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## Original Articles

# Deconstructing the Gratton effect: Targeting dissociable trial sequence effects in children, pre-adolescents, and adults

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## ABSTRACT

The *Gratton effect* refers to the observation that performance on congruency tasks is often enhanced when the congruency of the current trial matches that of the previous trial. This effect has been at the center of recent debates in the literature on cognitive control as researchers have sought to identify the cognitive and neural underpinnings of the effect. Here, we use a technique known as reach tracking to demonstrate that the Gratton effect originally observed in the flanker task is not a singular effect but the result of two separate trial sequence effects that impact dissociable processes underlying cognitive control. Further, our results indicate that these dissociable processes follow divergent developmental trajectories across childhood, pre-adolescence, and adulthood. Taken together, these findings suggest that manual dynamics can be used to disentangle how key processes underlying cognitive control contribute to the response time effects observed across a wide range of cognitive tasks and age groups.

## 1. Introduction

A central research goal of the psychological and brain sciences is to identify the cognitive and neural mechanisms that support cognitive control – the capacity to align one’s ongoing thoughts and actions with one’s current goals and context (Badre, 2008; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; Cohen, 2017; Egner, 2008, 2017; Miller & Cohen, 2001; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Shenav, Botvinick, & Cohen, 2013). Congruency tasks such as the flanker (Eriksen & Eriksen, 1974), Simon (1969), and Stroop (1935) tasks have been instrumental to these research efforts. These tasks intermittently require participants to override a prepotent response with a more controlled alternative response. In the flanker task, for example, participants are presented with a stimulus array that is comprised of a centrally presented target stimulus and surrounding distractor stimuli known as “flankers”. On congruent trials, all elements in the array cue the same response (e.g., →→→→→). On incongruent trials, the target and distractor stimuli cue competing responses (e.g., →→←→→). To ensure that the appropriate response is selected on incongruent trials, individuals must register the conflict between the two cued responses and then resolve that conflict in favor of the response cued by the target. The performance cost

associated with detecting and resolving conflict on incongruent trials relative to congruent trials is known as the *congruency effect*.

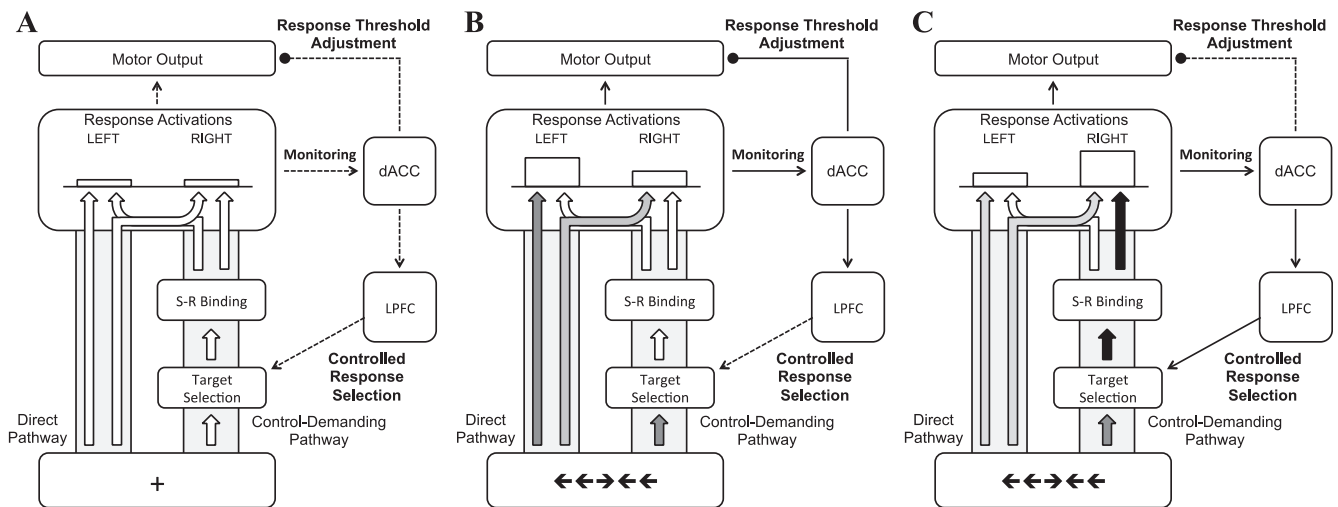
Although congruency tasks are among the most well studied tasks in cognitive psychology, researchers continue to debate how performance on the tasks should be interpreted. For instance, in recent years considerable debate has focused on the interpretation of trial sequence effects (TSEs) – effects in which qualities of one trial influence performance on a subsequent trial (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007, 2017; Kerns et al., 2004; Mayr, Awh, & Laurey, 2003; Schmidt & De Houwer, 2011; Ullsperger, Bylsma, & Botvinick, 2005).<sup>1</sup> This debate has reopened fundamental questions concerning how the cognitive and neural mechanisms underlying performance on congruency tasks function, as well as how these mechanisms change across development and differ between individuals.

The current study tests a proposal from Erb, Moher, Sobel, and Song (2016) that the TSE at the heart of recent debates – known as the *Gratton effect* (Gratton, Coles, & Donchin, 1992) – is the product of two separate TSEs that impact dissociable processes underlying cognitive control. In the following, we present a general model of flanker task performance and discuss how the Gratton effect has been interpreted within the context of the model. We then review recent research that has used a technique known as *reach tracking* to target how key

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<sup>1</sup> A related term used in the literature is *congruency sequence effect* (CSE), which refers to instances in which the congruency of a previous trial influences performance on a subsequent trial (see Egner, 2007). Whereas CSEs refer specifically to the role of a trial’s congruency in sequential effects, the term TSE is broader and encompasses other factors such as response repetition effects.



**Fig. 1.** Illustration of key pathways and processes proposed to underlie flanker task performance. Broad arrows illustrate the direct and control-demanding pathways. Activation levels along these pathways are illustrated by the shading within each arrow, with darker shading indicating higher levels of activation. Thin lines with arrows represent excitatory connections, whereas thin lines with circles represent inhibitory connections. Thin dashed lines represent non-active links, whereas thin solid lines represent active links. (A) Before the stimulus is presented, activation along the direct pathway and the control-demanding pathway is minimal. Consequently, response activations are low and the monitoring process does not register signals of conflict. (B) On incongruent trials, the direct pathway generates strong activation in favor of the response cued by the distractor stimuli (e.g., LEFT) and relatively weak activation in favor of the response cued by the target stimulus (e.g., RIGHT). The monitoring process registers co-activation between the competing responses. In response to this conflict, the threshold adjustment process temporarily halts motor output. (C) Halting motor output in this manner is proposed to provide additional time for top-down resources to be recruited in support of the controlled selection process, which increases activation along the control-demanding pathway, thereby swaying response activations in favor of the task-appropriate response. Elements of this model have been adapted from Ridderinkhof et al. (1995) and Shenhav et al. (2013).

processes featured in the model are impacted by TSEs. Finally, we test (i) whether the Gratton effect results from the combination of qualitatively different TSEs in the flanker task, and (ii) the extent to which developmental differences in flanker task performance are driven by these different TSEs.

### 1.1. Flanker model and TSEs

Performance on the flanker task has been proposed to reflect two different processing pathways: a direct pathway that generates response activations in light of the overall stimulus array, and a control-demanding pathway that can be directed to select the target stimulus and then bind the target stimulus to the appropriate response (see Fig. 1; Botvinick et al., 2001; Ridderinkhof, van der Molen, & Bashore, 1995). On incongruent trials, the direct pathway generates competing response activations, resulting in a processing conflict. This conflict is then registered by a monitoring process associated with the dorsal anterior cingulate cortex (dACC) which serves to recruit two processes of particular interest to the current discussion: a *threshold adjustment* process in which signals of conflict from the dACC put the “brake” on behavior by temporarily inhibiting motor output, and a *controlled selection* process involving the lateral prefrontal cortex (LPFC) in which top-down resources are marshaled in favor of the control-demanding pathway to ensure that the target is selected and then paired with the appropriate response (Erb et al., 2016; Shenhav et al., 2013). The threshold adjustment process is proposed to play a role in speed-accuracy trade-offs by providing additional time for the controlled selection process to sway response activations in favor of the correct response (Cavanagh et al., 2011; Frank, 2006; Wiecki & Frank, 2013).

Models of cognitive control have played an important role in accounting for TSEs in congruency tasks, with particular focus given to the Gratton effect – the observation that response times are faster on congruency repeat trials than congruency switch trials (Gratton et al., 1992; see Fig. 2A1). For instance, congruent trials preceded by a congruent trial (*cC trials*, where the lowercase letter denotes previous congruency and the uppercase letter denotes current congruency) tend to feature faster response times than congruent trials preceded by an

incongruent trial (*iC trials*). Similarly, response times tend to be faster on incongruent trials preceded by an incongruent trial (*ii trials*) relative to incongruent trials preceded by a congruent trial (*ci trials*) (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Gratton et al., 1992).

In the quarter-century since the Gratton effect was first reported in the flanker task (Gratton et al., 1992), a large body of research has sought to account for the effect and related TSEs (for reviews, see Duthoo et al., 2014; Egner, 2007, 2017; Schmidt & de Houwer, 2011). According to the *conflict adaptation account*, the Gratton effect is the product of conflict driven modulations of cognitive control (Botvinick et al., 2001; Ullsperger et al., 2005). On incongruent trials, top-down resources are marshaled in favor of the control-demanding pathway. This increase in top-down control is then carried over into the subsequent trial, where it serves to decrease the impact of the distractor stimuli. If this subsequent trial is also incongruent, decreasing the impact of the distractor stimuli in this manner facilitates performance, resulting in faster response times on *ii* relative to *ci* trials. However, if the subsequent trial is congruent, decreasing the impact of the distractor stimuli impairs performance because the distractors cue the correct response on congruent trials. Consequently, response times are slower on *iC* than *cC* trials.

