

Tracking the Within-Trial, Cross-Trial, and Developmental Dynamics of Cognitive Control: Evidence From the Simon Task

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Six- to 8-year-olds, 10- to 12-year-olds, and adults ($N = 108$) performed the Simon task by reaching to targets on a digital display. The spatial and temporal characteristics of their movements were used to assess how two key processes underlying cognitive control—a threshold adjustment process and a controlled selection process—unfold over the course of a response (within-trial dynamics), are modulated by recent experience (cross-trial dynamics), and contribute to age-related gains in control (developmental dynamics). The results indicate that the controlled selection process undergoes a more protracted development than the threshold adjustment process. The results also shed light on a prominent debate concerning the cross-trial dynamics of control by supporting the feature integration account over the conflict adaptation account.

Life is all about making choices. Sometimes the choices are simple; for example, when a child has plenty of food to share with his or her hungry friend. However, choices often pull us in competing directions; for example, when a child's impulse to speak out of turn conflicts with his or her knowledge that it is not polite to interrupt others. In such instances, we rely on our capacity for cognitive control to ensure that our ongoing thoughts and actions are aligned with our higher-order goals. Developmental and individual differences in this capacity have been linked to a range of important outcomes, including emotion regulation, theory of mind, and math and reading ability in childhood (e.g., Blair & Razza, 2007; Carlson, Moses, & Breton, 2002; Carlson & Wang, 2007), and physical health, success in the workplace, and caregiving behavior in adulthood (e.g., Deater-Deckard, Wang, Chen, & Bell, 2012; Miller, Barnes, & Beaver, 2011; for a review, see Diamond, 2013). Further, impairments in cognitive control have been observed in a range of disorders and diseases, including attention deficit hyperactivity disorder (ADHD), depression, disruptive behavior disorder, and Parkinson's disease (e.g., Elliott, 2003; Mullane, Corkum, Klein, & McLaughlin, 2009; Schoemaker et al., 2012).

Cognitive control is commonly assessed with tasks that intermittently require participants to override a prepotent response with a more control-demanding response. In the Simon task (e.g., Hommel, Proctor, & Vu, 2004; Simon, 1969), for example, participants are instructed to generate a left key-press in response to one stimulus (e.g., "O") and a right key-press in response to another stimulus (e.g., "X"), regardless of whether the stimulus appears on the left or right side of a display. On congruent trials, the task-relevant feature (e.g., stimulus form = "O") cues the same response as the task-irrelevant feature (e.g., stimulus location = LEFT). On incongruent trials, stimulus form (e.g., "O") and stimulus location (e.g., RIGHT) cue competing responses. Consequently, cognitive control is required on incongruent trials to ensure that the appropriate response is ultimately selected. A *Simon effect* is commonly observed in performance, with slower response times and higher error rates on incongruent relative to congruent trials.

Developmental investigations of the Simon task have revealed substantial age-related gains in cognitive control between childhood and adulthood as evidenced by reductions in the size of the Simon effect (e.g., Davidson, Amso, Anderson, & Diamond, 2006). However, fundamental questions remain concerning the nature of these gains. These questions center on the challenge of connecting the within-trial dynamics of control (*How do the various processes that underlie cognitive control unfold over the*

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course of a response?) and the cross-trial dynamics of control (*How do the demands placed on control fluctuate as a function of recent experience?*) with overarching developmental dynamics (*How are age-related gains in performance reflected in the within- and cross-trial dynamics of control?*).

The current study addresses this challenge by using a technique known as reach tracking to link the spatial and temporal characteristics of hand movements to the dynamics of cognitive control in 6- to 8-year-olds, 10- to 12-year-olds, and adults. Relative to the ballistic movements characteristic of button-press tasks, recording the path that a participant's hand travels to reach a response target presents a more detailed view of how cognitive processes unfold over time (for a discussion, see Song & Nakayama, 2009). In the following, we review existing research and theory concerning the within- and cross-trial dynamics of control. We then discuss how reach tracking can be used to shed light on age-related change in the functioning of these dynamics.

Within-Trial Dynamics: A Contemporary Model

Current models of cognitive control propose that adaptive responding in the Simon task is supported by a number of dissociable processes that serve distinct functional roles (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Kerns, 2006; Shenhav, Botvinick, & Cohen, 2013). For example, a monitoring process associated with the dorsal anterior cingulate cortex is proposed to detect signals of conflict stemming from the co-activation of competing responses on incongruent trials. This conflict sets in motion two processes of particular relevance to this study: a *threshold adjustment process* and a *controlled selection process*. The threshold adjustment process has been likened to a “brake” that temporarily inhibits motor output in response to signals of conflict (Cavanagh et al., 2011; Frank, 2006). Inhibiting responding in this manner is suggested to play a role in speed-accuracy trade-off effects by providing additional time for the second process of interest—the controlled selection process—to recruit top-down support to “steer” response activations in favor of the appropriate response by increasing attention to stimulus form and decreasing attention to stimulus location.

This model of cognitive control raises several questions concerning how the within-trial dynamics of control function across development. For example, do the threshold adjustment and controlled selection processes function similarly in children

and adults? And, to what extent do changes in the functioning of these processes contribute to age-related reductions in the size of the Simon effect?

In a series of recent studies, Erb and Marcovitch (in press), Erb, Moher, Sobel, and Song (2016), and Erb, Moher, Song, and Sobel (2017, 2018) tested the proposal that two of the measures afforded by reach tracking—*initiation time* (the time elapsed between stimulus onset and movement onset) and *reach curvature* (a measure of the degree to which a movement deviates from a direct path to the selected response location)—can be used to target the functioning of the threshold adjustment and controlled selection processes, respectively. Across multiple cognitive control tasks including the Stroop (1935) task and the Eriksen flanker task (Eriksen & Eriksen, 1974), the researchers found evidence that initiation times reflect the threshold adjustment process by indexing how long the “brake” is put on behavior, with higher levels of conflict resulting in greater inhibition of motor output and, consequently, longer initiation times. Their findings also indicated that reach curvatures reflect the controlled selection process by capturing the degree to which competing responses are co-active over the course of a response, with larger curvatures indicating that participants were more pulled toward the inappropriate response before top-down support could “steer” response activations in favor of the appropriate response. The current study aims to build on these findings by using reaching behavior (a) to investigate how the threshold adjustment and controlled selection processes function in the Simon task and (b) to determine the extent to which these processes contribute to age-related reductions in the Simon effect.

Cross-Trial Dynamics: Conflict Adaptation or Feature Integration?

In addition to presenting an account of how dissociable processes underlying cognitive control unfold over the course of a response, the model reviewed in the preceding section provides a framework for considering how the demands placed on control are modulated by recent experience. Although performance is generally worse on incongruent relative to congruent trials in the Simon task, not all trials of the same congruency tax cognitive control equally. For example, significant interactions between the congruency of the previous trial (denoted with lowercase *c* or *i*) and the current trial (denoted with uppercase *C* or *I*) are commonly

observed, such that response times are faster on congruency repeat trials (*cC* and *il* trials) relative to congruency switch trials (*iC* and *cl* trials; e.g., Hommel et al., 2004). This interaction between current and previous congruency is known as the congruency sequence effect (CSE) and can be quantified as the relative difference in performance on congruency switch and congruency repeat trials (e.g., $RT_{\text{Congruency Switch}} - RT_{\text{Congruency Repeat}}$).

Since the CSE was first reported a quarter-century ago (Gratton, Coles, & Donchin, 1992), a large body of research has sought to identify the cognitive and neural underpinnings of the effect (for reviews, see Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007). These efforts have generated a lively and ongoing debate in the literature on adult cognitive control. The two primary theoretical accounts to emerge from this debate have come to be known as the *conflict adaptation account* and the *feature integration account*.

The conflict adaptation account of the CSE draws directly from the model of cognitive control outlined earlier (Botvinick et al., 2001; Kerns, 2006). In the context of the Simon task, it proposes that conflict detected at the outset of an incongruent trial leads to the recruitment of top-down resources that increase attention to stimulus form (the task-relevant feature) and decrease attention to stimulus location (the task-irrelevant feature). This reallocation of attention on incongruent trials is then carried over into the subsequent trial. If the subsequent trial is also incongruent, this carryover enhances performance by minimizing the effect of stimulus location. Consequently, response times are faster on *il* relative to *cl* trials. If the subsequent trial is congruent, however, this reallocation of attention impairs performance because it dampens the effect of stimulus location, which cues the correct response on congruent trials. Thus, decreasing the impact of stimulus location results in slower response times on *iC* relative to *cC* trials.

