

Tracking the Dynamics of Global and Competitive Inhibition in Early and Late Adulthood: Evidence From the Flanker Task

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Inhibitory control is proposed to involve 2 dissociable processes that feature distinct types of inhibition: a threshold adjustment process involving the global inhibition of motor output and a controlled selection process involving competitive inhibition among coactive responses. Recent research with children and young adults indicates that the functioning of these processes can be targeted by measuring participants' hand movements as they perform inhibitory control tasks by reaching to touch response options on a digital display. The current study explores (a) whether this method can be used to target the functioning of the threshold adjustment process and controlled selection process in adults 65 to 75 years of age and, if so, (b) whether the functioning of each process changes between early and late adulthood. Results from the Eriksen flanker task indicate that reach tracking can be used to target the functioning of each process in late adulthood, with older adults and young adults generating similar patterns of initiation time and curvature effects. The congruency effect observed in response times was significantly larger in older adults than in young adults, indicating that inhibitory control declines in late adulthood. Importantly, this effect was specific to initiation times, suggesting that the threshold adjustment process functions differently in early adulthood than in late adulthood. These results present a new perspective on how age-related differences in inhibitory control are conceptualized and assessed, and raise important questions concerning how the threshold adjustment and controlled selection processes function across a wider range of tasks in late adulthood.

Keywords: aging, congruency sequence effect, flanker task, inhibitory control


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Inhibitory control refers to an individual's capacity to suppress habitual or prepotent responses selectively. Although the term *inhibition* is often used to refer to a unitary process or capacity, a growing body of evidence suggests that inhibitory control is supported by a number of dissociable processes that involve distinct types of inhibition (Aron, Robbins, & Poldrack, 2014; Munakata et al., 2011; Shenhav, Botvinick, & Cohen, 2013). In the following, we discuss how two of these processes are proposed to function in

the context of one of the most widely used measures of inhibitory control, the Eriksen flanker task (Eriksen & Eriksen, 1974; NIH Toolbox: Cognition Battery, see Zelazo et al., 2013). We then review recent research with children and young adults indicating that a technique known as reach tracking can be used to target how different processes underlying inhibitory control unfold over the course of a response (e.g., Erb & Marcovitch, 2018a; Erb, Moher, Sobel, & Song, 2016). Finally, we test whether these processes can also be targeted in older adults 65 to 75 years of age and, if so, how the functioning of these processes contribute to the age-related differences in inhibitory control observed between early and late adulthood (Aschenbrenner & Balota, 2017; Waszak, Li, & Hommel, 2010; Weintraub et al., 2013; Zelazo et al., 2014).

Inhibition in the Flanker Task

In the flanker task, participants are presented with a stimulus array comprised of a centrally presented target and surrounding distractors. On congruent trials, the target and distractors cue the same response (e.g., < < < < <). On incongruent trials, the target and distractors cue competing responses (e.g., < < > < <) and, consequently, greater demands are placed on inhibitory control. A congruency effect is regularly observed in the task, with slower response times and higher error rates on incongruent trials relative to congruent trials. The size of this effect is commonly used to assess age-related differences in inhibitory control, with

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larger congruency effects interpreted to reflect less effective control.

Research with the flanker task indicates that inhibitory control follows a U-shaped developmental trajectory, with larger congruency effects observed in childhood and late adulthood than in early adulthood (Gamboz, Zamarian, & Cavallero, 2010; Waszak et al., 2010; Weintraub et al., 2013; Zelazo et al., 2014). However, multiple studies have failed to observe age-related differences in the size of the congruency effect between early adulthood and late adulthood (Falkenstein, Hoormann, & Hohnsbein, 2001; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Larson et al., 2016; Posthuma, Mulder, Boomsma, & de Geus, 2002; Nieuwenhuis et al., 2002), with some studies even reporting smaller congruency effects in older adults than in young adults (Fernandez-Duque & Black, 2006; Mathewson, Dywan, & Segalowitz, 2005). Consequently, it is currently unclear the extent to which inhibitory control in the flanker task is impacted by aging.