The conflict adaptation account was called into question by research investigating the difference between response repeat trials (in which the response of the current trial matches that of the previous trial) and response switch trials (in which the response of the current trial differs from that of the previous trial) (Mayr et al., 2003; Nieuwenhuis et al., 2006). Although response times on response repeat trials showed the Gratton effect ( $cC-r < iC-r < ii-r < ci-r$ ; where “r” denotes a response repeat; see the right panel of Fig. 2A2), response switch trials did not. Rather, response switch trials revealed main effects of both current and previous congruency (but no interaction between the two), with slower response times on both incongruent trials and trials preceded by an incongruent trial ( $cC-s < iC-s < ci-s < ii-s$ ; where “s” denotes a response switch; see the left panel of Fig. 2A2). This observation posed a challenge for the conflict adaptation account, as it is unclear why conflict adaptation would occur on incongruent trials featuring a response repeat but not on incongruent trials featuring a response switch.

According to the *feature integration account*, the effect of response type (repeat vs. switch) on incongruent trials reflects how readily the stimulus of the current trial can be paired with the appropriate response (Hommel, 2004; Hommel, Proctor, & Vu, 2004). On cI-r trials (e.g.,  $\leftarrow\leftarrow\leftarrow\leftarrow$  preceded by  $\rightarrow\rightarrow\rightarrow\rightarrow$ ), the response of the previous trial (RIGHT) must be paired with a different stimulus ( $\leftarrow\leftarrow\leftarrow\leftarrow$ ) than that of the previous trial ( $\rightarrow\rightarrow\rightarrow\rightarrow$ ). This results in a processing conflict during S-R binding because the S-R pair formed on the previous trial ( $\rightarrow\rightarrow\rightarrow\rightarrow = \text{RIGHT}$ ) interferes with the formation of the appropriate S-R pair on the current trial ( $\leftarrow\leftarrow\leftarrow\leftarrow = \text{RIGHT}$ ). In the context of the model introduced above, S-R binding conflict in the flanker task can be understood to impair the ability of the controlled selection process to sway response activations in favor of the response cued by the target. S-R binding conflict does not occur on response switch trials, as these trials necessarily feature a different stimulus than the previous trial. Consequently, performance is not impaired on cI- relative to iI-s trials (Nieuwenhuis et al., 2006).

## 1.2. Reach tracking

Although feature integration theory presents an account of the Gratton effect observed on response repeat trials in two-alternative forced-choice (2AFC) versions of the flanker task (Mayr et al., 2003; Nieuwenhuis et al., 2006), what might account for the overall pattern of TSEs presented in Fig. 2A2? One possible explanation is provided by recent work by Erb and colleagues (Erb et al., 2016; Erb, Moher, Song, & Sobel, 2018) in which participants completed congruency tasks by reaching to response locations on a digital display while their hand movements were measured by an electromagnetic position and orientation recording system. This reach-tracking technique provides measures of *initiation time* (the time elapsed between stimulus onset and movement onset), *reach curvature* (a measure of the degree to which a reach movement deviates from a direct path to the selected response location), *movement time* (the time elapsed between movement onset and response completion), and *total time* (the time elapsed between stimulus onset and response completion).

Erb et al. (2016) proposed that initiation time could be used to target the threshold adjustment process by indexing the degree of motoric stopping experienced at the outset of a trial, with higher response thresholds generating longer periods of motoric stopping and, consequently, slower initiation times. In light of previous research indicating that reach curvature reflects the degree of co-activation between competing responses over the course of a movement (e.g., Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Freeman, Nakayama, & Ambady, 2013), the researchers further proposed that curvature could be used to target the controlled selection process. On this view, reach movements on incongruent trials should be pulled toward the prepotent response cued by the distractors until the controlled selection process can sway response activations in favor of the response cued by the target. If the controlled selection process is impaired – for example, by S-R binding conflict – reach curvatures should be larger, as it would take longer for response activations to be swayed in favor of the appropriate response.

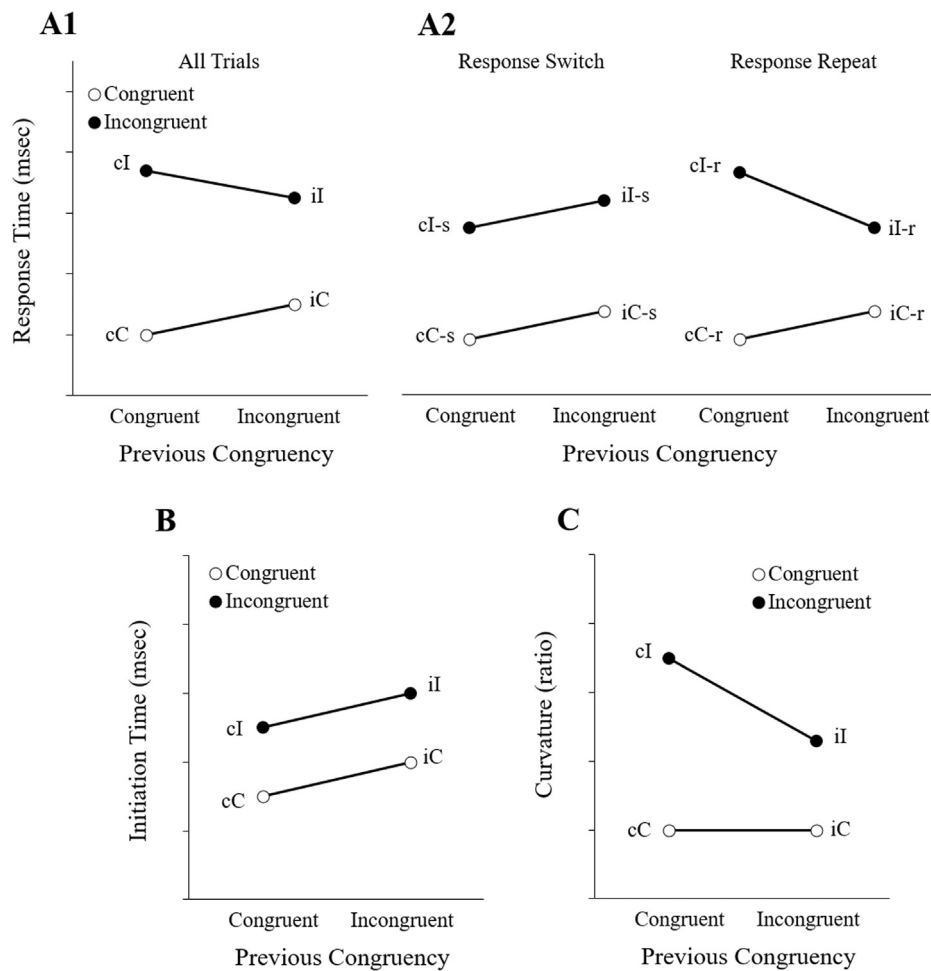
Erb et al. (2016) tested these predictions by presenting adult participants with a reach-tracking version of the flanker task. In the task, participants identified whether the target stimulus was a “B”, “A”, or “K” by reaching to touch one of three response locations on a digital display. Consistent with the claim that initiation time and curvature reflect distinct processes underlying cognitive control, the researchers observed different TSEs in each of the measures. Initiation times revealed main effects of current and previous congruency resulting in the following pattern of effects:  $cC < iC < cI < iI$  (see Fig. 2B). The researchers interpreted this pattern to reflect the threshold adjustment process, with conflict on incongruent trials serving to increase response thresholds from their existing levels, resulting in a main effect of current congruency ( $C < I$ ) that was carried over into the subsequent trial as an effect of previous congruency ( $c < i$ ).

In contrast to initiation times, reach curvatures revealed main effects of current congruency and previous congruency, as well as a significant interaction between the two, resulting in the following pattern of effects:  $cC = iC < iI < cI$  (see Fig. 2C). The researchers interpreted this pattern of results to reflect the impact of S-R binding conflict on the controlled selection process. Consistent with this interpretation, the difference between iI and cI trials disappeared when trials featuring S-R binding conflict were excluded from analysis, resulting in the following pattern:  $cC = iC < iI = cI$ . Excluding these trials from analysis did not alter the pattern of effects observed in initiation time.

The results of Erb et al. (2016) presented initial support for two intriguing proposals. First, the findings suggest that the Gratton effect results from the summation of two separate TSEs: one affecting the threshold adjustment process ( $cC < iC < cI < iI$ ) and the other affecting the controlled selection process ( $cC = iC < iI < cI$ ). Although Erb et al.’s results were suggestive of this possibility, total times (i.e., response times) in the task did not conform to the Gratton pattern, suggesting that the three-response version of the task used by the researchers placed different demands on cognitive control than the two-response versions used in previous research, which provide a more direct test of response repetition effects (Mayr et al., 2003; Nieuwenhuis et al., 2006). Demonstrating that the Gratton effect observed in the flanker task results from the summation of two distinct TSEs would present a fundamentally different approach to how TSEs are measured and interpreted. At a theoretical level, such a demonstration would highlight the limitations of accounts that appeal to a single process or mechanism underlying TSEs (e.g., conflict-driven modulations of top-down control). At a methodological level, it would suggest that traditional button-press measures present a limited – and potentially misleading – view of the cognitive dynamics underlying TSEs. At an empirical level, it would call into question the extent to which the TSEs previously reported across a wide range of different tasks were driven by the threshold adjustment process and controlled selection process.

Second, the results of Erb et al. (2016) suggest that reach tracking can be used to target the extent to which the threshold adjustment process and controlled selection process contribute to developmental and individual differences in cognitive control. To evaluate how these processes contribute to age-related gains in cognitive control, Erb et al. (2018) presented children 5–10 years of age and adults with a two-response version of the flanker task. As in Erb et al. (2016), the researchers observed distinct TSEs in initiation time and curvature, consistent with the claim that these measures reflected the threshold adjustment process and controlled selection process, respectively. The measures also presented different age-related gains, with reach curvatures but not initiation times revealing significant decreases in the size of the congruency effect between older children (8- to 10-year-olds) and adults. Interestingly, the age-related gains observed in reach curvatures were driven primarily by the subset of trials featuring S-R binding conflict, suggesting that these trials placed greater – and perhaps unique – demands on cognitive control relative to the other trial types. Such an interpretation is supported by previous developmental research by Hommel, Kray, and Lindenberger (2011) who found that S-R binding conflict had a greater effect on error rates in 9- to 10-year-olds than in young adults in a task that was developed by Hommel (1998) to systematically manipulate stimulus and response repetitions.