In contrast, the feature integration account proposes that the CSE stems from bottom-up associative memory effects. The account builds on the notion of an “object file” formulated by Kahneman and Treisman (1984) by proposing that associations between stimulus features (e.g., stimulus location and stimulus form) and response features (e.g., response location) are formed on each trial and stored in the format of an “event file” (Hommel, 2004; Hommel et al., 2004). On this view, if the current trial activates any feature from the previous trial’s event file, then all other features from that event file are also activated. In standard versions of

the Simon task featuring two response options, this causes conflict on trials that feature a different congruency than the previous trial (*iC* and *cl* trials) because the stimulus and response features of these trials partially overlap with the stimulus and response features of the previous trial.

To appreciate how the stimulus and response features of trials in the Simon task can partially overlap, consider the example of an *iC-s* trial (where “-s” denotes a response switch) listed in Table 1. Imagine that a participant completed an incongruent trial that required a LEFT response to an “O” that appeared on the RIGHT side of the display. If the participant then received a congruent trial that required a RIGHT response to an “X” at the RIGHT side of the display, the stimulus location of the current trial (RIGHT) would overlap with that of the previous trial (RIGHT), resulting in the activation of the previous trial’s response (LEFT).

This partial overlap of stimulus and response features does not occur on *cC* or *il* trials in standard versions of the Simon task and, consequently, congruency repeat trials do not generate the same degree of conflict as partial overlap trials (for a detailed account, see Hommel et al., 2004). Indeed, performance may even be facilitated on congruency repeat trials featuring a response repeat (*cC-r* and *il-r* trials, where “-r” denotes a response repeat) given that the stimulus and response features on these trials overlap fully with those of the previous trial. However, the CSE observed in the Simon task cannot be attributed solely to enhanced performance on *cC-r* and *il-r* trials because the CSE is observed on both response switch and response repeat trials (e.g., Keye, Wilhelm, Oberauer, & Van Ravenzwaaij, 2009).

Of interest to the current study is the extent to which the conflict adaptation and feature integration theories can account for the cross-trial and developmental dynamics of cognitive control in the Simon task. Although these accounts were not developed to generate predictions regarding how the CSE is reflected in reaching behavior or how the effect changes across development, one can derive divergent predictions from the accounts. For instance, the feature integration account proposes that performance on the Simon task is impaired on *iC* relative to *cC* trials because features from the previous trial’s event file are activated on *iC* trials and cue the inappropriate direction, as illustrated in the example earlier. Consequently, this account predicts that reach movements on *iC* trials will be more likely to exhibit a pull toward the inappropriate response than *cC* trials.

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Table 1

Illustration of Trial Types in the Simon Task as a Function of the Previous Trial's Congruency (*c vs. i*), the Current Trial's Congruency (*C vs. I*), and Whether the Current Trial Required A Response Switch (Denoted With “-s”) or a Response Repeat (Denoted With “-r”).

| | Previous trial | | | Current trial | | | Congruency repeat/switch | Degree of overlap |
|------|-------------------|-------------------|----------|-------------------|-------------------|----------|--------------------------|---------------------------------------|
| | Stimulus location | Stimulus identity | Response | Stimulus location | Stimulus identity | Response | | |
| cC-s | Left | O | Left | Right | X | Right | Repeat | No overlap |
| iC-s | Right | O | Left | Right | X | Right | Switch | Stimulus location repeats |
| cI-s | Left | O | Left | Left | X | Right | Switch | Stimulus location repeats |
| iI-s | Right | O | Left | Left | X | Right | Repeat | No overlap |
| cC-r | Left | O | Left | Left | O | Left | Repeat | Full overlap |
| iC-r | Right | O | Left | Left | O | Left | Switch | Stimulus identity and response repeat |
| cI-r | Left | O | Left | Right | O | Left | Switch | Stimulus identity and response repeat |
| iI-r | Right | O | Left | Right | O | Left | Repeat | Full overlap |

Conversely, the conflict adaptation account does not predict that iC trials will be more likely to exhibit a pull toward the inappropriate response. It proposes that response times are slower on iC relative to cC trials in the Simon task because participants down-regulate their attention to stimulus location, which happens to cue the correct response on these trials. Given that cC trials benefit more from stimulus location than iC trials, one can expect that participant's reach movements will be more direct to the correct response on cC than iC trials. However, from the perspective of the conflict adaptation account, there is no reason to expect that reach movements will be pulled toward the incorrect location on iC trials because neither stimulus location nor stimulus identity cue the incorrect response on congruent trials. Thus, the feature integration account and the conflict adaptation account present different predictions concerning the extent to which hand movements in the Simon task will exhibit an attraction toward the inappropriate response on iC trials.

It is important to note that elevated reach curvatures on iC relative to cC trials need not indicate that a participant was pulled toward the inappropriate response on iC trials. For example, reach trajectories may be more direct on cC trials than iC trials because more evidence is accumulated in favor of the appropriate response on cC trials, not because the inappropriate response was activated on iC trials. To address this possibility, one can compute a *change of mind* measure by using a participant's reaching behavior in a baseline task to identify movement trajectories that are characteristic of reaches to a left or right response target (e.g., Moher & Song, 2013; Resulaj, Kiani, Wolpert, & Shadlen, 2009). These personalized trajectories can

then be used to identify whether a change of mind occurred on each trial; that is, whether the participant's movement began in a manner characteristic of a reach to one target but was subsequently redirected toward the other target. If changes of mind occur more frequently on iC than cC trials, this would indicate that participants were indeed more likely to be pulled toward the inappropriate response on iC trials. Thus, the second question addressed in this study concerns whether changes of mind occur more frequently on iC than cC trials in the Simon task.

With regard to developmental dynamics, the conflict adaptation account lends itself to the prediction that the CSE in the Simon task will increase as cognitive control improves across development. This is because individuals with better top-down control (i.e., adults) should be better able to redirect their attention away from stimulus location and toward stimulus form than individuals with worse control (i.e., children). The feature integration account, on the other hand, predicts that the CSE should decrease between childhood and adulthood. This is because the ability to form and break associations between the features of event files is proposed to improve during this period (Hommel, Kray, & Lindenberger, 2011). Consequently, adults can be anticipated to resolve conflict on partial overlap trials (i.e., congruency switch trials) more effectively than children.

Despite the considerable attention that the CSE has received in the adult cognitive psychology and cognitive neuroscience literature on the Simon task (e.g., Burle, Allain, Vidal, & Hasbroucq, 2005; Hommel et al., 2004; Kerns, 2006; Keye et al., 2009; Scrolli, Pellicano, Nicoletti, Rubichi, & Castiello, 2015), relatively little research has investigated the effect

from a developmental perspective. Recent research has confirmed that the CSE is present in children's performance by 5–8 years of age (Ambrosi, Lemaire, & Blaye, 2016; Iani, Stella, & Rubichi, 2014). However, these studies did not observe significant age-related changes in the size of the CSE in the Simon task or compare child and adult performance. Consequently, a third question addressed in this study concerns whether age-related changes in the size of the CSE are consistent with the conflict adaptation account or the feature integration account.

The Current Study

To review, we raised three central questions to address in the current study concerning the dynamics of cognitive control in the Simon task:

1. *To what extent do the threshold adjustment and controlled selection processes contribute to age-related reductions in the Simon effect?* If the threshold adjustment and controlled selection processes follow distinct developmental trajectories, then the size of the Simon effect observed in initiation times and reach curvatures should decrease at different rates.
2. *Does reaching behavior in the Simon task reveal a greater pull toward the inappropriate response on iC trials than on cC trials?* The feature integration account of the CSE predicts that hand movements should be more likely to exhibit pull toward the inappropriate response on iC trials than cC trials, whereas the conflict adaptation account does not.
3. *Does the CSE increase or decrease from childhood to adulthood?* The conflict adaptation account predicts that the size of the CSE should increase with age, whereas the feature integration account predicts that it should decrease.

Method

Participants

A total of 108 individuals participated in the study, with 36 participants in each of three age groups: 6- to 8-year-olds ($M_{\text{age}} = 7.0$, $SD = 0.8$; 50% female), 10- to 12-year-olds ($M_{\text{age}} = 11.0$, $SD = 0.9$; 42% female), and adults ($M_{\text{age}} = 18.8$, $SD = 1.3$; 56% female). One additional participant was tested but excluded from the final sample due to an experimenter error in positioning the apparatus. Sample size was selected in light of recent research using reach tracking to investigate developmental

differences in cognitive control (Erb et al., 2018) and previous developmental investigations of the Simon task (e.g., Davidson et al., 2006; Iani et al., 2014). Child participants were relatively diverse in terms of race (57% White, 29% African American, 3% Asian American, 7% other, and 4% preferred not to respond) and family income (33% below \$60,000, 60% above \$60,000, and 7% preferred not to respond). Adult participants were also racially diverse (44% African American, 42% White, 6% Asian American, 3% other, and 5% preferred not to respond). No measures of personal or family income were collected for adult participants.

