et al., 2016; Erb et al., 2017, 2018b) provide preliminary evidence for the claim that hand tracking can be used to target the threshold adjustment process and the controlled selection process, the tasks used in these studies did not control for associative-priming confounds that have been demonstrated to impact performance substantially (e.g., Henson, Eckstein, Waszak, Frings, & Horner, 2014; Hommel et al., 2004; Schmidt & Weissman, 2016). This is problematic for two reasons. First, it is possible that the effect of previous congruency observed in initiation times was driven by the degree of overlap between the stimulus and response features of the current and previous trials, rather than by a threshold adjustment process that is sensitive to the congruency of the current and previous trials. If the pattern of effects observed in initiation times were driven by associative-priming effects, the theoretical framework outlined by Erb and colleagues would require substantial revision. Second,

respectively. Initiation time and curvature both revealed main effects of previous congruency and current congruency. However, only curvature revealed a significant interaction between the two. Error bars display standard errors

the extent to which the CSE observed in reaching behavior in previous studies stemmed from conflict adaptation or associative priming remains unclear. This question is particularly timely, given the central position that the CSE has come to occupy in recent research and theory in the cognitive control literature (for a review, see Egner, 2017).

To address these open questions, we developed a modified version of the Stroop task that featured two different sets of stimuli. One set was constructed using the colors red and blue, whereas the other set was constructed using the colors green and orange. The stimuli from each set were presented randomly within each block of trials. Consequently, some trials featured stimuli from the same set as the previous trial (i.e., set repeat trials), whereas others did not (i.e., set change trials).

This task design allowed for a subset of *confound-minimized trials* to occur, in which the stimulus and response features of the current trial did not overlap with those of the previous trial. For example, imagine that the previous trial required a LEFT response to the word “GREEN” presented in green text, whereas the current trial required a RIGHT response to the word “RED” presented in blue text. In this case, both the stimulus set and the response of the current trial differed from those in the previous trial (for further examples of confound-minimized trials, see the Set Change, Response Change section of Table 1). The task also featured a subset of trials that contained the same associative-priming confounds found in standard two-alternative forced choice (2AFC) versions of the task—namely, *set repeat trials*, in which the stimulus presented in the current trial (e.g., the word “BLUE” in red text) was taken from the same set as that in the previous trial (e.g., the word “BLUE” in blue text; for further examples, see the Set Repeat sections of Table 1).

If the pattern of effects observed by Erb and colleagues (Erb & Marcovitch, 2018a, 2018b; Erb et al., 2016; Erb et al., 2018b) in initiation times reflects the threshold adjustment process, then the initiation times in the current study

Table 1 Average performance for each measure as a function of set type (change, repeat), response type (change, repeat), previous congruency (c, i), and current congruency (C, I)