Although the results of Erb et al. (2018) provide additional support for the claim that initiation time and reach curvature can be used to target two dissociable processes underlying cognitive control, the study featured a number of manipulations that complicated the interpretation of TSEs and age-related differences. For instance, in an effort to evaluate the effect of the distractors, the researchers randomized the number of distractors presented on each trial (0, 2, or 4). This manipulation resulted in a higher proportion of trials featuring a stimulus switch and may have allowed S-R binding conflict to occur on a wider variety of trial types (e.g., iI-r trials). Additionally, children completed a



**Fig. 2.** (A) Hypothetical data illustrating the trial sequence effects observed in response times in button-press versions of the flanker task. (A1) illustrates the general pattern of effects observed by Gratton et al. (1992), whereas (A2) illustrates the pattern of effects observed when both congruency repetition (switch vs. repeat) and response repetition (switch vs. repeat) effects are analyzed (e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). (B) Hypothetical data illustrating the trial sequence effects observed in initiation time and (C) reach curvature by Erb et al. (2016).

child-friendly version of the flanker task featuring cartoon fish rather than the standard arrow version. It is therefore possible that initiation times failed to reveal significant age-related gains in cognitive control between older children and adults because the child-friendly stimuli were less likely than the standard stimuli to elicit conflict at the outset of a trial (i.e., conflict among the elements in the array may have been more pronounced in the arrays featuring arrows than the arrays featuring cartoon fish). Finally, child and adult total times in the study presented inconsistent patterns of effects and were not discussed in relation to the patterns of effects previously observed in response times (Mayr et al., 2003; Nieuwenhuis et al., 2006).

### 1.3. Current study

The current study builds on the results of Erb and colleagues (2018; Erb et al., 2016) to investigate two central questions: (i) *Does the Gratton effect result from the combination of different TSEs impacting distinct processes underlying cognitive control?* (ii) *To what extent are age-related gains in flanker task performance driven by these processes?* To address these questions, we presented children (6- to 8-year-olds), pre-adolescents (10- to 12-year-olds), and young adults (18- to 24-year-olds) with a reach-tracking version of the flanker task that featured arrow stimuli and two response options. In addition to providing a more controlled comparison of each age group's performance, this task design enabled us to test whether the Gratton effect observed in response times in previous studies (Gratton et al., 1992; Mayr et al., 2003;

Nieuwenhuis et al., 2006) resulted from the summation of two different patterns of TSEs linked to dissociable processes underlying cognitive control.

For the ease of interpretation, we divide the results and discussion of the current study into two sections. The first section focuses on the effects of previous congruency, current congruency, and response type (switch vs. repeat) across all age groups. If the Gratton effect is the product of two distinct TSEs that influence dissociable processes underlying cognitive control, then initiation times should reveal main effects of current and previous congruency ( $cC < iC < cI < iI$ ), whereas curvatures should be uniformly low on congruent trials, elevated on incongruent trials not featuring S-R binding conflict (cI-s, iI-s, and iI-r trials), and largest on incongruent trials featuring S-R binding conflict (cI-r trials). Crucially, total times should conform to the pattern of effects previously observed in response times on two-response versions of the task (see Fig. 2A2; Mayr et al., 2003; Nieuwenhuis et al., 2006).

The second section focuses on the impact of age on performance. If Erb et al. (2018) failed to observe age-related improvements between older children and adults because of the child-friendly stimuli used in their study, then initiation times in the current study can be expected to reveal a smaller congruency effect (i.e., a smaller difference between performance on incongruent and congruent trials) in adults than pre-adolescents. If the results observed by Erb et al. were not due to the child-friendly stimuli, then no such improvement should be observed between pre-adolescence and adulthood. Further, in keeping with the

results of Erb and colleagues, we predict that reach curvatures will reveal age-related gains in cognitive control between pre-adolescents and adulthood.

## 2. Method

### 2.1. Participants

A total of 135 individuals participated in the study, with 45 participants in each of three age groups: children (6–8 years of age;  $M = 6.9$  years,  $SD = 0.8$ ; 23 females), pre-adolescents (10–12 years of age;  $M = 11.0$  years,  $SD = 0.8$ ; 25 females), and adults (18–24 years of age;  $M = 18.7$  years,  $SD = 1.4$ ; 26 females). Inclusion in the final sample was restricted to right-handed individuals with normal or corrected-to-normal vision. One additional pre-adolescent was tested but excluded from the final data set after falling asleep during the experimental session and reporting sleep deprivation. Child participants received a small prize for participating, whereas adult participants received course credit. 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.

### 2.2. Materials

The experiment was conducted using a rear-mounted projector to display the task on a Plexiglass screen, as in previous work (e.g., Erb et al., 2016; Moher & Song, 2013; Song & Nakayama, 2008). The projector, screen, and an electromagnetic source were affixed to a wooden board that was mounted to a 91.4 cm by 152.4 cm table (see Fig. 3A). The projected display on the Plexiglass screen was 38 cm by 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 cm by 2 cm square marker was placed 27 cm in front of the screen, with the placement of the square changing based upon 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). In order to measure hand position, a small motion-

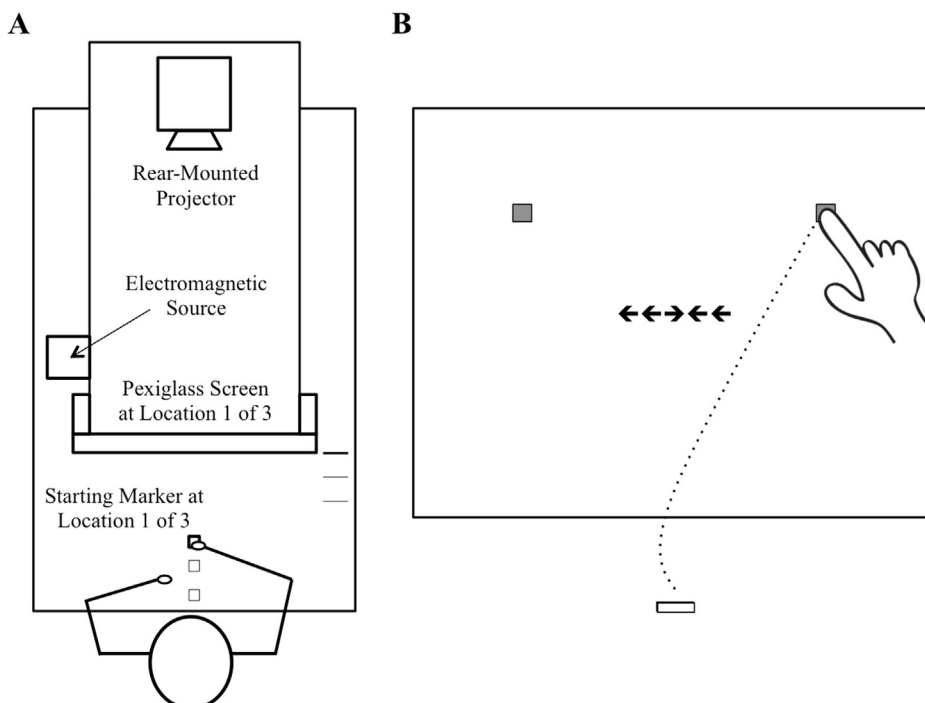
tracking sensor was secured to participants' right index finger with a Velcro strap. The sensor was 2.3 cm long, 1.3 cm wide, and 1.1 cm high, and weighed 3.7 g. The task was programmed in MATLAB (Mathworks).

Participants were presented with a two-response version of the flanker task in which an array of five grey arrows appeared in the center of the display following a cue. Participants identified which direction the arrow in the center of the stimulus array was facing by touching one of two grey squares that measured 1.7 cm by 1.7 cm (see Fig. 3B). The center of each grey square was 11.5 cm from the top of the projected display, with one square 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. Each array of arrows was 1.5 cm tall and 9 cm wide.

During each trial, a crosshair appeared 1 s before the stimulus array. The cue was located in the same location that the central target appeared, minimizing the demands placed on visual search. Each trial would not initiate until the participant's finger was resting on the starting marker for 1 s. If the participant's hand moved from this location before stimulus onset, the task was paused and did not resume until the participant returned their hand to the starting marker for 1 s. Participants had up to 5.5 s to respond following stimulus onset. A high tone sounded for correct responses provided in the allotted time (600 Hz for 200 ms). A low tone sounded for incorrect responses or responses that exceeded the allotted time (300 Hz for 200 ms).

### 2.3. Procedure

Participants first completed a nine-point calibration sequence followed by 16 baseline trials that required reaching to a square that appeared alone at the top left or right of the screen. Participants then received a practice block of 10 flanker trials before beginning the experiment. If participants expressed difficulty understanding the task, a second practice block was presented (9 children and 5 pre-adolescents completed an additional practice block). The experiment consisted of three blocks of 48 trials, for a total of 144 trials. Each block featured 24 congruent trials in which the target and distractors cued the same response and 24 incongruent trials in which the target and distractors cued opposing responses. Trial presentation was randomized and the correct response was evenly divided between the two response locations.



**Fig. 3.** (A) Diagram of experimental setup from aerial view. The task was displayed on a Plexiglass screen mounted upright on the table in front of the participant. The position of the screen was adjustable to three different locations to accommodate participants of different ages. 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 flanker task from the perspective of the participant.



## 2.4. Data processing

The processing procedures used in the current 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 (Song & Nakayama, 2006, 2007, 2008); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, thresholds were adjusted manually. Manual adjustments were most typically required when participants rapidly pulled their finger away from the screen after having touched a target or stopped entirely during their movement (e.g., after realizing that they had been moving toward the incorrect target).

Trajectories for calculating curvature were measured in two-dimensional xy space by calculating a line from the start to the end point of the movement, and measuring the orthogonal deviation of the actual movement from that line at each sample. Curvature was defined as the maximum point of deviation in centimeters divided by the length of the line from the start to the end points of the movement in centimeters (following Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Moher & Song, 2013).