All participants were right-handed with normal or corrected-to-normal vision. Child participants received a small prize for participating, whereas adult participants received course credit. Data collection took place at the University of North Carolina at Greensboro between July 2016 and February 2017. 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 Plexiglass screen (e.g., 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 91.4×152.4 cm table (see Appendix S1, Section 1 of the Supplementary Materials for a diagram). The projected display on the Plexiglass screen was 38×50 cm. The apparatus was designed such that the screen could be positioned at one of three locations on the table to accommodate participants of different ages. A 2×2 cm square marker was placed 27 cm in front of the screen, with the placement of the square changing based on the position 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, Massachusetts, USA).

Participants were presented with a two-response version of the Simon task in which a green heart or green sun measuring 3×3 cm appeared under one

of two response targets located on the left and right side of the screen. The response targets were gray squares with a black outline that measured 2.5×2.5 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 in from the left side of the projected display and the other square located 11.25 cm in from the right side. The distance from the center of the response target to the center of the heart and sun stimuli was 3.5 cm.

The response targets remained on the screen throughout the Simon task. 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 0.7×0.7 cm appeared in the center of the display for 1 s before a heart or sun stimulus appeared below one of the response targets. 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 returned their hand to the starting block for 1 s. Participants had up to 3 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).

Procedure

Participants first completed a 9-point calibration sequence followed by 16 baseline trials that required the participant to reach to one of the response targets that appeared alone at the top left or right of the screen. Participants then received a practice block of 16 trials of the Simon task before beginning the experiment. The experiment consisted of four blocks of 40 trials. Each block featured 20 congruent trials in which stimulus location and stimulus form cued the same response and 20 incongruent trials in which stimulus location and stimulus form cued opposing responses. Trial presentation was randomized such that the correct response was evenly divided between the two-response locations. Half of the participants were instructed to touch the left response target for the heart stimulus and the right response target for the sun stimulus, whereas the other half of participants received the opposite mapping. The stimulus-response mapping remained constant across the entire experiment for each participant. Participants were reminded of the appropriate mapping before each block of trials. No visual cues were provided

to remind participants of the appropriate mapping during the practice or experimental blocks.

Data Processing

The processing procedures used in this study were largely adapted from 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 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, thresholds were adjusted manually.

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; total time (also known as response time) was calculated as the time elapsed between stimulus onset and response completion and was the sum of initiation time and movement time. Trajectories for calculating curvature were measured in two-dimensional xy space by calculating a line from the start to the endpoint 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 endpoints of the movement in centimeters (following Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Moher & Song, 2013).

To identify changes of mind, we adopted the method used by Moher and Song (2013) and others (e.g., Spivey, Grosjean, & Knoblich, 2005). First, we resampled each participant's reach movements on the baseline and experimental trials to create 101 samples equally spaced in time along the x-dimension. We then used the resampled baseline movements to calculate the average reach trajectory for a movement to the left or right response target for each participant, with all resampled movements initiating from the same point in space. This enabled us to establish zones around these average trajectories that extended 1.5 SDs to the left and right of each sample. We then evaluated whether participants' resampled movements on the experimental trials were in the incorrect zone for a minimum of

15 samples before the correct response was ultimately selected. Samples that were in both zones did not count toward this minimum. Trials that met the minimum were labeled as a change of mind trial.

Results

Log transformations were applied to the initiation time, curvature, movement time, and total time data to minimize the effect of age-related differences in processing speed. Given (a) that it is inappropriate to perform a log transformation on a negative number, and (b) that reach curvatures can be positive or negative, a constant of 1 was added to each curvature value to ensure that all values were positive before the log transformation was applied. The analyses reported next for initiation time, curvature, movement time, and total time were conducted with the log-transformed (L-T) data. See Appendix S1, Section 2 of the Supplementary Materials for the corresponding analysis of the untransformed data.

The first trial of each block was excluded from analysis given that these trials were not preceded by another trial. To control for post-error performance adjustments (e.g., Danielmeier & Ullsperger, 2011), all inaccurate responses and trials following an inaccurate response were also excluded from analysis for each of the measures reported next apart from error rate. This resulted in an average of 9% ($SD = 7$), 4% ($SD = 2$), and 3% ($SD = 1$) of trials being excluded from analysis for 6- to 8-year-olds, 10- to 12-year-olds, and adults, respectively. Performance on each measure was analyzed with a series of mixed analyses of variance (ANOVAs) featuring age group (6- to 8-year-olds, 10- to 12-year-olds, adults) as a between-subjects factor and previous congruency (c, i), current congruency (C, I), and response type (switch, repeat) as within-subjects factors. Only effects that reached significance ($\alpha = .05$) in the full ANOVAs were considered for follow-up tests. All post hoc comparisons featured Bonferroni corrections to adjust for multiple comparisons.

Table 2 presents average performance on each measure and trial type across all participants and then by age group (6- to 8-year-olds, 10- to 12-year-olds, and adults). These averages were computed using raw initiation times, movement times, curvatures, and total times. For averages of the L-T data, see Appendix S1, Section 2 of the Supplementary Materials.

Error Rates

Average error rate for each trial type across all participants is shown in Figure 1A. The analysis of variance (ANOVA) on error rates revealed a main effect of age group, $F(2, 105) = 25.74$, $p < .001$, $\eta_p^2 = .33$, with post hoc tests showing significantly larger error rates in 6- to 8-year-olds ($M = 2.8\%$, $SD = 2.9$) than in 10- to 12-year-olds ($M = 0.5\%$, $SD = 0.7$) and adults ($M = 0.1\%$, $SD = 0.2$), both p -values $< .001$. The main effect of current congruency was significant, $F(1, 105) = 16.87$, $p < .001$, $\eta_p^2 = .14$, as was the interaction between current congruency and age group, $F(2, 105) = 10.36$, $p < .001$, $\eta_p^2 = .16$. Post hoc tests evaluating the effect of current congruency at each age group revealed a larger Simon effect in 6- to 8-year-olds ($M = 2.6\%$, $SD = 4.2$) than in 10- to 12-year-olds ($M = 0.2\%$, $SD = 1.1$) and adults ($M = 0.1\%$, $SD = 0.5$), p -values $< .001$ (see Figure 2A). A significant interaction between response type and age group was also observed, $F(2, 105) = 3.13$, $p = .048$, $\eta_p^2 = .06$. Post hoc tests evaluating the effect of response type at each age group revealed that the difference between response repeat and response switch trials (response switch–response repeat) was significantly larger in 6- to 8-year-olds ($M = 0.7\%$, $SD = 2.2$) than in 10- to 12-year-olds ($M = -0.3\%$, $SD = 1.1$), $p = .020$. The size of this effect did not differ significantly between 6- and 8-year-olds and adults ($M = 0.00\%$, $SD = 0.6$), $p = .129$.

The interaction between previous congruency and current congruency was significant, $F(1, 105) = 18.69$, $p < .001$, $\eta_p^2 = .15$, as was the interaction among previous congruency, current congruency, and age group, $F(2, 105) = 9.30$, $p < .001$, $\eta_p^2 = .15$. To directly compare the size of the CSE at each age group, a difference score was computed for each participant by subtracting average performance on congruency repeat trials (cC and iI trials) from average performance on congruency switch trials (iC and cI trials). Post hoc tests revealed a significantly larger CSE in 6- to 8-year-olds ($M = 1.9\%$, $SD = 3.1$) than in 10- to 12-year-olds ($M = 0.3\%$, $SD = 1.3$) and adults ($M = 0.1\%$, $SD = 0.5$), both p -values $< .01$ (Figure 2A).