	Previous Stimulus	Previous Response	Current Stimulus	Current Response	Description	Error Rate (%)	Initiation Time (ms)	Reach Curvature (ratio)	Movement Time (ms)	Response Time (ms)		
Set Change	Response Change	cC	RED (red)	LEFT	ORANGE (orange)	RIGHT	No stimulus or response	1.0 (2.4)	453 (95)	.081 (.043)	460 (60)	913 (126)
		iC	BLUE (red)	LEFT	ORANGE (orange)	RIGHT	repetition (confound-minimized trials)	1.2 (4.0)	461 (94)	.086 (.046)	463 (66)	924 (130)
		cI	RED (red)	LEFT	GREEN (orange)	RIGHT		2.0 (4.3)	482 (111)	.122 (.060)	484 (68)	966 (148)
		iI	BLUE (red)	LEFT	GREEN (orange)	RIGHT		2.5 (4.7)	501 (125)	.130 (.065)	495 (72)	996 (167)
Response Repeat		cC	RED (red)	LEFT	GREEN (green)	LEFT	No stimulus repetition,	4.3 (7.7)	482 (123)	.119 (.069)	489 (92)	971 (172)
		iC	BLUE (red)	LEFT	GREEN (green)	LEFT	response repetition	2.9 (5.2)	481 (112)	.116 (.066)	480 (75)	961 (148)
		cI	RED (red)	LEFT	ORANGE (green)	LEFT		5.3 (8.1)	487 (118)	.169 (.087)	515 (84)	1002 (150)
		iI	BLUE (red)	LEFT	ORANGE (green)	LEFT		4.0 (6.7)	496 (113)	.181 (.090)	527 (102)	1022 (176)
Set Repeat	Response Change	cC	RED (red)	LEFT	BLUE (blue)	RIGHT	No stimulus or response	0.9 (2.0)	462 (105)	.085 (.046)	458 (62)	920 (136)
		iC	BLUE (red)	LEFT	BLUE (blue)	RIGHT	repetition	0.9 (2.4)	467 (102)	.105 (.061)	478 (69)	945 (133)
		cI	RED (red)	LEFT	RED (blue)	RIGHT	Distractor repeat, distractor becomes target	1.2 (3.2)	481 (109)	.116 (.057)	482 (69)	963 (143)
		iI	BLUE (red)	LEFT	RED (blue)	RIGHT	Distractor repeat, target becomes distractor	1.5 (3.8)	503 (130)	.122 (.068)	490 (80)	993 (160)
Response Repeat		cC	RED (red)	LEFT	RED (red)	LEFT	target becomes distractor	0.3 (1.6)	429 (82)	.055 (.029)	447 (60)	876 (121)
		iC	BLUE (red)	LEFT	RED (red)	LEFT	Full repetition	0.6 (2.4)	445 (89)	.052 (.027)	446 (60)	890 (127)
		cI	RED (red)	LEFT	BLUE (red)	LEFT	Target repeat, target becomes distractor	1.5 (3.4)	456 (99)	.112 (.064)	482 (69)	938 (141)
		iI	BLUE (red)	LEFT	BLUE (red)	LEFT	Target repeat, distractor becomes target	1.1 (3.9)	463 (117)	.070 (.038)	461 (68)	924 (163)

An example of each trial type is presented, with word meanings appearing in capitalized letters and text color appearing in parentheses. Numbers appearing in parentheses display the standard deviations. Note that these examples were all created using red and blue as the colors featured in the previous stimulus, but equivalent examples could have been created using orange and green as the colors featured in the previous stimulus.

should reveal main effects of previous and current congruency on confound-minimized trials. If the associative-priming account of initiation times is correct, however, then initiation times on confound-minimized trials should not reveal an effect of previous congruency. If, on the other hand, the CSEs observed in reach curvatures by Erb and colleagues were driven by conflict adaptation, then a CSE should be observed in reach curvatures regardless of the presence or absence of associative-priming confounds. This is because the conflict-adaptation account predicts that conflict-driven modulations of top-down control should occur even when such confounds are minimized. Alternatively, if the CSEs previously observed in reach curvatures were driven by associative-priming effects, then the reach curvatures in the present study should not reveal a CSE on confound-minimized trials, given that the controlled selection process would not be facilitated or impeded by the stimulus and response features of the previous trial.

Method

Participants

Forty-five adults participated in the study for course credit ($M = 19.7$ years, $SD = 3.0$; 26 females, 18 males, one nonbinary). One additional individual participated but was excluded from the final sample due to language-based difficulties comprehending the instructions and materials. All participants were right-handed with normal or corrected-to-normal visual acuity. None of the participants reported mild or severe colorblindness. Testing took place at the University of North Carolina at Greensboro. The Institutional Review Board at the University of North Carolina at Greensboro approved the protocol.

Materials

The experiment was conducted using a rear-mounted projector to display the task on a Plexiglas screen (see Erb et al., 2016; Moher & Song, 2013). The projector, screen, and an electromagnetic source were affixed to a wooden board that was mounted to a 91 cm \times 152 cm table (see Fig. 2A). The projected display on the Plexiglas screen measured 38 cm \times 50 cm. A 2 cm \times 2 cm square marker was placed 27 cm in front of the screen. The square served as a starting marker from which participants initiated their movements. Reach movements and response selections were measured at a rate of approximately 160 Hz with an electromagnetic position and orientation recording system (Liberty, Polhemus). A small motion-tracking sensor was secured to participants' right index finger with a Velcro strap. The sensor was 2.26 cm long, 1.27 cm wide, and 1.14 cm high, and weighed 3.7 g. The task was programmed in MATLAB (MathWorks, Natick, MA).