## 3. Results

To minimize the effect of age-related differences in processing speed, log transformations were applied to the total time, initiation time, curvature, and movement time data. Given that it is inappropriate to perform a log transformation on non-positive values, a constant of 1 was added to each curvature value before the log transformation was applied. The analyses reported below for total time, initiation time, curvature, and movement time were conducted with the log-transformed (L-T) data. For analysis of the untransformed data, see the Supplementary Materials.<sup>2</sup>

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 trials and trials following an inaccurate trial were also excluded from analysis for each of the measures reported below with the exception of error rate. Performance on each measure was analyzed with a series of mixed ANOVAs featuring Age Group (Children, 6–8 years; Pre-Adolescents, 10–12 years; and Adults, 18–24 years) as a between-subjects factor and Previous Congruency (c, i), Current Congruency (C, I), and Response Type (Switch, Repeat) as within-subjects factors. These analyses were selected to maintain continuity with previous research investigating TSEs in 2AFC versions of the flanker task (Mayr et al., 2003; Nieuwenhuis et al., 2006). All post-hoc comparisons featured Bonferroni corrections to adjust for multiple comparisons. In the following, we present the results in two sections. Section 1 focuses on the effects of Previous Congruency, Current Congruency, and Response Type across all participants, whereas Section 2 focuses on how these factors interacted with Age Group.

### 3.1. Section 1: Results

#### 3.1.1. L-T total time

Total times revealed the Gratton effect, with a significant effect of Current Congruency,  $F(1, 132) = 249.95, p < .001, \eta_p^2 = 0.65$ , and a significant interaction between Previous Congruency and Current

Congruency,  $F(1, 132) = 52.25, p < .001, \eta_p^2 = 0.28$  (see Fig. 4A1). Consistent with previous research investigating the effect of response type in 2AFC versions of the flanker task (Mayr et al., 2003; Nieuwenhuis et al., 2006), a three-way interaction among Previous Congruency, Current Congruency, and Response Type was observed in total times,  $F(1, 132) = 32.92, p < .001, \eta_p^2 = 0.20$ . To account for this interaction, we evaluated the effects of Current Congruency and Previous Congruency on response switch and response repeat trials separately.

Response switch trials revealed main effects of Current Congruency,  $F(1, 132) = 204.39, p < .001, \eta_p^2 = 0.61$ , and Previous Congruency,  $F(1, 132) = 42.66, p < .001, \eta_p^2 = 0.24$ , with longer total times on incongruent trials and trials preceded by an incongruent trial (see the left panel of Fig. 4A2). Response repeat trials revealed the Gratton effect, with significant main effects of Current Congruency and Previous Congruency, as well as a significant interaction between them,  $p$ -values  $< .001, \eta_p^2 > 0.08$  (see the right panel of Fig. 4A2). Follow-up tests revealed a significant effect of Previous Congruency on congruent trials featuring a response repeat,  $F(1, 132) = 25.17, p < .001, \eta_p^2 = 0.16$ , with faster total times on cC-r than iC-r trials. A significant main effect of Previous Congruency was also observed on incongruent trials featuring a response repeat,  $F(1, 132) = 66.25, p < .001, \eta_p^2 = 0.33$ , with faster total times on il-r than ci-r trials.

#### 3.1.2. L-T initiation time

Initiation times revealed significant main effects of Previous Congruency,  $F(1, 132) = 61.71, p < .001, \eta_p^2 = 0.32$ , and Current Congruency,  $F(1, 132) = 197.81, p < .001, \eta_p^2 = 0.60$  (see Fig. 4B). The interaction between Previous Congruency and Current Congruency also reached significance,  $F(1, 132) = 4.08, p = .045, \eta_p^2 = 0.03$ . Follow-up tests revealed that initiation times were significantly faster on cC relative to iC trials,  $F(1, 134) = 68.20, p < .001, \eta_p^2 = 0.34$ , and on ci relative to il trials,  $F(1, 134) = 22.46, p < .001, \eta_p^2 = 0.14$ . However, the effect of Previous Congruency was significantly larger on congruent than incongruent trials,  $F(1, 134) = 4.83, p = .030, \eta_p^2 = 0.03$ .

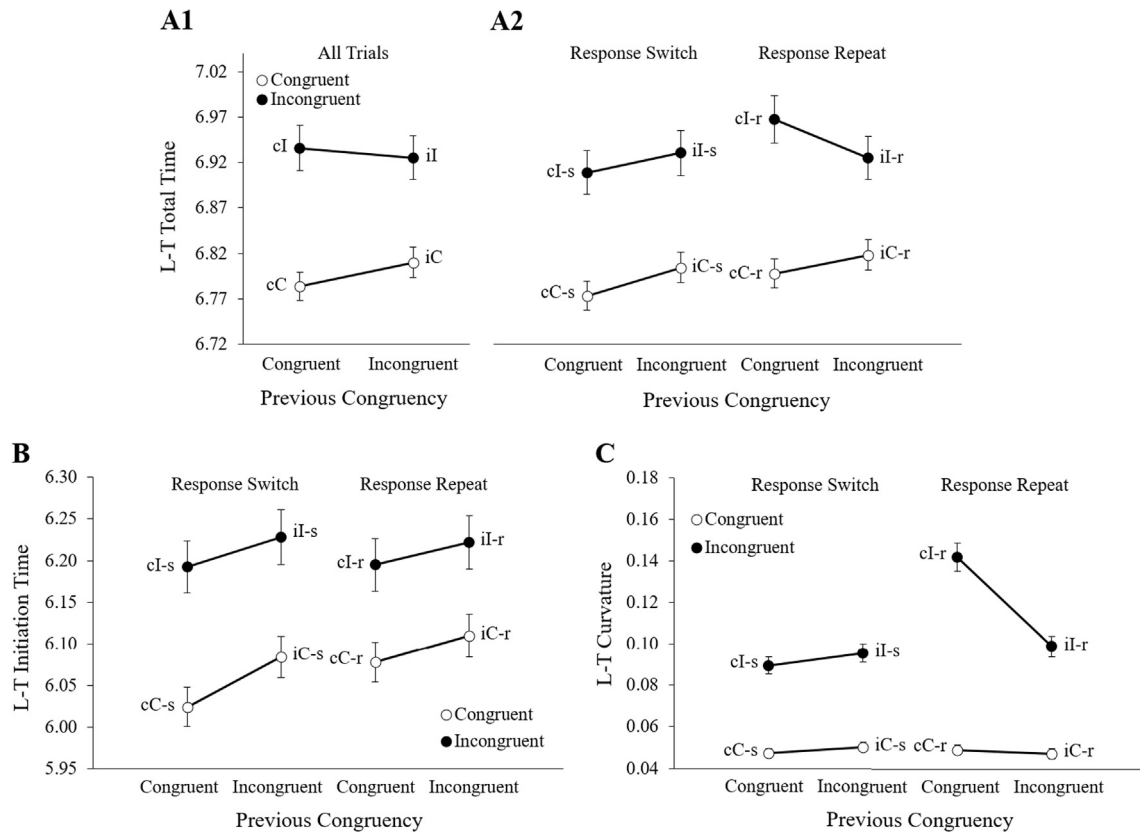
Initiation times also revealed a significant main effect of Response Type,  $F(1, 132) = 22.57, p < .001, \eta_p^2 = 0.15$ , and a significant interaction between Response Type and Current Congruency,  $F(1, 132) = 22.82, p < .001, \eta_p^2 = 0.15$ . Follow-up tests revealed a significant effect of Response Type on congruent trials,  $F(1, 134) = 49.43, p < .001, \eta_p^2 = 0.27$ , with faster initiation times on C-s relative to C-r trials. No effect of response type was observed on incongruent trials (I-s and I-r trials),  $p = .54$ .

The interaction between Response Type and Previous Congruency was also significant,  $F(1, 132) = 5.60, p = .019, \eta_p^2 = 0.04$ . Follow-up tests revealed a significant effect of Response Type on trials preceded by a congruent trial,  $F(1, 134) = 26.42, p < .001, \eta_p^2 = 0.16$ , with faster initiation times on c-s trials relative to c-r trials. No effect of Response Type was observed on trials preceded by an incongruent trial (i-s and i-r trials),  $p = .12$ .

#### 3.1.3. L-T reach curvature

All main effects and interactions between Previous Congruency, Current Congruency, and Response Type met statistical significance in reach curvatures,  $p$ -values  $< .001, \eta_p^2 > 0.18$  (see Fig. 4C). To account for these interactions, we evaluated the effects of Previous Congruency and Response Type on congruent and incongruent trials separately. Congruent trials revealed no significant effects of Previous Congruency or Response Type,  $p$ -values  $> .08$ . Incongruent trials revealed main effects of Previous Congruency and Response Type, as well as a significant interaction between the two,  $F(1, 134) = 73.61, p < .001, \eta_p^2 = 0.35$ . Follow-up tests revealed a significant effect of Previous Congruency on response repeat trials,  $F(1, 134) = 82.54, p < .001, \eta_p^2 = 0.38$ , with larger curvatures on ci-r than il-r trials. The difference between ci-s and il-s trials did not reach significance,  $F(1, 134) = 3.44, p = .066, \eta_p^2 = 0.03$ .

<sup>2</sup> The primary conclusions of the current study remain unchanged across both sets of analyses.



**Fig. 4.** (A1) Average log-transformed (L-T) total time as a function of Previous Congruency and Current Congruency for all age groups. (A2) Average L-T total time, (B) L-T initiation time, and (C) L-T reach curvature as a function of Previous Congruency, Current Congruency, and Response Type for all age groups. Error bars display standard errors.