L-T Initiation Time

Average L-T initiation time for each trial type across all participants is shown in Figure 1B. The ANOVA on initiation times revealed a main effect of age group, $F(2, 105) = 77.00$, $p < .001$, $\eta_p^2 = .59$, with post hoc tests showing significantly slower initiation

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Table 2

Average Performance on Each Measure as a Function of Previous Congruency (*c, i*), Current Congruency (*C, I*), and Response Type (*-s, -r*), With Standard Deviations Presented in Parentheses

| | Error rate (%) | Initiation time (ms) | Curvature (ratio) | Movement time (ms) | Change of mind (%) | Total time (ms) |
|---------------------|----------------|----------------------|-------------------|--------------------|--------------------|-----------------|
| All participants | | | | | | |
| cC-s | 0.4 (1.7) | 503 (159) | 0.079 (0.046) | 477 (79) | 6.9 (8.2) | 980 (212) |
| iC-s | 1.0 (2.8) | 540 (168) | 0.111 (0.066) | 496 (103) | 12.8 (11.5) | 1,036 (243) |
| cl-s | 2.2 (4.8) | 521 (165) | 0.157 (0.093) | 508 (105) | 22.9 (17.8) | 1,029 (239) |
| il-s | 1.1 (3.7) | 529 (165) | 0.112 (0.082) | 492 (102) | 16.5 (16.9) | 1,021 (240) |
| cC-r | 0.2 (1.2) | 496 (142) | 0.055 (0.036) | 465 (80) | 4.8 (6.4) | 961 (199) |
| iC-r | 0.9 (2.6) | 533 (163) | 0.106 (0.066) | 500 (107) | 12.0 (10.8) | 1,033 (239) |
| cl-r | 2.1 (4.3) | 529 (165) | 0.180 (0.112) | 529 (122) | 24.2 (18.8) | 1,058 (252) |
| il-r | 1.1 (3.0) | 536 (163) | 0.110 (0.080) | 494 (112) | 14.5 (16.4) | 1,031 (243) |
| 6- to 8-year-olds | | | | | | |
| cC-s | 0.9 (2.5) | 662 (151) | 0.111 (0.042) | 544 (73) | 11.7 (9.1) | 1,206 (182) |
| iC-s | 2.6 (4.2) | 715 (148) | 0.152 (0.069) | 588 (107) | 20.1 (11.2) | 1,303 (204) |
| cl-s | 5.6 (6.9) | 679 (164) | 0.226 (0.096) | 601 (103) | 35.9 (17.0) | 1,280 (219) |
| il-s | 3.2 (5.8) | 691 (159) | 0.188 (0.084) | 584 (106) | 32.9 (17.4) | 1,275 (218) |
| cC-r | 0.3 (1.9) | 638 (128) | 0.077 (0.034) | 525 (86) | 7.8 (7.9) | 1,163 (185) |
| iC-r | 2.3 (3.8) | 696 (154) | 0.147 (0.063) | 592 (117) | 17.8 (11.4) | 1,287 (214) |
| cl-r | 4.7 (6.2) | 683 (161) | 0.275 (0.115) | 648 (122) | 38.8 (18.5) | 1,331 (219) |
| il-r | 2.6 (4.5) | 705 (146) | 0.181 (0.084) | 588 (126) | 26.3 (19.3) | 1,293 (215) |
| 10- to 12-year-olds | | | | | | |
| cC-s | 0.4 (1.4) | 471 (69) | 0.072 (0.042) | 456 (70) | 5.4 (7.6) | 927 (98) |
| iC-s | 0.5 (1.8) | 509 (74) | 0.110 (0.060) | 466 (71) | 12.1 (10.8) | 975 (98) |
| cl-s | 0.6 (1.6) | 492 (77) | 0.150 (0.074) | 484 (82) | 20.4 (15.5) | 976 (101) |
| il-s | 0.2 (1.0) | 501 (73) | 0.090 (0.050) | 459 (71) | 10.8 (9.5) | 959 (100) |
| cC-r | 0.1 (0.8) | 476 (69) | 0.055 (0.033) | 447 (65) | 4.2 (5.1) | 923 (93) |
| iC-r | 0.5 (2.0) | 503 (79) | 0.107 (0.069) | 475 (76) | 11.6 (10.5) | 978 (98) |
| cl-r | 1.2 (2.3) | 504 (84) | 0.159 (0.084) | 488 (76) | 20.1 (15.0) | 992 (100) |
| il-r | 0.7 (1.9) | 506 (70) | 0.095 (0.056) | 464 (79) | 12.3 (12.5) | 970 (92) |
| Adults | | | | | | |
| cC-s | 0.0 (0.0) | 375 (76) | 0.053 (0.034) | 432 (41) | 3.7 (5.4) | 808 (93) |
| iC-s | 0.0 (0.0) | 397 (76) | 0.073 (0.044) | 433 (46) | 6.3 (8.0) | 830 (93) |
| cl-s | 0.5 (1.6) | 390 (79) | 0.095 (0.052) | 439 (43) | 12.6 (12.2) | 830 (93) |
| il-s | 0.0 (0.0) | 396 (80) | 0.057 (0.038) | 432 (45) | 5.9 (7.1) | 828 (100) |
| cC-r | 0.1 (0.7) | 374 (58) | 0.033 (0.026) | 425 (45) | 2.3 (4.7) | 798 (84) |
| iC-r | 0.0 (0.0) | 400 (73) | 0.065 (0.032) | 435 (43) | 6.7 (7.5) | 834 (97) |
| cl-r | 0.3 (1.3) | 401 (88) | 0.106 (0.048) | 452 (49) | 13.6 (12.7) | 852 (105) |
| il-r | 0.0 (0.0) | 398 (72) | 0.056 (0.028) | 431 (46) | 5.0 (7.2) | 829 (94) |

Note. Note that these averages were computed using raw initiation times, movement times, curvatures, and total times.

times in 6- to 8-year-olds ($M = 6.458$, $SD = 0.205$) than in 10- to 12-year-olds ($M = 6.170$, $SD = 0.141$), $p < .001$, and significantly slower initiation times in 10- to 12-year-olds than adults ($M = 5.938$, $SD = 0.183$), $p < .001$. Initiation times were slower on incongruent trials ($M = 6.200$, $SD = 0.282$) than congruent trials ($M = 6.178$, $SD = 0.274$), as evidenced by a significant effect of current congruency, $F(1, 105) = 26.26$, $p < .001$, $\eta_p^2 = .20$. The effect of current congruency did not interact with age group, $F(2, 105) = 0.22$, $p = .80$ (Figure 2B). Initiation times were also slower on trials preceded by an incongruent trial ($M = 6.210$, $SD = 0.282$) relative to

those preceded by a congruent trial ($M = 6.167$, $SD = 0.277$), as evidenced by the significant effect of previous congruency, $F(1, 105) = 91.94$, $p < .001$, $\eta_p^2 = .47$. The interaction between previous congruency and age group did not reach significance, $F(2, 105) = 2.59$, $p = .080$.

A significant interaction between current congruency and response type was observed, $F(1, 105) = 6.02$, $p = .016$, $\eta_p^2 = .05$. Follow-up tests revealed a significant effect of response type on incongruent trials, $F(1, 107) = 7.00$, $p = .009$, $\eta_p^2 = .06$, with slower initiation times on I-r trials ($M = 6.207$, $SD = 0.279$) than I-s trials ($M = 6.192$, $SD = 0.287$).