The response targets that participants reached to touch were gray squares with a black outline that measured 2.5 cm \times 2.5 cm. The center of each response target was 12.5 cm from the top of the projected display, with one response target located 11.25 cm from the left side of the projected display and the other square located 11.25 cm from the right side. The stimuli were 1 cm tall and ranged in width from 3.2 cm to 5.8 cm. The response targets remained on the screen throughout the task.

Participants were presented with a two-response version of the Stroop task that involved two sets of stimuli, each comprising four distinct stimuli. One set of stimuli comprised the words "RED" and "BLUE" appearing in either red or blue text, and the other set comprised the words "GREEN" and "ORANGE" appearing in either green or orange text. Participants were instructed to identify the color of text that each stimulus was presented in by reaching to touch a response target located toward the top left or top right of the display (see Fig. 2B), with the colors red and green mapped to the left response target and the colors blue and orange mapped to the right response target.

As is illustrated in Table 1, this version of the Stroop task generated trials that featured no overlap with the stimulus and response elements presented on the previous trial (set change, response change trials), trials that featured no overlap with the stimulus elements presented on the previous trial but the same response as on the previous trial (set change, response repeat trials), and trials that were comparable to those presented in standard 2AFC versions of the task (set repeat trials that featured a response change or a response repeat). This task therefore allowed for comparisons to be made between trials that minimized associative-priming effects (confound-minimized trials) and trials that allowed for various associative-priming effects to occur (confound-laden trials).

Procedure

Participants initiated each trial by resting their finger on the starting marker located on the table between the participant and the display. A crosshair measuring 0.7 cm \times 0.7 cm appeared in the center of the display for 1 s before a stimulus appeared in the same location. If the participant's hand moved from the starting marker before the stimulus appeared, the task was paused and did not resume until the participant had returned their hand to the starting marker for 1 s. Participants had up to 3.5 s to respond following stimulus onset. A high tone sounded for correct responses provided in the allotted time (600 Hz for 200 ms), and a low tone sounded for incorrect responses or responses that exceeded the allotted time (300 Hz for 200 ms).

Participants first completed a nine-point calibration sequence, followed by 16 baseline trials that required them to reach to one of the response targets that appeared alone at the top left or right of the screen. Participants then completed a

practice block of 24 trials of the Stroop task before beginning the experiment. The experiment consisted of five blocks of 56 trials each, with each stimulus presented seven times per block in a randomized order.

Data processing

The processing procedures used in the present study were largely adapted from those of Moher and Song (2013). 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 the hand movement speed exceeded 25.4 cm/s. Each individual trial was visually inspected, as in previous work (e.g., Song & Nakayama, 2007); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, the thresholds were adjusted manually to ensure that the movement ended at the selected target. Manual adjustments were most frequently required when participants rapidly pulled their finger away from the display after having touched the response target, resulting in a movement trajectory traveling back to the starting point. Occasionally, manual adjustments were required when participants would come to a stop during their movement (e.g., before redirecting their movement toward the alternate response target). An average of 3.4% ($SD =$

3.0%) of experimental trials were adjusted manually for each participant.

Initiation time was calculated as the time elapsed between stimulus onset and movement onset; movement time was calculated as the time elapsed between movement onset and response completion; and response time was calculated as the time elapsed between stimulus onset and response completion, and thus was the sum of the initiation time and movement time. Trajectories for calculating curvature were measured in two-dimensional x - y 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. Curvature was defined as the maximum point of deviation, in centimeters, divided by the length of the line from the start to the end point of the movement, in centimeters (following Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Moher & Song, 2013). Curvatures were positive if the point of maximum deviation was on the same side as the competing response (e.g., if a move to the left target was curved toward the right) and were negative if the maximum deviation was on the side of the target response (e.g., if a move to the left target was curved toward the left).