Performance on the flanker task has been proposed to reflect two different processing pathways: a *direct pathway* that is sensitive to the overall stimulus array and a *control-demanding pathway* that can be directed to attend to specific elements of the array (e.g., the target) to support goal-driven stimulus-response translation (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Ridderinkhof, van der Molen, & Bashore, 1995). On incongruent trials, these pathways generate competing response activations, with the direct pathway generating stronger activation in favor of the response cued by the distractors. According to contemporary models of cognitive control, signals of conflict stemming from these competing response activations are registered by a monitoring process that subsequently engages two processes of particular relevance to the current study: a *threshold adjustment process* that temporarily puts a “brake” on behavior by increasing one’s threshold to initiate a response and a *controlled selection process* that “steers” top-down resources to increase activation along the control-demanding pathways (Erb et al., 2016; Frank, 2006; Shenav et al., 2013).

The threshold adjustment process has been described as featuring a *global* form of inhibition involving the dorsal anterior cingulate cortex (dACC) and subthalamic nucleus (STN; Cavanagh et al., 2011; Frank, 2006; Munakata et al., 2011). This form of inhibition is described as *global* because it is proposed to suppress responding in a generalized manner rather than targeting a specific response (Aron et al., 2014). In the flanker task, for instance, the threshold adjustment process does not inhibit a particular response (e.g., a left or right button-press) but instead inhibits motor output for both responses. Inhibiting motor output in this more global manner is proposed to play a role in speed–accuracy trade-off effects by allowing additional time for the controlled selection process to sway response activations in favor of the goal-relevant response (Frank, 2006). In the cognitive aging literature, global inhibition is perhaps most closely associated with the restraint function of inhibition discussed by Hasher, Zacks, and colleagues (Hasher, Zacks, & May, 1999; Lustig, Hasher, & Zacks, 2007), which focuses on inhibition’s role in suppressing prepotent responses.

In contrast to the global form of inhibition featured in the response inhibition process, the controlled selection process is proposed to involve a *competitive* form of inhibition in which increased activity in the control-demanding pathway decreases

activity along the direct pathway through lateral inhibitory connections between the pathways (Munakata et al., 2011). This competitive inhibitory dynamic enables participants to rapidly sway response activations in favor of the goal-relevant response. Effective inhibitory control in the flanker task can therefore be understood to reflect both the global inhibition of motor output via the threshold adjustment process and competitive inhibition of the direct pathway via the controlled selection process. In terms of the theory of cognitive aging advanced by Braver, Barch, and colleagues (e.g., Braver & Barch, 2002; Rush, Barch, & Braver, 2006), competitive inhibition can be understood to reflect the ability of the dorsolateral portion of the prefrontal cortex to use active representations of task-relevant information to bias processing in favor of one pathway and, consequently, to decrease the relative activation of alternative pathways.

Despite the fundamental roles that the threshold adjustment process and controlled selection process are proposed to perform in supporting inhibitory control, our current understanding of how these processes function across the life span is limited. This gap in our understanding is partly attributable to the challenges associated with targeting the functioning of each process. This is because the behavioral tasks commonly used to assess age-related differences in inhibitory control rely on button-press measures of accuracy and response time that provide relatively limited insight into how the processes underlying inhibitory control unfold over the course of a trial (e.g., Song & Nakayama, 2009). To address this limitation, Erb and colleagues (Erb & Marcovitch, 2018a, 2018b; Erb, McBride, & Marcovitch, 2019; Erb et al., 2016; Erb, Moher, Song, & Sobel, 2017, 2018) have used a technique known as *reach tracking* to target how the threshold adjustment process and controlled selection process are reflected in participants’ hand movements as they perform inhibitory control tasks by reaching to touch response options on a digital display.¹ In addition to accuracy and response time, this method provides measures of *initiation time* (the time elapsed between stimulus onset and movement onset), *movement time* (the time elapsed between movement onset and response completion), and *curvature* (a measure of the degree to which a movement deviates from a direct path to the selected response target; computed by dividing the length of the maximum deviation from a direct path by the length of the direct path).