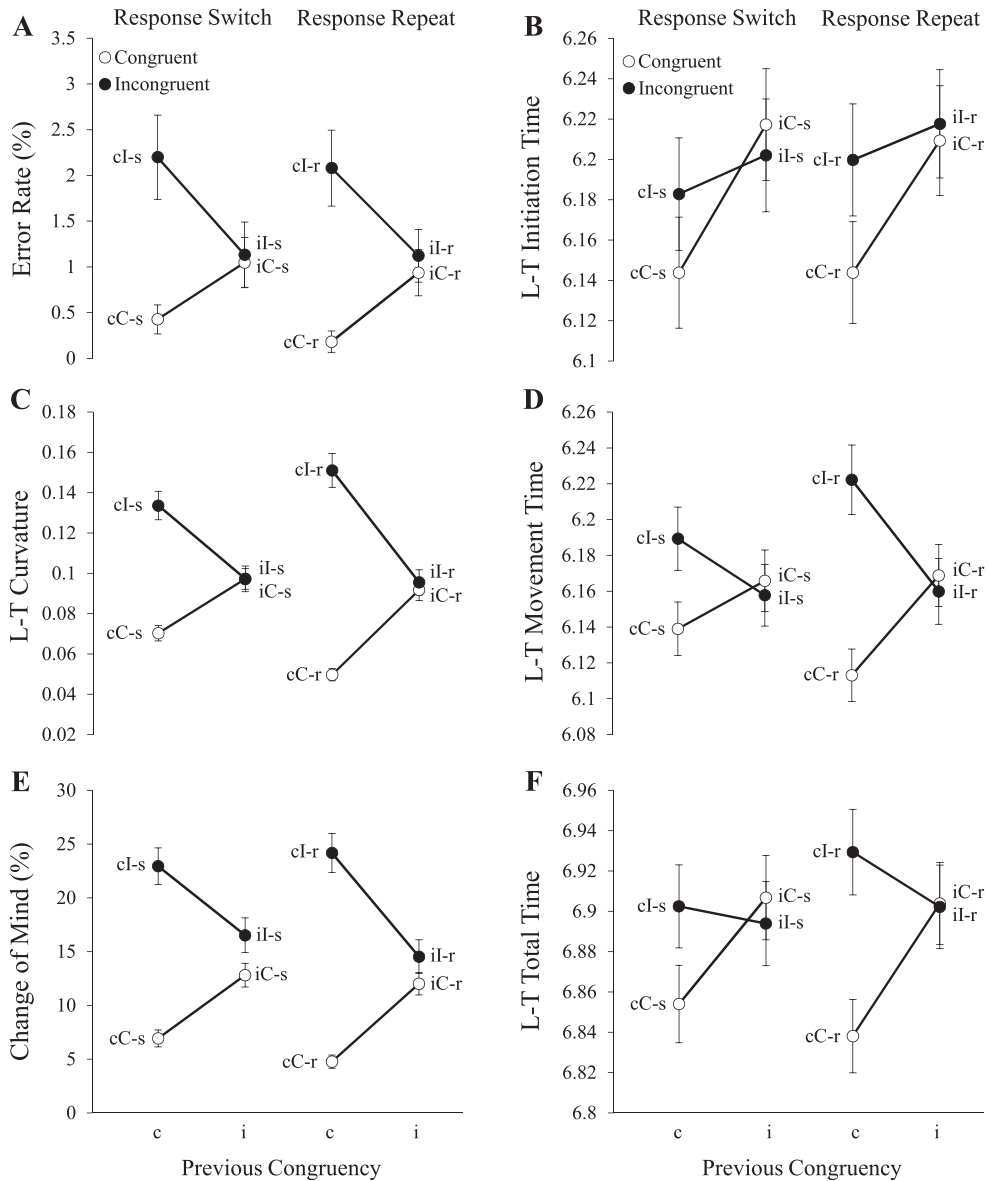


Figure 1. Average performance for the measures of (A) error rate, (B) log-transformed (L-T) initiation time, (C) L-T curvature, (D) L-T movement time, (E) change of mind, and (F) L-T total time across all participants as a function of previous congruency (c, i), current congruency (C, I), and response type (-s, -r). Error bars display standard errors.

The effect of response type on congruent trials was not significant, $F(1, 107) = 0.25, p = .62$.

Finally, the interaction between previous congruency and current congruency was significant, $F(1, 105) = 28.95, p < .001, \eta_p^2 = .22$. Follow-up tests revealed significantly faster initiation times on cC trials ($M = 6.143, SD = 0.271$) than iC trials ($M = 6.212, SD = 0.281$), $F(1, 107) = 118.26, p < .001, \eta_p^2 = .52$, and significantly faster initiation times on cI trials ($M = 6.190, SD = 0.287$) than iI trials ($M = 6.210, SD = 0.283$), $F(1, 107) = 8.72, p = .004, \eta_p^2 = .08$. Follow-up tests also revealed that the

difference between cC and cI trials was significant, $F(1, 107) = 50.56, p < .001, \eta_p^2 = .32$, whereas the difference between iC and iI trials was not, $F(1, 107) = 0.09, p = .75$. The interaction between previous congruency, current congruency, and age group did not approach significance, $F(2, 105) = 0.82, p = .92$.

L-T Curvature

Average L-T curvature for each trial type across all participants is shown in Figure 1C. The ANOVA

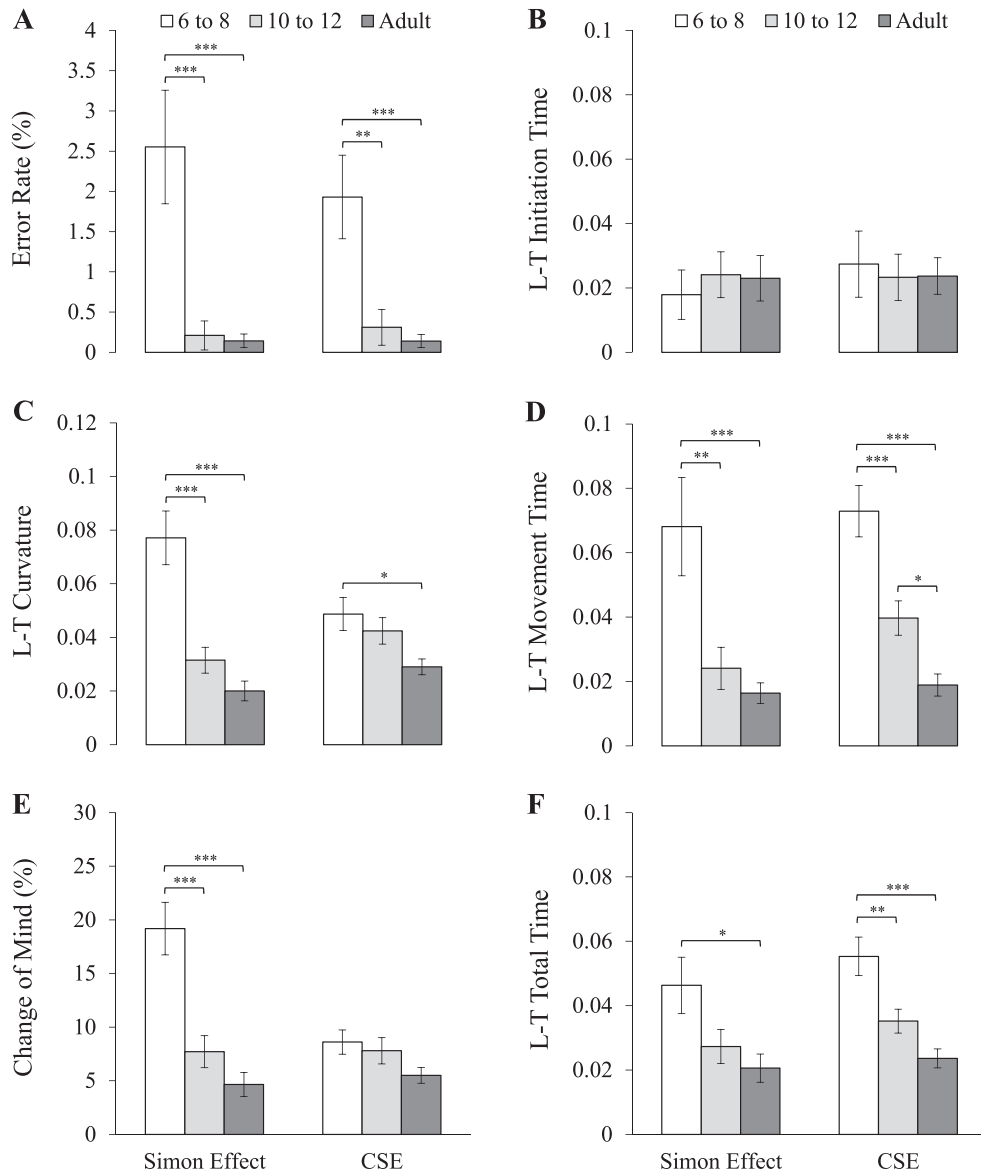


Figure 2. The average Simon effect (I-C) and congruency sequence effect (CSE; congruency switch-congruency repeat) observed in the measures of (A) error rate, (B) log-transformed (L-T) initiation time, (C) L-T curvature, (D) L-T movement time, (E) change of mind, and (F) L-T total time as a function of age group (6- to 8-year-olds, 10- to 12-year-olds, and adults). Error bars display standard errors. * $p < .05$. ** $p < .01$. *** $p < .001$.

on reach curvatures revealed a main effect of age group, $F(2, 105) = 48.67$, $p < .001$, $\eta_p^2 = .48$, with post-hoc tests showing significantly larger reach curvatures in 6- to 8-year-olds ($M = 0.142$, $SD = 0.039$) than 10- to 12-year-olds ($M = 0.091$, $SD = 0.039$), $p < .001$, and in 10- to 12-year-olds relative to adults ($M = 0.061$, $SD = 0.025$), $p = .001$. Reach curvatures revealed a number of interactions, including a four-way interaction between previous congruency, current congruency, response type, and age group, $F(2, 105) = 4.61$, $p = .012$, $\eta_p^2 = .08$ (Figure 2C).