Results

The first trial of each block was excluded from the analysis, given that these trials were not preceded by another trial. To

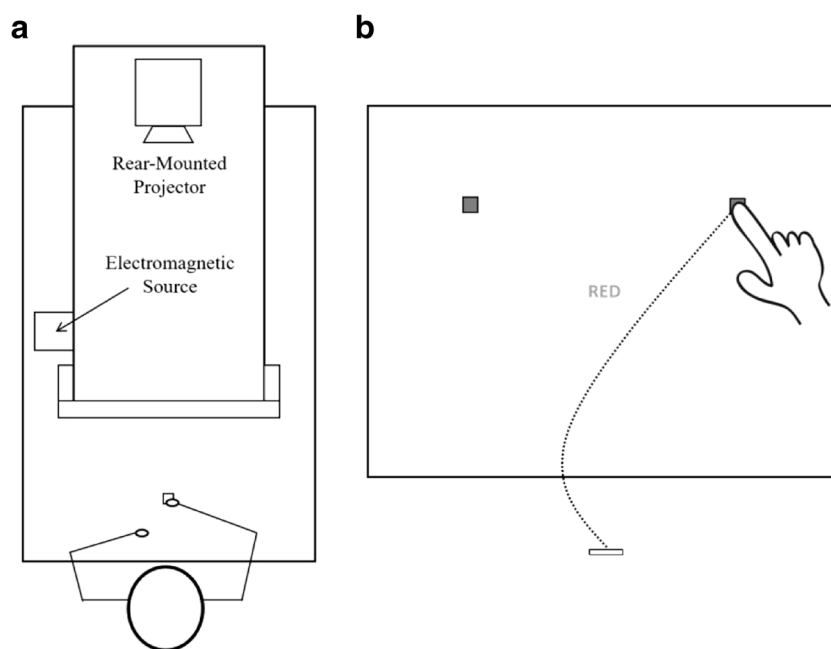


Fig. 2 **a** Diagram of the experimental setup from a top-down view. The task was displayed on a Plexiglas screen mounted upright on the table in front of the participant. All movements were initiated from a starting marker mounted on the table 27 cm in front of the screen. **b** Illustration of an incongruent trial in the Stroop task (the word “RED” presented in

blue text) from the perspective of the participant. From “Deconstructing the Gratton Effect: Targeting Dissociable Trial Sequence Effects in Children, Pre-Adolescents, and Adults,” by C. D. Erb and S. Marcovitch, 2018, *Cognition*, 179, p. 154. Copyright 2018 by Elsevier B.V. Adapted with permission

control for posterror performance adjustments (e.g., Danielmeier & Ullsperger, 2011), all inaccurate responses and the trial following an inaccurate response were also excluded from analysis for all measures but error rate, resulting in 6% of the experimental trials being excluded from analysis for the measures of initiation time, curvature, movement time, and response time. The data were analyzed using a series of 2 (set: change vs. repeat) \times 2 (response: change vs. repeat) \times 2 (previous congruency: c vs. i) \times 2 (current congruency: C vs. I) repeated measures analyses of variance (ANOVAs). In the interest of space, the results reported below focus on the effects of previous congruency and current congruency on confound-minimized (set change, response change) trials and on set repeat trials (the subset of trials featured in standard 2AFC tasks). A complete account of the results is available in section 1 of the [supplementary materials](#). The data and analysis files for this study are available at the Open Science Framework: https://osf.io/rfyvg/?view_only=e86125d2bba248fc98301649d249efd0. The descriptive statistics for each measure and trial type are shown in Table 1. Figure 3 illustrates the patterns of effects observed on confound-minimized trials and set repeat trials for each measure, and Table 2 displays the corresponding inferential statistics.