**3.1.4. L-T movement time**

All main effects and interactions among Previous Congruency, Current Congruency, and Response Type met statistical significance in movement times,  $p$ -values < .001,  $\eta_p^2 > 0.14$  (see Table 1). To account for these interactions, we evaluated the effects of Previous Congruency and Response Type on congruent and incongruent trials separately. Congruent trials revealed a significant main effect of Previous Congruency,  $F(1, 132) = 6.76, p = .010, \eta_p^2 = 0.05$ , with slower

movement times on iC than cC trials. Incongruent trials revealed main effects of Previous Congruency and Response Type, as well as a significant interaction between the two,  $F(1, 132) = 56.50, p < .001, \eta_p^2 = 0.30$ . Follow-up tests revealed a significant effect of Previous Congruency on response repeat trials,  $F(1, 132) = 71.77, p < .001, \eta_p^2 = 0.35$ , with slower movement times on cI-r than iI-r trials. The difference between cI-s and iI-s trials did not approach significance,  $F(1, 132) = 0.29, p = .59$ .

**Table 1**

Average performance on each measure as a function of trial type and age. Standard deviations shown in parentheses.

| Age Group            |                      | cC-s          | iC-s          | cI-s          | iI-s          | cC-r          | iC-r          | cI-r          | iI-r          |
|----------------------|----------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| L-T Total Times      | 6–8                  | 6.948 (0.144) | 7.003 (0.150) | 7.209 (0.250) | 7.235 (0.266) | 6.981 (0.142) | 7.015 (0.157) | 7.296 (0.265) | 7.222 (0.230) |
|                      | 10–12                | 6.721 (0.138) | 6.741 (0.133) | 6.800 (0.135) | 6.823 (0.143) | 6.750 (0.122) | 6.763 (0.132) | 6.870 (0.150) | 6.829 (0.134) |
|                      | 18+                  | 6.650 (0.097) | 6.667 (0.103) | 6.713 (0.113) | 6.729 (0.114) | 6.660 (0.102) | 6.674 (0.102) | 6.731 (0.110) | 6.721 (0.108) |
|                      | All Ages             | 6.773 (0.180) | 6.804 (0.194) | 6.907 (0.279) | 6.929 (0.288) | 6.797 (0.183) | 6.818 (0.195) | 6.966 (0.304) | 6.924 (0.271) |
|                      | L-T Initiation Times | 6–8           | 6.293 (0.217) | 6.393 (0.214) | 6.564 (0.324) | 6.625 (0.329) | 6.359 (0.223) | 6.409 (0.237) | 6.562 (0.315) |
| 10–12                | 5.957 (0.205)        | 6.003 (0.183) | 6.079 (0.199) | 6.098 (0.226) | 6.021 (0.182) | 6.045 (0.197) | 6.087 (0.234) | 6.099 (0.199) |               |
| 18+                  | 5.822 (0.145)        | 5.857 (0.149) | 5.935 (0.184) | 5.963 (0.188) | 5.855 (0.146) | 5.876 (0.151) | 5.935 (0.200) | 5.954 (0.180) |               |
| All Ages             | 6.024 (0.275)        | 6.084 (0.292) | 6.193 (0.363) | 6.228 (0.382) | 6.078 (0.281) | 6.110 (0.297) | 6.195 (0.368) | 6.222 (0.373) |               |
| L-T Reach Curvatures | 6–8                  | 0.060 (0.029) | 0.063 (0.030) | 0.118 (0.050) | 0.124 (0.061) | 0.065 (0.028) | 0.060 (0.032) | 0.189 (0.082) | 0.123 (0.066) |
|                      | 10–12                | 0.050 (0.020) | 0.055 (0.017) | 0.090 (0.036) | 0.096 (0.036) | 0.054 (0.023) | 0.052 (0.022) | 0.148 (0.065) | 0.111 (0.042) |
|                      | 18+                  | 0.032 (0.022) | 0.032 (0.023) | 0.060 (0.038) | 0.066 (0.037) | 0.029 (0.019) | 0.030 (0.025) | 0.088 (0.047) | 0.063 (0.035) |
|                      | All Ages             | 0.047 (0.026) | 0.050 (0.027) | 0.090 (0.048) | 0.096 (0.052) | 0.049 (0.028) | 0.047 (0.029) | 0.142 (0.078) | 0.099 (0.056) |
|                      | L-T Movement Times   | 6–8           | 6.174 (0.106) | 6.185 (0.114) | 6.358 (0.199) | 6.346 (0.216) | 6.166 (0.094) | 6.187 (0.109) | 6.499 (0.257) |
| 10–12                |                      | 6.068 (0.122) | 6.070 (0.122) | 6.102 (0.124) | 6.121 (0.120) | 6.071 (0.110) | 6.073 (0.114) | 6.207 (0.127) | 6.137 (0.119) |
| 18+                  |                      | 6.064 (0.119) | 6.068 (0.124) | 6.079 (0.123) | 6.085 (0.125) | 6.056 (0.123) | 6.062 (0.122) | 6.105 (0.123) | 6.078 (0.121) |
| All Ages             |                      | 6.102 (0.126) | 6.108 (0.131) | 6.180 (0.198) | 6.184 (0.197) | 6.098 (0.119) | 6.107 (0.127) | 6.270 (0.245) | 6.181 (0.174) |
| Error Rates (%)      |                      | 6–8           | 0.2 (1.0)     | 0.2 (1.1)     | 1.3 (3.0)     | 3.2 (5.1)     | 0.3 (1.3)     | 0.0 (0.0)     | 6.1 (8.4)     |
|                      | 10–12                | 0.1 (0.8)     | 0.2 (1.2)     | 0.3 (1.4)     | 0.7 (2.0)     | 0.2 (1.4)     | 0.0 (0.0)     | 1.1 (3.3)     | 0.6 (2.9)     |
|                      | 18+                  | 0.0 (0.0)     | 0.0 (0.0)     | 0.3 (1.4)     | 0.7 (2.4)     | 0.0 (0.0)     | 0.0 (0.0)     | 0.4 (1.9)     | 0.0 (0.0)     |
|                      | All Ages             | 0.1 (0.7)     | 0.1 (0.9)     | 0.6 (2.1)     | 1.5 (3.6)     | 0.2 (1.1)     | 0.0 (0.0)     | 2.5 (5.9)     | 0.7 (2.9)     |

### 3.1.5. Error rate

Error rates revealed a number of significant main effects and interaction effects between Previous Congruency, Current Congruency, and Response Type, including the three-way interaction between the factors,  $F(1, 132) = 18.84, p < .001, \eta_p^2 = 0.12$  (see Table 1). To account for these interactions, we evaluated the effects of Previous Congruency and Response Type on congruent and incongruent trials separately. Congruent trials revealed no significant effects of Previous Congruency or Response Type,  $p$ -values  $> .16$ . Incongruent trials revealed a main effect of Response Type,  $F(1, 132) = 4.17, p = .043, \eta_p^2 = 0.03$ , and a significant interaction between Previous Congruency and Response Type,  $F(1, 132) = 20.72, p < .001, \eta_p^2 = 0.14$ . Follow-up tests revealed a significant effect of Previous Congruency on response switch trials,  $F(1, 132) = 10.02, p = .002, \eta_p^2 = 0.07$ , with higher error rates on *il*-s than *cl*-s trials. Response change trials also revealed a significant effect of Previous Congruency,  $F(1, 132) = 14.33, p < .001, \eta_p^2 = 0.10$ , with higher error rates on *cl*-r than *il*-r trials.

## 3.2. Section 1: Discussion

Total times in the current study revealed the same pattern of effects observed in response times by Gratton et al. (1992), with a main effect of current congruency and an interaction between previous and current congruency ( $cC < iC < il < cI$ ) (see Fig. 4A1). Consistent with previous research investigating the effect of response type in 2AFC versions of the flanker task (Mayr et al., 2003; Nieuwenhuis et al., 2006), total times revealed the Gratton effect in response repeat trials ( $cC-r < iC-r < il-r < cI-r$ ) but not in response switch trials ( $cC-s < iC-s < cl-s < il-s$ ) (see Fig. 4A2). These results establish that the reach-tracking task used in the current study generates comparable findings to the 2AFC button-press tasks featured in previous research.

As predicted, initiation times and reach curvatures revealed distinct patterns of TSEs that combined to produce the pattern of effects observed in total times. Consistent with the claim that initiation times reflect the threshold adjustment process, we observed main effects of previous and current trial congruency ( $cC < iC < cI < iI$ ), indicating that conflict on incongruent trials resulted in elevated response thresholds that carried over into the subsequent trial. Crucially, this pattern of effects was observed in both response switch and response repeat trials (see Fig. 4B).

In contrast to the TSEs observed in initiation times, reach curvatures were low on congruent trials, elevated on incongruent trials not featuring S-R binding conflict (*iC*-s, *il*-s, and *il*-r trials), and largest on incongruent trials featuring S-R binding conflict (*cl*-r trials) (see Fig. 4C). These results are consistent with the claim that reach curvature can be used to target the functioning of the controlled selection process. On this view, S-R binding conflict on *cl*-r trials impedes the ability of the controlled selection process to marshal top-down support in favor of the appropriate response. This prolongs the impact of the distractor stimuli, resulting in reach movements that are more curved toward the incorrect response. Although the feature integration account proposes that S-R binding conflict also occurs on *iC*-r trials in the version of the flanker task used in the current study, both the target and distractors cue the correct response on *iC*-r trials. Consequently, reach movements on these trials are biased toward the correct response location and are not impaired by S-R binding conflict.

It is important to note that, in addition to the current study and that of Erb et al. (2016), a number of previous studies have investigated TSEs in congruency tasks using hand-tracking techniques. For example, Scorolli, Pellicano, Nicoletti, Rubichi, and Castiello (2015) measured hand movements in a reaching version of the Simon task. However, participants were unable to change their response after a movement was initiated. Consequently, initiation times likely reflected a combination of both the threshold adjustment process and the controlled selection process, given that participants needed to ensure that the correct response was selected before initiating a movement. Similarly,

Scherbaum, Dshemuchadse, Fischer, and Goschke (2010) reported TSEs from a mouse-tracking version of the Simon task. However, participants were required to initiate a movement before the imperative stimulus was presented, which precluded the measurement of initiation times. Thus, the tasks used in these did not enable the researchers to capture different patterns of TSEs in initiation times and movement trajectories. Other studies have investigated performance on congruency tasks using hand-tracking techniques but did not report TSEs (e.g., Buetti & Kerzel, 2009; Incerca & McLennan, 2017; Rubichi, Nicoletti, Umiltà, & Zorzi, 2000).