Follow-up tests revealed a significant Simon effect on response repeat trials, $F(1, 107) = 96.72$, $p < .001$, $\eta_p^2 = .47$, and response switch trials, $F(1, 107) = 55.99$, $p < .001$, $\eta_p^2 = .34$. However, the Simon effect observed on response repeat trials ($M = 0.053$, $SD = 0.057$) was significantly larger than the Simon effect observed on response switch trials ($M = 0.032$, $SD = 0.045$), $F(1, 107) = 35.56$, $p < .001$, $\eta_p^2 = .25$. Post hoc tests on response repeat trials revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 0.095$, $SD = 0.072$) than in

10- to 12-year-olds ($M = 0.039$, $SD = 0.035$) or adults ($M = 0.027$, $SD = 0.026$), p -values $< .001$. Post hoc tests on response switch trials also revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 0.060$, $SD = 0.057$) than in 10- to 12-year-olds ($M = 0.024$, $SD = 0.029$) or adults ($M = 0.012$, $SD = 0.027$), p -values $< .001$.

Follow-up tests revealed significant CSEs on both response repeat trials, $F(1, 107) = 141.13$, $p < .001$, $\eta_p^2 = .57$, and response switch trials, $F(1, 107) = 105.41$, $p < .001$, $\eta_p^2 = .50$. However, the CSE observed on response repeat trials ($M = 0.050$, $SD = 0.043$) was significantly larger than the CSE observed on response switch trials ($M = 0.031$, $SD = 0.032$), $F(1, 107) = 16.98$, $p < .001$, $\eta_p^2 = .14$. Post hoc tests on response repeat trials revealed a significantly larger CSE in 6- to 8-year-olds ($M = 0.068$, $SD = 0.051$) than in adults ($M = 0.034$, $SD = 0.023$), $p = .002$. The CSE observed on response repeat trials was not significantly larger in 6- to 8-year-olds than in 10- to 12-year-olds ($M = 0.047$, $SD = 0.045$), $p = .09$. Post hoc tests on response switch trials did not reveal any significant age-related differences in the size of the CSE, p -values $> .15$.

L-T Movement Time

Average L-T movement time for each trial type across all participants is shown in Figure 1D. The ANOVA on movement times revealed a main effect of age group, $F(2, 105) = 34.66$, $p < .001$, $\eta_p^2 = .40$, with post hoc tests showing significantly slower movement times in 6- to 8-year-olds ($M = 6.310$, $SD = 0.139$) than 10- to 12-year-olds ($M = 6.119$, $SD = 0.154$) and adults ($M = 6.064$, $SD = 0.098$), p -values $< .001$. The main effect of current congruency was significant, $F(1, 105) = 41.11$, $p < .001$, $\eta_p^2 = .28$, as was the interaction between current congruency and age group, $F(2, 105) = 8.25$, $p < .001$, $\eta_p^2 = .14$. Post hoc tests revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 0.068$, $SD = 0.091$) than in 10- to 12-year-olds ($M = 0.024$, $SD = 0.039$) and adults ($M = 0.016$, $SD = 0.019$), p -values $< .01$ (see Figure 2D).

The interaction between previous congruency and current congruency was significant, $F(1, 105) = 166.44$, $p < .001$, $\eta_p^2 = .61$, as was the interaction between previous congruency, current congruency, and age group, $F(2, 105) = 21.39$, $p < .001$, $\eta_p^2 = .29$. Post hoc tests revealed a significantly larger CSE in 6- to 8-year-olds ($M = 0.073$, $SD = 0.048$) than 10- to 12-year-olds ($M = 0.040$, $SD = 0.032$), $p < .001$, and a significantly larger CSE

in 10- to 12-year-olds than adults ($M = 0.019$, $SD = 0.021$), $p < .05$ (see Figure 2D).

The interaction between current congruency and response type was significant, $F(1, 105) = 21.37$, $p < .001$, $\eta_p^2 = .17$. Follow-up tests revealed a significant Simon effect on both response repeat trials, $F(1, 107) = 44.09$, $p < .001$, $\eta_p^2 = .29$, and response switch trials, $F(1, 107) = 13.96$, $p < .001$, $\eta_p^2 = .12$. However, the Simon effect was significantly larger on response repeat trials ($M = 0.051$, $SD = 0.080$) than response switch trials ($M = 0.021$, $SD = 0.060$), $F(1, 107) = 22.82$, $p < .001$, $\eta_p^2 = .18$. The interaction between current congruency, response type, and age group also reached significance, $F(2, 105) = 5.86$, $p = .004$, $\eta_p^2 = .10$. Post hoc tests on response repeat trials revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 0.099$, $SD = 0.111$) than in 10- to 12-year-olds ($M = 0.029$, $SD = 0.053$) and adults ($M = 0.025$, $SD = 0.029$), p -values $< .001$. Post hoc tests on response switch trials did not reveal any significant differences in the size of the Simon effect, although the difference between 6- to 8-year-olds ($M = 0.040$, $SD = 0.089$) and adults ($M = 0.007$, $SD = 0.024$) approached significance, $p = .061$.

Finally, a significant interaction was observed between previous congruency, current congruency, and response type, $F(1, 105) = 21.96$, $p < .001$, $\eta_p^2 = .17$. Follow-up tests revealed significant CSEs on both response repeat trials, $F(1, 107) = 108.55$, $p < .001$, $\eta_p^2 = .50$, and response switch trials, $F(1, 107) = 40.50$, $p < .001$, $\eta_p^2 = .27$. However, the CSE observed on response repeat trials ($M = 0.060$, $SD = 0.059$) was significantly larger than the CSE observed on response switch trials ($M = 0.029$, $SD = 0.047$), $F(1, 107) = 22.80$, $p < .001$, $\eta_p^2 = .18$. The four-way interaction between previous congruency, current congruency, response type, and age group did not reach significance, $F(2, 105) = 2.28$, $p = .11$.

Change of Mind

Average change of mind for each trial type across all participants is shown in Figure 1E. A main effect of age group was observed in the change of mind measure, $F(2, 105) = 43.37$, $p < .001$, $\eta_p^2 = .45$, with post hoc tests showing significantly more changes of mind in 6- to 8-year-olds ($M = 23.6\%$, $SD = 9.2$) relative to 10- to 12-year-olds ($M = 12.1\%$, $SD = 7.8$) $p < .001$, and in 10- to 12-year-olds relative to adults ($M = 7.1\%$, $SD = 5.9$), $p = .022$. The effect of current congruency was significant, $F(1, 105) = 107.87$, $p < .001$, $\eta_p^2 = .51$, as

was the interaction between current congruency and age group, $F(2, 105) = 19.64, p < .001, \eta_p^2 = .27$. Post hoc tests revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 19.2\%, SD = 14.7$) than in 10- to 12-year-olds ($M = 7.7\%, SD = 9.0$) and adults ($M = 4.6\%, SD = 6.7$), both p -values $< .001$ (see Figure 2E).

The interaction between previous congruency and current congruency was significant, $F(1, 105) = 136.42, p < .001, \eta_p^2 = .57$, as was the interaction between previous congruency, current congruency, and response type, $F(1, 105) = 4.79, p = .031, \eta_p^2 = .04$. Follow-up tests revealed significant CSEs on response repeat trials, $F(1, 107) = 109.82, p < .001, \eta_p^2 = .51$, and response switch trials, $F(1, 107) = 55.64, p < .001, \eta_p^2 = .34$. However, the CSE observed on response repeat trials ($M = 8.6\%, SD = 8.5$) was significantly larger than the CSE observed on response switch trials ($M = 6.1\%, SD = 8.5$), $F(1, 107) = 5.03, p = .027, \eta_p^2 = .04$. The interaction between previous congruency, current congruency, response type, and age group did not reach significance, $F(2, 105) = 2.96, p = .056, \eta_p^2 = .05$.

Finally, a follow-up test evaluating the effect of previous congruency, response type, and age group on congruent trials revealed that changes of mind were significantly more frequent on iC trials ($M = 12.2\%, SD = 9.6$) than cC trials ($M = 5.9\%, SD = 6.4$), as evidenced by a significant main effect of previous congruency, $F(1, 105) = 101.93, p < .001, \eta_p^2 = .49$. A significant interaction between previous congruency and age group was also observed on congruent trials, $F(2, 105) = 6.65, p = .002, \eta_p^2 = .11$. Follow-up tests revealed that changes of mind were significantly more frequent on iC trials than on cC trials at each age group, p -values $< .001$. However, the difference between iC trials and cC trials was larger in 6- to 8-year-olds ($M = 9.0\%, SD = 8.0$) than adults ($M = 3.4\%, SD = 3.7$), $p = .001$. The difference between iC trials and cC trials observed in 10- to 12-year-olds ($M = 6.5\%, SD = 7.3$) did not differ significantly from the other age groups, p -values $> .13$.