Initiation times on confound-minimized trials revealed significant main effects of previous congruency and current congruency, but no interaction between the two. Initiation times on set repeat trials also revealed significant main effects of previous congruency and current congruency, but no interaction between the two. Thus, initiation times revealed the same pattern of effects (cC < iC < cI < iI) regardless of the presence of associative-priming effects.

Reach curvatures on confound-minimized trials revealed a significant main effect of current congruency, but no main effect of previous congruency or interaction between previous and current congruency. Set repeat trials, however, revealed a significant main effect of current congruency and a significant interaction between previous and current congruency, with larger reach curvatures on congruency switch than on congruency repeat trials. Thus, a CSE was not observed on confound-minimized trials, but a CSE was observed on set repeat trials, which featured substantial associative-priming effects. The same pattern of results was observed when an alternative measure of spatial attraction, area under the curve, was evaluated (see section 2 of the [supplementary materials](#)).

To compare whether the size of the CSE observed in reach curvatures differed between the two conditions, we computed CSE scores for confound-minimized trials and for set repeat trials by subtracting the average performance on congruency repeat trials (cC and iI trials) from the average performance on congruency switch trials (iC and cI trials; see Erb & Marcovitch, 2018b). The results of this analysis revealed a significantly larger CSE in curvatures in set repeat than in

confound-minimized trials, $F(1, 44) = 4.18, p = .047, \eta_p^2 = .09$. In section 3 of the [supplementary materials](#), we discuss the extent to which initiation time differences might explain the presence or absence of the CSE in confound-minimized and set repeat trials.

Movement times on confound-minimized trials revealed a significant main effect of current congruency, but no main effect of previous congruency or interaction between previous and current congruency. Set repeat trials, however, revealed a significant main effect of current congruency and a significant interaction between current congruency and previous congruency, with longer movement times on congruency switch than on congruency repeat trials.

Response times on confound-minimized trials revealed significant main effects of previous congruency and current congruency but no interaction between the two. Similarly,

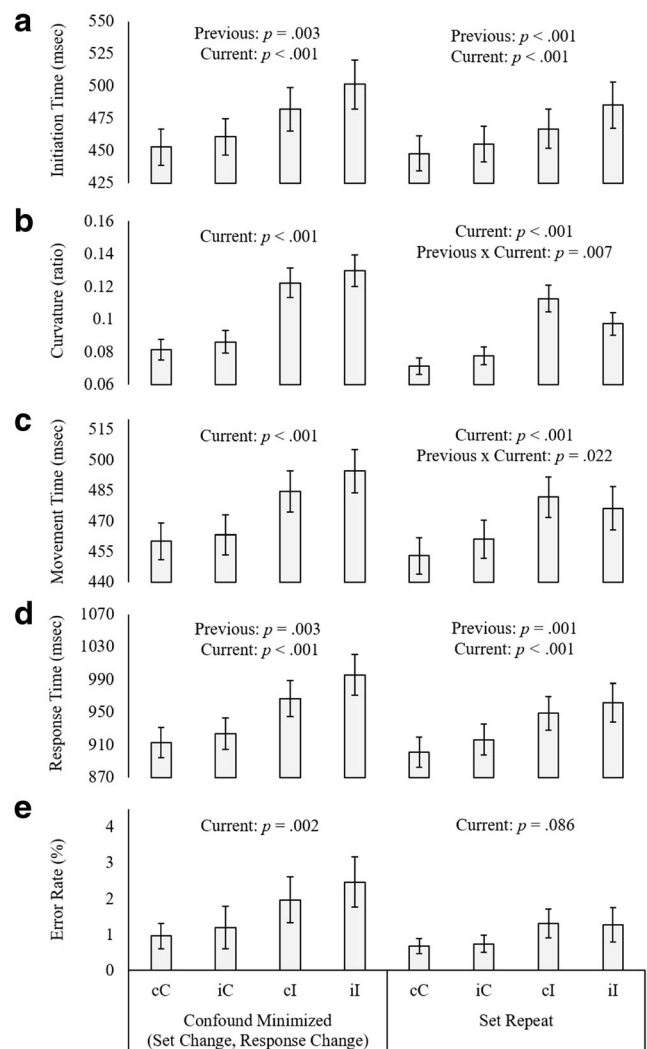


Fig. 3 Average performance on confound-minimized (set change, response change) trials (left panels) and set repeat trials (right panels) as a function of previous congruency (c vs. i) and current congruency (C vs. I) for the measures (a) initiation time, (b) curvature, (c) movement time, (d) response time, and (e) error rate. Error bars display standard errors