Next, we turn to the results pertaining to the effects of age group. In general, responding can be expected to improve across development; for example, average total times should decrease between childhood and adulthood. The question of particular interest to the current study concerns the extent to which the threshold adjustment and controlled selection processes contribute to age-related reductions in the size of the congruency effect. If these processes follow different developmental trajectories, as suggested by Erb et al. (2018), then the congruency effects observed in initiation times and reach curvatures should decrease at different rates.

## 3.3. Section 2: Results

### 3.3.1. L-T total time

Average total times decreased with age,  $F(2, 132) = 106.57, p < .001, \eta_p^2 = 0.62$ . Post-hoc comparisons revealed significantly slower total times in children relative to pre-adolescents,  $p < .001$ , in children relative to adults,  $p < .001$ , and in pre-adolescents relative to adults,  $p = .007$ . The interaction between Age Group and Current Congruency was also significant,  $F(2, 132) = 51.01, p < .001, \eta_p^2 = 0.44$ . Post-hoc comparisons revealed a significantly larger congruency effect (computed by subtracting each participant's average performance on congruent trials from their average performance on incongruent trials;  $I - C$ ) in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ , but not in pre-adolescents relative to adults,  $p = .70$  (see Fig. 5A).

Total times revealed a number of significant interactions among Age Group, Previous Congruency, Current Congruency, and Response Type, including a four-way interaction among the factors,  $F(2, 132) = 3.22, p = .043, \eta_p^2 = 0.05$ . To account for these interactions, we analyzed the effects of Age Group, Previous Congruency, and Current Congruency on response switch and response change trials separately. Response switch trials revealed a significant interaction between Age Group and Current Congruency,  $F(2, 132) = 41.48, p < .001, \eta_p^2 = 0.39$ . Post-hoc tests revealed a significantly larger congruency effect ( $I - C$ ) in response switch trials in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ . Response switch trials also revealed a significant interaction between Age Group and Previous Congruency,  $F(2, 132) = 3.17, p = .045, \eta_p^2 = 0.05$ . However, post-hoc tests did not reveal any significant differences in the effect of Previous Congruency ( $i - c$ ) on response switch trials among the age groups,  $p$ -values  $> .54$ .

Total times on response repeat trials revealed a significant interaction among Age Group, Previous Congruency, and Current Congruency,  $F(2, 132) = 11.97, p < .001, \eta_p^2 = 0.15$ . To account for this interaction, we evaluated the effects of Current Congruency and Age Group on response repeat trials preceded by a congruent trial separately from response repeat trials preceded by an incongruent trial. Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by a congruent trial (*cl*-r – *cC*-r) was significantly larger in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ , but not in pre-adolescents relative to adults,  $p = .21$ . Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by an incongruent trial (*il*-r – *iC*-r) was significantly larger in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ , but not in pre-adolescents relative to adults,  $p = .92$ .



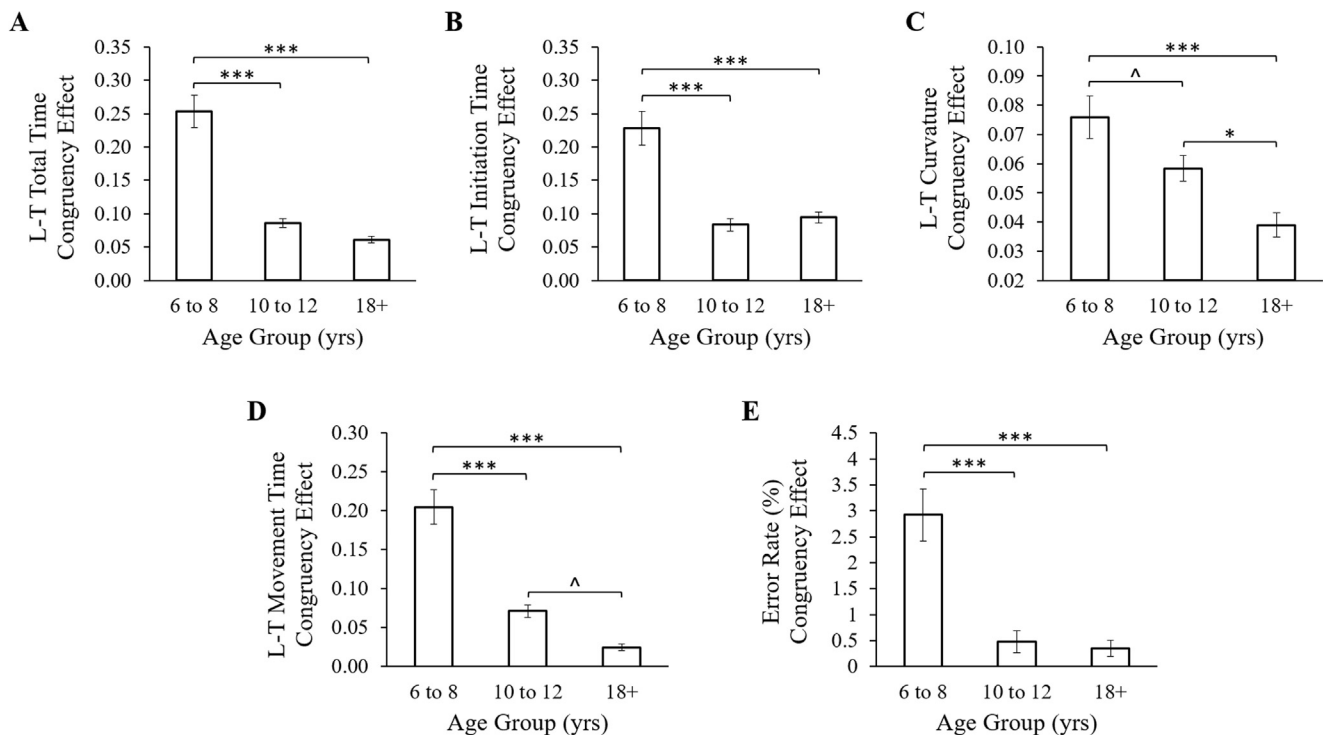


Fig. 5. Average congruency effect (I - C) for (A) log-transformed (L-T) total times, (B) L-T initiation times, (C) L-T curvatures, (D) L-T movement times, and (E) error rates as a function of age group. Error bars display standard errors.  $p < .10$ ,  $* p < .05$ ,  $** p < .01$ , and  $*** p < .001$ .

### 3.3.2. L-T initiation time

Average initiation times decreased with age,  $F(2, 132) = 95.26$ ,  $p < .001$ ,  $\eta_p^2 = 0.59$ . Post-hoc comparisons revealed significantly slower initiation times in children relative to pre-adolescents,  $p < .001$ , and in pre-adolescents relative to adults,  $p = .002$ . The interaction between Age Group and Current Congruency was significant,  $F(2, 132) = 22.96$ ,  $p < .001$ ,  $\eta_p^2 = 0.26$ . Post-hoc comparisons revealed a significantly larger congruency effect (I - C) in children relative to pre-adolescents and adults,  $p$ -values  $< .001$  (see Fig. 5B). The interaction between Age Group and Previous Congruency was also significant,  $F(2, 132) = 7.37$ ,  $p < .001$ ,  $\eta_p^2 = 0.10$ . Post-hoc comparisons did not reveal significant differences in the effect of Previous Congruency (i - c) between any of the age groups,  $p$ -values  $> .08$ .

### 3.3.3. L-T reach curvature

Average reach curvatures decreased with age,  $F(2, 132) = 38.73$ ,  $p < .001$ ,  $\eta_p^2 = 0.37$ . Post-hoc comparisons revealed significantly larger reach curvatures in children relative to pre-adolescents,  $p = .006$ , and in pre-adolescents relative to adults,  $p < .001$ . The interaction between Age Group and Current Congruency was also significant,  $F(2, 132) = 12.58$ ,  $p < .001$ ,  $\eta_p^2 = 0.16$  (see Fig. 5C). Post-hoc comparisons revealed a significantly larger congruency effect (I - C) in children relative to adults,  $p < .001$ , and in pre-adolescents relative to adults,  $p = .038$ . The congruency effect observed in children was not significantly larger than that observed in pre-adolescents,  $p = .072$ .

The interaction among Previous Congruency, Current Congruency, and Age Group reached significance,  $F(2, 132) = 3.53$ ,  $p = .032$ ,  $\eta_p^2 = 0.05$ . Follow-up tests revealed a significant interaction between Current Congruency and Age Group on trials preceded by a congruent trial,  $F(2, 132) = 14.01$ ,  $p < .001$ ,  $\eta_p^2 = 0.18$ , as well as trials preceded by an incongruent trial,  $F(2, 132) = 5.42$ ,  $p = .005$ ,  $\eta_p^2 = 0.08$ . Post-hoc tests on trials preceded by a congruent trial revealed a significantly larger congruency effect (cI - cC) in children relative to pre-adolescents,  $p = .023$ , in children relative to adults,  $p < .001$ , and in pre-adolescents and adults,  $p = .033$  (see Fig. 6A). Post-hoc tests on trials

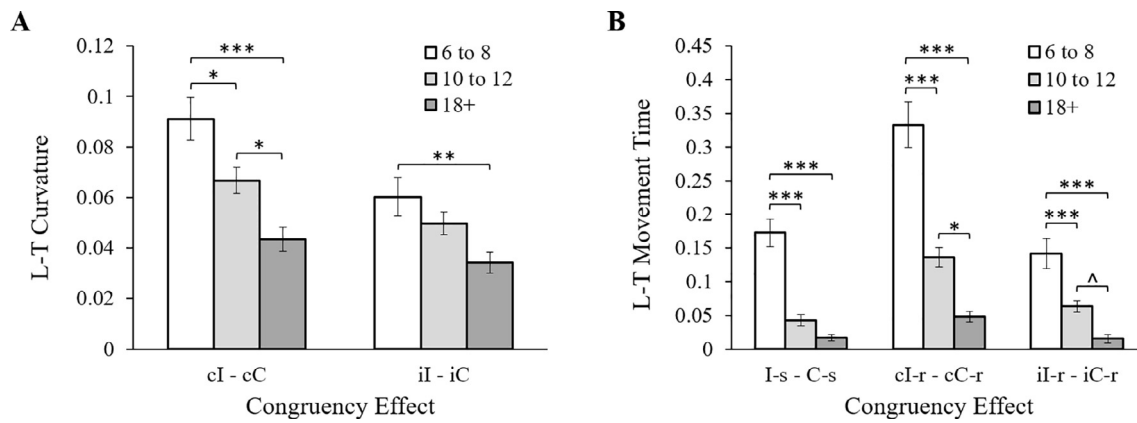
preceded by an incongruent trial (iI and iC trials) revealed a significantly larger congruency effect (iI - iC) in children relative to adults,  $p = .004$ , but no other differences among the age groups,  $p$ -values  $> .16$ .