L-T Total Time

Average L-T total time for each trial type across all participants is shown in Figure 1F. A main effect of age group was observed in total times, $F(2, 105) = 103.66, p < .001, \eta_p^2 = .66$, with post hoc tests revealing significantly slower total times in 6- to 8-year-olds ($M = 7.111, SD = 0.151$) than in 10- to 12-year-olds ($M = 6.855, SD = 0.095$), $p < .001$, and in

10- to 12-year-olds than in adults ($M = 6.706, SD = 0.110$), $p < .001$. Total times revealed a significant main effect of current congruency, $F(1, 105) = 71.29, p < .001, \eta_p^2 = .40$, a significant interaction between current congruency and age group, $F(2, 105) = 4.30, p = .016, \eta_p^2 = .08$, a significant interaction between current congruency and response type, $F(1, 105) = 26.40, p < .001, \eta_p^2 = .20$, and a significant interaction between current congruency, response type, and age group, $F(2, 105) = 5.76, p = .004, \eta_p^2 = .10$. Follow-up tests revealed a significant Simon effect on response repeat trials, $F(1, 107) = 76.50, p < .001, \eta_p^2 = .42$, and response switch trials, $F(1, 107) = 17.23, p < .001, \eta_p^2 = .14$. However, the Simon effect was significantly larger on response repeat trials ($M = 0.044, SD = 0.053$) than response switch trials ($M = 0.018, SD = 0.045$), $F(1, 107) = 23.51, p < .001, \eta_p^2 = .18$. Post hoc tests on response repeat trials revealed a significantly larger Simon effect in 6- to 8-year-olds ($M = 0.072, SD = 0.066$) than in 10- to 12-year-olds ($M = 0.033, SD = 0.043$) and adults ($M = 0.027, SD = 0.031$), p -values $< .01$. Post hoc tests on response switch trials did not reveal any significant differences in the size of the Simon effect, p -values $> .99$.

The main effect of previous congruency was significant, $F(1, 105) = 73.25, p < .001, \eta_p^2 = .41$, as was the interaction between previous congruency and age group, $F(2, 105) = 9.52, p < .001, \eta_p^2 = .15$. Post hoc tests revealed a significantly larger effect of previous congruency (i-c) in 6- to 8-year-olds ($M = 0.033, SD = 0.033$) than in 10- to 12-year-olds ($M = 0.017, SD = 0.026$) and adults ($M = 0.010, SD = 0.016$), p -values $< .05$. The interaction between previous congruency and current congruency was significant, $F(1, 105) = 230.04, p < .001, \eta_p^2 = .69$, as was the interaction between previous congruency, current congruency, and age group, $F(2, 105) = 12.22, p < .001, \eta_p^2 = .19$ (see Figure 2F). Post hoc tests revealed a significantly larger CSE in 6- to 8-year-olds ($M = 0.055, SD = 0.036$) than in 10- to 12-year-olds ($M = 0.035, SD = 0.022$) and adults ($M = 0.024, SD = 0.018$), p -values $< .01$.

Finally, a significant interaction was observed between previous congruency, current congruency, and response type, $F(1, 105) = 8.22, p = .005, \eta_p^2 = .07$. Follow-up tests revealed significant CSEs on both response repeat trials, $F(1, 107) = 115.19, p < .001, \eta_p^2 = .52$, and response switch trials, $F(1, 107) = 69.09, p < .001, \eta_p^2 = .39$. However, the CSE observed on response repeat trials ($M = 0.046, SD = 0.045$) was significantly larger than the CSE observed on response switch trials ($M = 0.030, SD = 0.037$), $F(1, 107) = 8.77, p = .004, \eta_p^2 = .08$. The

interaction between previous congruency, current congruency, response type, and age group did not approach significance, $F(2, 105) = 0.98, p = .38$.

Discussion

Given the central role that cognitive control plays in supporting adaptive behavior across the lifespan (e.g., Blair & Razza, 2007; Carlson & Wang, 2007; Carlson et al., 2002; Deater-Deckard et al., 2012; Miller et al., 2011; Mullane et al., 2009), an important challenge facing researchers in the psychological and brain sciences is to identify how the various processes proposed to underlie control unfold over the course of a trial (within-trial dynamics), are modulated by recent experience (cross-trial dynamics), and function across different age groups (developmental dynamics). This study was designed to shed light on these dynamics by using reaching behavior to target how two processes underlying cognitive control function in the Simon task—a task that, in addition to revealing substantial developmental and individual differences in cognitive control (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Davidson et al., 2006; Mullane et al., 2009), has featured prominently in ongoing debates surrounding the cross-trial dynamics of control (e.g., Burle et al., 2005; Hommel et al., 2004; Kerns, 2006; Keye et al., 2009; Scorolli et al., 2015). Specifically, this study addressed three central questions, which we discuss, in turn, in the following sections.

To What Extent Do the Threshold Adjustment and Controlled Selection Processes Contribute to Age-Related Reductions in the Simon Effect?

In the light of previous reach-tracking research investigating cognitive control in children and adults (Erb & Marcovitch, in press; Erb et al., 2016, 2017, 2018), we proposed that initiation time and reach curvature could be used to target how the threshold adjustment process and controlled selection process function in the Simon task at different points in development. Consistent with this claim, we observed distinct patterns of effects in the measures, as illustrated in Figures 1B and 1C. Initiation times were significantly slower on incongruent trials ($C < I$) and trials preceded by an incongruent trial ($c < i$), indicating that conflict on incongruent trials resulted in higher response thresholds that carried over into the next trial. Conversely, reach curvatures were lowest on cC trials, middling on iC

and iI trials, and highest of cI trials. This pattern has been suggested to reflect the controlled selection process, with larger reach curvatures indicating that participants were more pulled toward the inappropriate response before top-down support could be marshaled in favor of the appropriate response (Erb et al., 2016).

In addition to revealing different cross-trial dynamics, initiation times and reach curvatures captured different developmental dynamics. Reach curvatures revealed a substantial reduction in the size of the Simon effect between 6- to 8-year-olds and 10- to 12-year-olds, whereas no interaction between current congruency and age group was observed in initiation times. Thus, the results of this study indicate that the age-related reductions in the size of the Simon effect observed between childhood and adulthood are driven primarily by changes in the functioning of the controlled selection process. This finding suggests that participants in each age group adjusted their response thresholds to similar degrees after conflict was detected, but older children and adults were better able to resolve this conflict by swaying response activations in favor of the task-appropriate response.

Age-related reductions of the Simon effect have previously been attributed to improved inhibitory control—which refers to an individual's capacity to suppress or override a prepotent or habitual response—as opposed to gains in other capacities such as working memory (see Davidson et al., 2006). It is important to note, however, that distinct types of inhibition have been proposed to underlie inhibitory control (for a review, see Munakata et al., 2011). For instance, the controlled selection process is proposed to involve a *competitive* form of inhibition in which increased activation along one processing pathway (e.g., the pathway that supports the processing of stimulus identity in the Simon task) suppresses activity in competing pathways (e.g., the pathway that supports the processing of stimulus location) through lateral inhibitory connections between the pathways (Erb et al., 2018). Conversely, the threshold adjustment process is proposed to involve a *global* form of inhibition in which signals of conflict result in the inhibition of all candidate responses rather than one specific response. Given that the current study revealed age-related reductions of the Simon effect in curvature but not initiation time, our results indicate that the developmental gains observed in the Simon task after 6 to 8 years of age primarily reflect changes in processes involving competitive rather than global inhibition.

Does Reaching Behavior in the Simon Task Reveal a Greater Pull Toward the Inappropriate Response on iC Trials Than on cC Trials?

Larger reach curvatures and more frequent changes of mind were observed on congruency switch trials than congruency repeat trials. Crucially, changes of mind occurred more frequently on iC trials than cC trials in each of the three age groups. This observation is particularly surprising from a conflict adaptation perspective because neither stimulus form nor stimulus location cue the incorrect response on iC trials. Thus, it is unclear how the conflict adaptation account could accommodate the results of this study without a substantial amendment to the theory.

The feature integration account, on the other hand, can readily explain why changes of mind are more frequent on iC than cC trials. It proposes that overlap between the stimulus and response features of the current and previous trials can result in the activation of the incorrect direction. This overlap occurs on congruency switch trials (iC, cI) but not on congruency repeat (cC, iI) trials in standard two-response versions of the Simon task (Table 1). Consequently, the feature integration account predicts that changes of mind are more likely to occur on iC than on cC trials, consistent with the results of the current study.

Does the CSE Increase or Decrease From Childhood to Adulthood?