Table 2 ANOVA results from confound-minimized (set change, response change) trials and set repeat trials

Measure	Effect	Confound Minimized				Set Repeat			
		<i>F</i>	<i>p</i>	η_p^2	Direction	<i>F</i>	<i>p</i>	η_p^2	Direction
Initiation time	Previous	9.57	= .003	.18	c < i	15.88	< .001	.27	c < i
	Current	36.12	< .001	.45	C < I	29.75	< .001	.40	C < I
	Interaction	1.93	= .17	.04		2.61	= .11	.06	
Curvature	Previous	1.63	= .21	.04		1.49	= .23	.03	
	Current	42.69	< .001	.49	C < I	42.28	< .001	.49	C < I
	Interaction	0.06	= .81	< .01		7.86	= .007	.15	CSE
Movement time	Previous	2.40	= .13	.05		0.25	= .62	< .01	
	Current	31.07	< .001	.41	C < I	27.39	< .001	.38	C < I
	Interaction	0.81	= .37	.02		5.68	= .022	.11	CSE
Response time	Previous	9.86	= .003	.18	c < i	12.02	= .001	.21	c < i
	Current	52.41	< .001	.54	C < I	42.32	< .001	.49	C < I
	Interaction	2.44	= .13	.05		0.07	= .80	< .01	
Error rate	Previous	0.84	= .37	.02		0.002	= .97	< .01	
	Current	11.39	= .002	.21	C < I	3.09	= .086	.07	
	Interaction	0.08	= .78	< .01		0.04	= .84	< .01	

Only the main effects of previous congruency and current congruency and the interaction between previous and current congruency are reported here. See the [supplementary materials](#) for the full set of results. Degrees of freedom = 1, 44 for all analyses.

response times on set repeat trials revealed significant main effects of previous congruency and current congruency but no interaction between the two.

Error rates on confound-minimized trials revealed a significant main effect of current congruency, but no main effect of previous congruency or interaction between previous and current congruency. Set repeat trials did not reveal any significant effects, although the effect of current congruency approached significance.

Discussion

The results of the present study demonstrate that initiation times and reach curvatures can be used to target the functioning of two dissociable processes that underlie decision behavior. Initiation times revealed main effects of both current and previous congruency, regardless of the presence or absence of potential associative-priming confounds (see Fig. 3A). These findings, along with the behavioral results of Erb and colleagues (Erb & Marcovitch, 2018a, 2018b; Erb et al., 2016; Erb et al., 2018b) and the single-unit recording results of Sheth et al. (2012), indicate that initiation times can be used to target the functioning of a threshold adjustment process that is sensitive to the degree of conflict detected between the current and previous trial. On this view, the coactivation of competing responses on incongruent trials results in heightened response thresholds, with longer periods of motoric stopping and, consequently, slower initiation times. These heightened thresholds are then carried over into the following trial, resulting

in slower initiation times on trials preceded by an incongruent trial (iC and iI trials) than on those preceded by a congruent trial (cC and cI trials). Crucially, neither the associative-priming account nor the conflict-adaptation account offers an explanation of the pattern of effects observed in initiation times.