The interaction among Current Congruency, Response Type, and Age Group reached significance,  $F(2, 132) = 3.67$ ,  $p = .028$ ,  $\eta_p^2 = 0.05$ . Follow-up tests revealed significant interactions between Current Congruency and Age Group on response switch trials,  $F(2, 132) = 8.14$ ,  $p < .001$ ,  $\eta_p^2 = 0.11$ , and on response repeat trials,  $F(2, 132) = 11.89$ ,  $p < .001$ ,  $\eta_p^2 = 0.15$ . Post-hoc tests on response switch trials revealed a significantly larger congruency effect (I-s - C-s) in children relative to pre-adolescents,  $p = .028$ , and in children relative to adults,  $p = .001$ , but no difference between pre-adolescents and adults,  $p = .56$ . Post-hoc tests on response repeat trials revealed a significantly larger congruency effect (I-r - C-r) in children relative to adults,  $p < .001$ , and in pre-adolescents relative to adults,  $p = .007$ , but no difference between children and pre-adolescents,  $p = .26$ .

The interaction among Previous Congruency, Response Type, and Age Group also reached significance,  $F(2, 132) = 5.23$ ,  $p = .007$ ,  $\eta_p^2 = 0.07$ . Follow-up tests revealed a significant interaction between Previous Congruency and Age Group on response repeat trials,  $F(2, 132) = 6.57$ ,  $p = .002$ ,  $\eta_p^2 = 0.09$ , with larger curvatures on trials preceded by a congruent relative to an incongruent trial. Post-hoc tests on response repeat trials revealed a significantly larger effect of previous congruency in children relative to adults,  $p = .002$ , but not in children relative to pre-adolescents,  $p = .053$ , or in pre-adolescents relative to adults,  $p = .76$ . Follow-up tests on response switch trials did not reveal a significant interaction between Previous Congruency and Age Group,  $F(2, 132) = 0.12$ ,  $p = .88$ .

### 3.3.4. L-T movement time

Average movement times decreased with age,  $F(2, 132) = 37.61$ ,  $p < .001$ ,  $\eta_p^2 = 0.36$ . Post-hoc comparisons revealed significantly slower movement times in children relative to pre-adolescents,  $p < .001$ , and in children relative to adults,  $p < .001$ . The interaction between Age Group and Current Congruency was also significant,  $F(2,$



**Fig. 6.** (A) Average congruency effect observed in log-transformed (L-T) reach curvatures on trials preceded by a congruent trial (cI - cC) and trials preceded by an incongruent trial (iI - iC) as a function of age group. (B) Average congruency effect observed in L-T movement times on response switch trials (I-s - C-s), response repeat trials preceded by a congruent trial (cI-r - cC-r), and response repeat trials preceded by an incongruent trial (iI-r - iC-r) as a function of age group. Error bars display standard errors.  $\hat{p} < .10$ ,  $\hat{p} < .05$ ,  $\hat{p} < .01$ , and  $\hat{p} < .001$ .

132) = 48.17,  $p < .001$ ,  $\eta_p^2 = 0.42$  (see Fig. 5D). Post-hoc comparisons revealed a significantly larger congruency effect (I - C) in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ , but not in pre-adolescents relative to adults,  $p = .059$ .

Movement times revealed a number of significant interactions among Age Group, Previous Congruency, Current Congruency, and Response Type, including a four-way interaction among the factors,  $F(2, 132) = 9.61$ ,  $p < .001$ ,  $\eta_p^2 = 0.13$ . To account for these interactions, we analyzed the effects of Age Group, Previous Congruency, and Current Congruency on response switch and response change trials separately. Response switch trials revealed a significant interaction between Age Group and Current Congruency,  $F(2, 132) = 40.05$ ,  $p < .001$ ,  $\eta_p^2 = 0.38$ . Post-hoc tests revealed a significantly larger congruency effect (I-s - C-s) in movement times on response switch trials in children relative to pre-adolescents and adults,  $p$ -values  $< .001$  (see Fig. 6B).

Response repeat trials revealed a significant interaction among Age Group, Previous Congruency, and Current Congruency,  $F(2, 132) = 18.52$ ,  $p < .001$ ,  $\eta_p^2 = 0.22$ . To account for this interaction, we evaluated the effects of Current Congruency and Age Group on response repeat trials preceded by a congruent trial separately from response repeat trials preceded by an incongruent trial. Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by a congruent trial (cI-r - cC-r) was significantly larger in children relative to pre-adolescents,  $p < .001$ , in children relative to adults,  $p < .001$ , and in pre-adolescents relative to adults,  $p = .015$  (see Fig. 6B). Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by an incongruent trial (iI-r - iC-r) was significantly larger in children relative to pre-adolescents,  $p < .001$ , and in children relative to adults,  $p < .001$ , but not in pre-adolescents relative to adults,  $p = .057$ .

### 3.3.5. Error rate

Average error rates decreased with age,  $F(2, 132) = 17.27$ ,  $p < .001$ ,  $\eta_p^2 = 0.21$ . Post-hoc comparisons revealed significantly larger error rates in children relative to pre-adolescents and adults,  $p$ -values  $< .001$ . The interaction between Age Group and Current Congruency was also significant,  $F(2, 132) = 17.36$ ,  $p < .001$ ,  $\eta_p^2 = 0.21$ . Post-hoc comparisons revealed a significantly larger congruency effect (I - C) in children relative to pre-adolescents and adults,  $p$ -values  $< .001$  (see Fig. 5E).

Error rates revealed a number of significant interactions among Age Group, Previous Congruency, Current Congruency, and Response Type, including a four-way interaction among the factors,  $F(2, 132) = 9.50$ ,  $p < .001$ ,  $\eta_p^2 = 0.13$ . To account for these interactions, we analyzed

the effects of Age Group, Previous Congruency, and Current Congruency on response switch and response change trials separately. Response switch trials revealed a significant interaction between Age Group and Current Congruency,  $F(2, 132) = 8.18$ ,  $p < .001$ ,  $\eta_p^2 = 0.11$ . Post-hoc tests revealed a significantly larger congruency effect (I-s - C-s) in error rates on response switch trials in children relative to pre-adolescents and adults,  $p$ -values  $< .01$ .

Response repeat trials revealed a significant interaction among Age Group, Previous Congruency, and Current Congruency,  $F(2, 132) = 7.40$ ,  $p < .001$ ,  $\eta_p^2 = 0.10$ . To account for this interaction, we evaluated the effects of Current Congruency and Age Group on response repeat trials preceded by a congruent trial separately from response repeat trials preceded by an incongruent trial. Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by a congruent trial (cI-r - cC-r) was significantly larger in children relative to pre-adolescents,  $p < .001$ , and in children relative to adults,  $p < .001$ . Post-hoc tests revealed that the congruency effect observed on response repeat trials preceded by an incongruent trial (iI-r - iC-r) was significantly larger in children relative to adults,  $p = .018$ , but no other differences among the age groups were observed,  $p$ -values  $> .20$ .

## 3.4. Section 2: Discussion

Age-related gains in cognitive control were observed in each of the collected measures. However, the timing of these gains differed between the measures. Initiation times revealed improvements between childhood and pre-adolescence, but not between pre-adolescence and adulthood (see Fig. 5B). This observation provides convergent support for the claim that the threshold adjustment process reaches adult-like levels by pre-adolescence, at least in the context of the flanker task (Erb et al., 2018). In contrast to the previous study by Erb and colleagues, each of the age groups tested in the current study received the same task and stimuli. Consequently, the age-related gains observed in initiation times in the current study cannot be attributed to task differences.

Reach curvatures revealed age-related gains in cognitive control between childhood and pre-adolescence, and between pre-adolescence and adulthood (see Fig. 6A), indicating that the controlled selection process undergoes a more protracted development than the threshold adjustment process. Similarly, the four-way interaction among Age Group, Previous Congruency, Current Congruency, and Response Type observed in movement times revealed significant age-related gains between childhood and pre-adolescence, as well as between pre-adolescence and adulthood (see Fig. 6B). Follow-up tests demonstrated that these gains were driven by cI-r trials, suggesting that adults were better

able to manage S-R binding conflict than pre-adolescents, consistent with the findings of [Hommel et al. \(2011\)](#). Taken together, these curvature and movement time results suggest that the age-related gains in flanker task performance observed in previous research (e.g., [Li, Hämmerer, Müller, Hommel, & Lindenberger, 2009](#); [Waszak, Li, & Hommel, 2010](#)) were driven by improvements in the functioning of the controlled selection process.