Significant interactions between previous congruency, current congruency, and age group were observed in error rates, movement times, reach curvatures, and total times. Each of these measures indicated that the size of CSE decreased with age, though the precise nature of this reduction varied across the measures: error rates and total times revealed a significant reduction between 6- to 8-year-olds and 10- to 12-year-olds; movement times revealed a significant reduction between 6- to 8-year-olds and 10- to 12-year-olds and between 10- to 12-year-olds and adults; and reach curvatures revealed a significant reduction between 6- to 8-year-olds and adults, though this reduction was specific to response repeat trials. From a feature integration perspective, the observed decrease in the size of the CSE can be interpreted to reflect age-related gains in the ability to form and break associations between stimulus and response features. This is because congruency switch trials in the Simon task involve stimulus and response features

that overlap with the event-file formed on the previous trial, whereas congruency repeat trials do not. This interpretation is consistent with previous research indicating that the ability to form and break associations between event-file elements improves between childhood and adulthood (e.g., Erb et al., 2018; Hommel et al., 2011). This ability has also been linked to fluid intelligence (Colzato, Van Wouwe, Lavender, & Hommel, 2006), which has been found to increase between childhood and adulthood (Fry & Hale, 2000).

From a conflict adaptation perspective, it is unclear why the size of the CSE would decrease between childhood and adulthood, given that individuals with stronger top-down control (i.e., adults) should also be able to focus their attention on stimulus form more effectively than individuals with weaker top-down control (i.e., children). Keye et al. (2009) followed a similar logic in their investigation of individual differences in adult performance of the Simon task. The authors reasoned that if the conflict adaptation account were correct, then adults with stronger cognitive control should generate larger CSEs than those with weaker cognitive control. However, this prediction was not supported by their findings. Thus, investigations of both developmental and individual differences in the Simon task appear to be incompatible with the conflict adaptation account of the CSE. Appendix S1, Section 3 of the Supplementary Materials explores how the findings of the present study relate to other prominent accounts of the CSE, including the *repetition expectancy account* (Duthoo, Wühr, & Notebaert, 2013) and the *contingency learning account* (Schmidt & De Houwer, 2011).

Relation to Previous Reach-Tracking Findings

The results of this study present further evidence that reaching behavior can be used to target how key processes underlying cognitive control function across different timescales. Distinct cross-trial dynamics have been observed in initiation times and reach curvatures in previous research with the Stroop task (Erb et al., 2016), the Eriksen flanker task (Erb et al., 2016, 2018), and a computerized version of the Dimensional Change Card Sort (DCCS) task (Erb et al., 2017; Zelazo, 2006). While multiple studies have investigated reaching behavior in the Simon task with adults (e.g., Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010; Scorolli et al., 2015), these studies were not optimally designed to target different patterns of effects in initiation time and reach curvature. For example, the

design used by Scherbaum et al. (2010) required participants to initiate a movement before the stimulus appeared on each trial, whereas the design used by Scorolli et al. (2015) did not allow participants to change their response after a movement was initiated. Thus, this study is the first to our knowledge to target distinct cross-trial dynamics in initiation time and reach curvature in the Simon task. Further discussion of how the results of this study relate to previous reach-tracking research is presented in Appendix S1, Section 3 of the Supplementary Materials.

Relation to Previous Developmental Findings

The within- and cross-trial dynamics of control have been explored from a developmental perspective in a wide range of tasks beyond the Simon task (e.g., Barker & Munakata, 2015; Chatham, Frank, & Munakata, 2009; Chevalier, Kelsey, Wiebe, & Espy, 2014; Cragg & Nation, 2008; Erb et al., 2017, 2018; Simpson et al., 2012; Waxer & Morton, 2011). Of particular relevance to the current study is Chevalier et al.'s (2014) event-related potential investigation of the Go/No-Go task in 5-year-olds. In their task, participants were presented with one of eight pictures on each trial. Six of the pictures cued a "go" response that required children to lift their thumb off of a "home" button and then press a "go" button, whereas the other two pictures cued participants to withhold responding ("no-go"). This method enabled the researchers to measure response initiation times in a manner similar to that of the current study by recording the time elapsed between stimulus onset and when the "home" button was released.

Chevalier and colleagues found that initiation times were faster on failed inhibition trials (i.e., "no-go" trials in which the child released the "home" button and pressed the "go" button) than partial inhibition trials (i.e., "no-go" trials in which the child released the "home" button but did not press the "go" button). The researchers also found that partial inhibition trials were preceded by faster successful "go" trials (i.e., "go" trials in which the child successfully released the "home" button and pressed the "go" button) than successful inhibition trials (i.e., "no-go" trials in which the child did not release the "home" button). Further, "go" trials following partial inhibition trials were found to feature slower initiation times than "go" trials following successful inhibitions. Taken together, these results suggest that Chevalier and colleagues' initiation time measure

captured the threshold adjustment process in the Go/No-Go task. On this view, response thresholds can be expected to decrease across stretches of conflict-free "go" trials. The lower the thresholds drop, the more likely it is that participants will fail to withhold responding when a "no-go" trial does occur. Similarly, given that conflict is particularly pronounced on partial inhibition trials, response thresholds can be expected to be elevated on "go" trials following partial inhibition trials relative to "go" trials following successful inhibition trials.

As discussed earlier, the results of this study indicate that children's performance of the Simon task is modulated by recent experience to a greater degree than that of adults'. From a distance, these results may appear to be at odds with previous research investigating the transition from *reactive*, "in-the-moment" control to *proactive*, "before-the-moment" control (e.g., Chatham et al., 2009; Munakata, Snyder, & Chatham, 2012). For example, Chatham et al. (2009) presented 3- and 8-year-olds with the AX continuous performance task (AX-CPT), a task in which participants are instructed to generate a target response to a specific probe ("X"), but only when the probe is preceded by a specific cue ("A" but not "B"). The researchers found that only the 8-year-olds reliably prepared for the presentation of the "X" probe following the presentation of the "A" cue, indicating that the older children but not the younger children were proactively engaging control.

This finding raises the question of why greater modulations of performance are observed in younger children relative to adults in the Simon task, whereas the inverse appears to be true in other tasks (e.g., Chatham et al., 2009; Waxer & Morton, 2011). We suspect that these differences reflect the extent to which various tasks enable children to prepare for specific upcoming events. For example, the Simon task does not provide response-relevant cues before the imperative stimulus and, consequently, participants are limited in their ability to prepare for upcoming events. Participants can, of course, engage control proactively in the Simon task by up-regulating attention before the imperative stimulus is presented (indeed, improved proactive control may have contributed to the age-related reductions in the Simon effect observed in this study). However, tasks that provide response-relevant cues before the imperative stimulus—such as the AX-CPT and the DCCS—allow proactive control to function in a much different manner.

Limitations

This study investigated the dynamics of cognitive control between middle childhood and early adulthood in healthy, typically developing individuals. At present, it is unclear how the threshold adjustment process and controlled selection process function during early childhood and middle to late adulthood. Similarly, it is unclear the extent to which the functioning of these processes is impacted by various disorders and diseases linked to impairments in cognitive control (e.g., Elliott, 2003; Mullane et al., 2009; Schoemaker et al., 2012). Future research should, therefore, extend this line of inquiry to a broader range of age groups, as well as to individuals diagnosed with disorders such as ADHD or diseases such as Parkinson's disease. Future research should also explore the within-trial, cross-trial, and developmental dynamics of control in "confound-minimized" versions of the Simon task that limit the extent to which the stimulus and response features of the current trial overlap with those of the previous trial (e.g., Weissman, Jiang, & Egner, 2014).

Conclusion

Current models of cognitive control propose that flexible, adaptive thought and behavior is supported by a number of dissociable processes that perform distinct functional roles (e.g., Shenhav et al., 2013). An important challenge facing developmental researchers is to identify how these processes function across development, differ between individuals, and are impacted by disorders and diseases known to impair cognitive control. Recording the spatial and temporal characteristics of reaching behavior presents new opportunities to investigate how processes operating in parallel across perception, cognition, and action interact and unfold to support flexible responding (Buc Calderon, Verguts, & Gevers, 2015; Cisek & Kalaska, 2010). Although reach tracking (and related techniques such as mouse tracking) are commonly used to assess a wide range of cognitive capacities in adults, including attention, language, numerical cognition, cognitive control, and social perception (for reviews, see Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009), relatively little research has used reaching behavior to explore these capacities from a developmental perspective (for a review, see Erb, 2018). Thus, the present study contributes to a small but growing body of research that highlights the promise of incorporating continuous behavioral measures into developmental research.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Additional information regarding the Materials (Section 1), Results (Section 2), and Discussion (Section 3).