In contrast to initiation times, reach curvatures exhibited a strong sensitivity to associative-priming effects. As is predicted by the associative-priming account, reach curvatures did not reveal a CSE in confound-minimized trials but did reveal a CSE in set repeat trials, which involved the associative-priming effects present in standard 2AFC versions of the Stroop task (see Fig. 3B). These findings are consistent with the claim that reach curvatures reflect the functioning of a controlled selection process that directs top-down resources to support goal-directed stimulus–response translation (Erb et al., 2016). According to this interpretation, associative-priming effects influence performance by either impeding or facilitating an individual's ability to form the appropriate stimulus–response pair, resulting in reach movements that feature more or less curvature. Notably, the observed reach curvature effects failed to support the conflict-adaptation account of the CSE, which predicts that conflict-driven modulations of top-down control will result in a CSE even when associative-priming confounds are minimized. This finding is consistent with a number of previous studies that have failed to observe a CSE in the Stroop task after controlling for alternative explanations (e.g., Schmidt & De Houwer, 2011; Weissman, Jiang, & Egner, 2014).

Response times in the present study reflected a combination of the effects observed in initiation times and curvatures, revealing main effects of previous and current congruency but no evidence of the CSE. This finding is consistent with previous hand-tracking research indicating that response times can obscure the underlying effects of interest. For instance, Erb and Marcovitch (2018a) recently found evidence that the CSE observed in response times in 2AFC versions of the flanker task results from the combination of two distinct patterns of effects, one observed in initiation times and the other observed in curvatures and movement times. Given that the present study did not involve both button-press and reach-tracking versions of the same task, it is unclear whether button-press response times in the task would reveal the same pattern of response time effects observed with reaching behavior. An important avenue for future research to explore, therefore, concerns the extent to which the behavioral effects observed in reaching tasks correspond to those observed in traditional button-press tasks.

Relation to previous hand-tracking studies

The results of the current study present a number of notable differences, relative to previous studies investigating the CSE using hand-tracking techniques. For example, Scherbaum, Dshemuchadse, Fischer, and Goschke (2010, Exp. 2) observed a significant CSE in participants' hand movements in a mouse-tracking version of the Simon task, even after stimulus repetitions were excluded from the analysis, whereas the present study did not reveal a CSE in reach curvatures in confound-minimized trials. We suspect that the CSE observed by Scherbaum et al. stemmed in part from distractor repetition effects, in which the stimulus location of the current trial repeated that of the previous trial (stimulus location serves as the distractor in the Simon task, akin to word meaning in the Stroop task). Previous research by Erb and Marcovitch (2018b) indicated that distractor repetition effects play an important role in driving the CSE observed in the Simon task. It is also important to note that the Scherbaum et al. study used numerical stimuli that have been found to generate strong spatial associations that extend into online hand movements (e.g., Erb, Moher, Song, & Sobel, 2018a; Santens, Goossens, & Verguts, 2011; Song & Nakayama, 2008). Consequently, the task may have featured a spatial–numerical association of response codes effect (Dehaene, Bossini, & Giraux, 1993) that could further complicate a direct comparison of the two studies, given that the stimuli used in the present study did not feature preexisting spatial associations.

The curvature results in the present study also differ slightly from those of Erb et al. (2016, Exp. 1). In the present study, reach curvatures on set repeat trials revealed the pattern typically associated with the CSE, including descriptively smaller curvatures on cC than on iC trials (see Fig. 3B), whereas Erb

et al. (2016) did not observe a significant difference between the curvatures on cC and iC trials (see Fig. 1B). It is important to note, however, that Erb et al. (2016) used a modified three-response version of the Stroop task designed by Kerns et al. (2004) to control for associative-priming effects. Although this version of the Stroop task allowed for some potential associative-priming effects to be excluded from the analysis, it did not effectively control for a range of other associative-priming effects (e.g., instances in which the distractor of the previous trial became the target on the current trial). Furthermore, the task may have introduced contingency-learning effects not featured in standard 2AFC tasks (see Erb et al., 2016; Schmidt & De Houwer, 2011). Consequently, the task used by Erb et al. (2016) likely featured a different collection of confounds than the set repeat trials in the present study.