#### 4. General discussion

In the quarter-century since the Gratton effect was first reported, a large body of research has sought to identify the cognitive and neural underpinnings of the effect (e.g., [Duthoo et al., 2014](#); [Egner, 2007, 2017](#); [Kerns et al., 2004](#); [Mayr et al., 2003](#); [Schmidt & De Houwer, 2011](#); [Ullsperger et al., 2005](#)). The results of the current study indicate that the Gratton effect originally observed in the flanker task is not a singular effect but the result of two separate trial sequence effects that impact dissociable processes underlying cognitive control. Initiation times and curvatures revealed distinct TSEs, consistent with the claim that these measures reflect a threshold adjustment process and a controlled selection process, respectively ([Erb & Marcovitch, in press](#); [Erb et al., 2016](#); [Erb, Moher, Song, & Sobel, 2017, 2018](#)). When combined, these TSEs generate the same pattern of effects originally observed by [Gratton et al. \(1992\)](#), as well as the patterns observed in more recent studies comparing response repeat and response switch trials ([Mayr et al., 2003](#); [Nieuwenhuis et al., 2006](#)). Although previous studies have hinted at the possibility that the effects observed by Gratton and colleagues resulted from the combination of two separate TSEs ([Erb et al., 2018](#); [Erb et al., 2016](#)), the current study presents the most rigorous and compelling empirical support for this claim to date.

The results of the current study present fundamental implications for the literature on TSEs. At a theoretical level, our results present a challenge to accounts of TSEs that fail to consider how dissociable processes underlying cognitive control may be differentially impacted by recent experience. For example, both the conflict adaptation account and the feature integration account explain TSEs by appealing to a single process or mechanism: the former appeals to conflict-driven modulations of top-down control, whereas the latter appeals to the degree to which the stimulus and response features of the current trial overlap with those of the previous trial. Crucially, neither of these accounts offers a unified explanation of the pattern of effects observed in initiation times in the current study. For instance, although the feature integration account presents a compelling explanation of why reach curvatures are elevated on cI-r relative to iI-r trials, the account fails to explain why initiation times are slower on iI-r relative to cI-r trials.

Relatedly, at a methodological level, our findings highlight the difficulties associated with interpreting the TSEs observed in response times. Button-press measures of response time provide limited insight into how the processes underlying cognitive control unfold over time. As our findings demonstrate, this can be particularly problematic when these processes are differentially impacted by qualities of the previous trial. Hand-tracking techniques such as reach tracking and mouse tracking present a more detailed view of how the processes underlying decision behavior unfold over the course of an individual trial (i.e., within-trial dynamics), as well as how these processes are impacted by qualities of the previous trial (i.e., cross-trial dynamics) ([Erb & Marcovitch, in press](#)). Thus, our findings underscore the importance of incorporating hand-tracking techniques into future studies investigating TSEs.

At an empirical level, our results raise fundamental questions concerning the extent to which the TSEs reported in previous studies were misinterpreted to reflect conflict adaptation or feature integration instead of the threshold adjustment process. For example, [Ullsperger et al. \(2005, Experiment 2\)](#) presented participants with a modified version of the flanker task that enabled the researchers to control for feature integration effects by excluding from analysis all trials that featured a

stimulus element from the previous trial. The researchers observed a significant Gratton effect in participants' response times and, given that feature integration effects were controlled for, interpreted their findings as evidence of conflict adaptation. However, the Gratton effect that they observed was largely driven by slower response times on iC relative to cC trials. The results of the current study indicate that this difference was at least partially driven by the threshold adjustment process. Consequently, one of the findings frequently cited as evidence of conflict adaptation in the flanker task may have been misinterpreted. Future research should therefore explore how the threshold adjustment process and conflict resolution process function under the many different conditions that have been constructed to investigate TSEs in congruency tasks (for a recent review, see [Egner, 2017](#)).

##### 4.1. Developmental findings

In contrast to the considerable amount of research on the Gratton effect in the literature on adult cognition, comparatively little research has investigated the effect in children and adolescents in the context of the flanker task (e.g., [Ambrosi, Lemaire, & Blaye, 2016](#); [Cragg, 2016](#); [Erb et al., 2018](#); [Nieuwenhuis et al., 2006](#); [Stins, Polderman, Boomsma, & de Geus, 2007](#); [Takarae, Schmidt, Tassone, & Simon, 2009](#)). This gap in the literature is particularly striking given that developmental and individual differences in cognitive control are often assessed with versions of the flanker task that are known to generate the Gratton effect in adults (e.g., NIH Toolbox: Cognition Battery; see [Zelazo et al., 2013](#)), raising questions concerning the extent to which the effect contributes to developmental and individual differences in performance.

The results of the present investigation indicate that the processes underlying the Gratton effect in adults are present and functioning in a similar manner by early childhood, with children's initiation times and reach curvatures presenting the same overall pattern of effects observed in adults. A number of age-related differences were observed, however. Initiation times revealed age-related reductions in the size of the congruency effect between childhood and pre-adolescence (see [Fig. 5B](#)), whereas reach curvatures and movement times revealed age-related reductions between each of the age groups tested (see [Fig. 6](#)). These findings indicate that the controlled selection process undergoes a more protracted development than the threshold adjustment process. Crucially, the developmental trajectories observed in the current study cannot be attributed to differences in the task presented to each age group, as was the case in previous research ([Erb et al., 2018](#)).

What might be driving the gains in cognitive control observed in reach curvatures and movement times between pre-adolescence and adulthood? Although these gains may reflect general improvements in cognitive control (e.g., in the degree of top-down resources that can be marshaled in favor of the control-demanding pathway), it is unclear why these improvements would be specific to particular trial types (e.g., cI-r trials in the case of movement times). One explanation discussed by [Erb et al. \(2018\)](#) draws on the feature integration account of the Gratton effect ([Hommel et al., 2004](#); [Hommel, 2004](#)). On this view, the age-related gains observed in reach curvatures between pre-adolescence and adulthood reflect improvements in the capacity to efficiently and flexibly bind and unbind stimuli and responses. As noted by [Hommel et al. \(2011\)](#), age-related gains in this capacity may reflect changes in dopaminergic modulation (citing [Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006](#); [Schmiedek, Li, & Lindenberger, 2009](#)). However, further research is necessary to identify the extent to which the behavioral gains in cognitive control observed in the current study can be linked to such changes.

Developmental and individual differences in cognitive control have been linked to a wide range of outcomes, including math and reading ability in childhood ([Blair & Razza, 2007](#); [Fuhs & McNeil, 2013](#)) and levels of mental and physical health in adulthood (for a review, see [Diamond, 2013](#)). The results of the current study, along with those of [Erb et al. \(2018\)](#), raise important questions concerning how the

threshold adjustment process and controlled selection process contribute to these outcomes. For example, a meta-analysis by Mullane, Corkum, Klein, and McLaughlin (2009) found that children with attention deficit/hyperactivity (ADHD) generated larger congruency effects in the flanker and Simon tasks than children without ADHD (cf. Schwartz & Verhaeghen, 2008). However, it is currently unclear the extent to which the threshold adjustment process and controlled selection process contribute to this difference. Similarly, it is unclear whether this difference is driven by particular trial types, such as those featuring S-R binding conflict. Consequently, future research should explore how the behavioral dynamics observed in the current study differ between individuals with and without conditions that have been linked to impairments in cognitive control.

#### 4.2. Limitations

It is important to note that the 2AFC version of the flanker task used in the current study was not designed to control for a range of associative priming effects that have been demonstrated to influence performance in previous studies (for a review, see Henson, Eckstein, Waszak, Frings, & Horner, 2014). For example, distractor repetition effects were confounded with response type in the current study, such that response switch trials featured a distractor switch when congruency repeated (e.g.,  $\leftarrow\leftarrow\leftarrow\leftarrow$  followed by  $\rightarrow\leftarrow\rightarrow\rightarrow$ ), whereas response repeat trials featured a distractor switch when congruency switched (e.g.,  $\leftarrow\leftarrow\leftarrow\leftarrow$  followed by  $\rightarrow\rightarrow\leftarrow\rightarrow$ ). The effects attributed to response type in the current study can therefore be interpreted in subtly different ways. However, these subtly different interpretations do not substantially alter the primary conclusions presented above, including the claim that the Gratton effect originally observed in response times in the flanker task results from the combination of two distinct patterns of effects.

Furthermore, it would have been inappropriate to use a confound-minimized version of the task to address the questions of interest in the current study for two reasons. First, the task needed to be comparable to the version originally used by Gratton et al. (1992), as well as the versions used in subsequent research investigating the role of response repetitions and alternations (e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). Second, as mentioned above, the task used in the current study is commonly used to assess developmental and individual differences in cognitive control (NIH Toolbox: Cognition Battery; see Zelazo et al., 2013). It is therefore important to understand how the various TSEs observed in the task contribute to age-related differences in performance.

Nevertheless, future research should use confound-minimized tasks (e.g., Aschenbrenner & Balota, 2017; Weissman, Jiang, & Egner, 2014) to investigate the extent to which different aspects of reaching behavior are impacted by associative priming effects. If the pattern of effects observed in initiation times in the current study does indeed reflect the threshold adjustment process, then initiation times in confound-minimized congruency tasks should also present main effects of previous and current trial congruency. If the conflict adaptation account is correct, reach curvatures in confound-minimized tasks should present the Gratton effect. If the feature integration account is correct, reach curvatures can be expected to reveal a main effect of current congruency alone.

#### 4.3. Conclusion

Despite being one of the most well studied tasks in cognitive psychology, a unified account of response times in the flanker task has remained elusive, with recent investigations focusing on the conditions under which the Gratton effect is observed (for reviews, see Duthoo et al., 2014; Egner, 2007, 2017; Schmidt & De Houwer, 2011). The results of the current study present a framework for moving beyond general questions concerning the presence or absence of the Gratton

effect to target how specific processes underlying cognitive control function across different tasks and conditions. Reach tracking is a particularly effective technique in this regard as it enables researchers to target effects that may otherwise be obscured in overall response times (e.g., Song & Nakayama, 2009).

The present investigation focused on how the threshold adjustment and controlled selection processes function in the context of a task designed to assess attention and cognitive control. However, these processes can be expected to underlie performance on a wide range of tasks that require managing the co-activation of competing responses. Although techniques such as reach tracking and mouse tracking are commonly used to investigate aspects of language processing, memory, numerical cognition, and decision-making (for reviews, see Erb, 2018; Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009), it is currently unclear how the threshold adjustment and controlled selection processes function to support these capacities. Future research should therefore explore how these processes function across a broader range of cognitive tasks by combining hand-tracking measures with a focus on the cross-trial dynamics of performance.

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#### Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.cognition.2018.06.007>.

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