The pattern of curvatures observed in set repeat trials in the present study also differed from the pattern observed by Erb and Marcovitch (2018a) in a 2AFC version of the flanker task. Erb and Marcovitch (2018a) observed a significant CSE in reach curvatures but, in contrast to the present study, their curvatures did not differ significantly between cC and iC trials. Again, we suspect that task differences likely underlie these different patterns of effects. For instance, as was discussed by Erb et al. (2016), the Stroop task can be understood to feature within-stimulus conflict, because different dimensions of the same stimulus (namely, text color and word meaning) cue competing responses, whereas the flanker task can be understood to feature between-stimulus conflict, because distinct stimuli (e.g., leftward- and rightward-facing arrows) cue competing responses. Research by MacLeod (1998) supports the importance of this distinction, revealing substantially larger congruency effects in standard Stroop tasks than in “separated” versions of the task that involve multiple stimuli (e.g., the word “BLUE” in black text surrounded by red asterisks). Notably, the patterns of initiation times observed by both Erb et al. (2016) and Erb and Marcovitch (2018a) were highly similar to those observed in the present study, providing further evidence that initiation time and curvature are differentially sensitive to the dissociable processes underlying cognitive control.

Future directions

The present study evaluated how initiation time and curvature are differentially impacted by conflict. Conflict, however, can take a number of different forms. For example, imagine a Stroop task in which the colors red and green are mapped to a LEFT response, the colors blue and orange are mapped to a RIGHT response, and all possible word–color pairings are presented (unlike in the present study, which prevented certain pairings). This task would feature trials in which text color and word meaning were inconsistent but the same response was

nevertheless cued (e.g., the word “RED” in green text). Such trials can be described as featuring stimulus-level but not response-level conflict. Other trials, however, could feature both stimulus- and response-level conflict, as was the case with incongruent stimuli in the present study (e.g., the word “BLUE” in red text).

An important direction for future research to explore concerns the extent to which different types of conflict might differentially impact initiation time and curvature. This line of research is particularly relevant in light of fMRI research indicating that stimulus- and response-level conflict differentially activate the inferior frontal gyrus, middle temporal area, and superior parietal lobe (Wendelken, Ditterich, Bunge, & Carter, 2009), as well as different subregions of the dorsal anterior cingulate cortex (Kim, Kroger, & Kim, 2011). Additionally, behavioral work by Verbruggen, Notebaert, Liefoghe, and Vandierendonck (2006) suggests that stimulus-level conflict plays a particularly important role in driving the CSE. Hand-tracking tasks should therefore be developed to investigate the effects of stimulus- and response-level conflict in tasks that control for both associative-priming and contingency-learning effects.

Conclusion

Hand-tracking techniques present new opportunities to shed light on how the processes underlying decision behavior unfold over time. The results of the present study indicate that performance on tasks involving conflict is fundamentally structured by two dissociable processes: a threshold adjustment process that temporarily puts the “brake” on behavior when signals of conflict are detected, and a controlled selection process that “steers” top-down resources in favor of goal-relevant responses (e.g., Cavanagh et al., 2011; Frank, 2006; Shenhav et al., 2013). In contrast to previous hand-tracking studies (Erb & Marcovitch, 2018a, 2018b; Erb et al., 2016; Erb et al., 2018b), the task used in the present study allowed for a direct comparison of confound-minimized and confound-laden trials. Crucially, this comparison revealed that the effects observed in initiation times and reach curvatures cannot be accounted for in terms of associative-priming confounds alone. In addition to clarifying the nature of the processes that underlie the congruency sequence effect in the Stroop task, these findings raise fundamental questions concerning how the threshold adjustment process and the controlled selection process contribute to performance on tasks designed to target a range of psychological phenomena, including perception (e.g., Hackley & Valle-Inclán, 1998), memory (e.g., Ratcliff & Starns, 2009), language (e.g., Connine, 1987), social cognition (e.g., Greenwald, McGhee, & Schwartz, 1998), and risk taking (e.g., Lejuez et al., 2002).

Author note C.D.E. designed the experiment under the guidance of S.M. The data collection and analysis were performed by C.D.E. and A.G.M. C.D.E. wrote the majority of the manuscript, with A.G.M. and S.M. providing critical revisions.

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