Erb et al. (2016) proposed that initiation time could be used to target the functioning of the threshold adjustment process in cognitive control tasks by indexing how long the “brake” is placed on motor output before the onset of a reaching movement. From this view, conflict on incongruent trials should result in higher thresholds with longer periods of motoric inhibition and, consequently, slower initiation times. In light of previous electrophysiology research indicating that conflict from the preceding trial results in higher thresholds on the current trial (Sheth et al., 2012), Erb et al. predicted that initiation times would also be elevated on trials preceded by an incongruent trial relative to trials preceded by a congruent trial. Results from the flanker and Stroop tasks were consistent with these predictions, revealing main effects of current

¹ Hand-tracking techniques have been used to investigate a wide range of topics in psychology beyond inhibitory control. For recent reviews of this literature, see Erb (2018), Freeman and Johnson (2016), and Song (2017).

congruency and previous congruency, resulting in the following pattern of effects: $cC < iC < cI < iI$ (where lowercase letters denote the congruency of the previous trial and uppercase letters denote the congruency of the current trial).

Erb et al. (2016) further proposed that curvature could be used to target the functioning of the controlled selection process by indexing how active competing responses are over the course of a movement. Larger curvatures reflect delays in the controlled selection process' ability to sway response activations in favor of the goal-relevant response. Consistent with this view, participants' hand movements on incongruent trials in the flanker and Stroop tasks exhibited a pull toward the response cued by the distractors, indicating that the incorrect response was at least partially activated before the controlled selection process swayed response activations in favor of the response cued by the target. In contrast to the pattern of effects observed in initiation times, curvatures revealed a *congruency sequence effect* (CSE) in which a larger congruency effect was observed in trials preceded by a congruent trial (e.g., cC and cI trials) relative to trials preceded by an incongruent trial (e.g., iC and iI trials).

Building on previous work by Mayr, Awh, and Laurey (2003) and Nieuwenhuis et al. (2006) investigating the CSE in button-press versions of the flanker task, Erb and Marcovitch (2018a) evaluated the effects of current congruency, previous congruency, and response repetition type (i.e., whether the response provided on the current trial repeated the response of the previous trial or switched relative to the response of the previous trial) in a two-alternative forced-choice (2AFC) version of the task adapted for use with reach tracking. Their results demonstrated that the CSE observed in response times in 2AFC versions of the task reflects a combination of two distinct patterns of effects, with one pattern observed in initiation times and the other observed in curvatures (see Figure 1).² As in Erb et al. (2016), initiation times revealed main effects of current and previous congruency in both response switch and response repeat trials (see Figure 1B). Reach curvatures, however, revealed a CSE on response repeat trials but not on response switch trials (see Figure 1C; for a discussion of why the CSE was restricted to response repeat trials, see Section 1 of the online supplementary materials).

In addition to finding distinct patterns of trial sequence effects in initiation times and curvatures, Erb and Marcovitch (2018a) observed different age-related gains in inhibitory control between 6- to 8-year-olds, 10- to 12-year-olds, and college-aged adults. Initiation times revealed a significant decrease in the size of the congruency effect between 6- to 8-year-olds and 10- to 12-year-olds but no subsequent reduction between 10- to 12-year-olds and adults. Conversely, the congruency effect observed in curvatures did not decrease significantly between 6- to 8-year-olds and 10- to 12-year-olds but did decrease significantly between 6- to 8-year-olds and adults, suggesting that the controlled selection process begins functioning in an adult-like manner later in development than the threshold adjustment process.

The current study aims to build on the findings of Erb and Marcovitch (2018a) to investigate two central questions: Can initiation time and curvature be used to target the functioning of the threshold adjustment process and the controlled selection process in adults 65 to 75 years of age? And, if so, how does the functioning of these processes contribute to putative age-related differences in inhibitory control between early and late adulthood?

To address these questions, we presented adults 18 to 34 years of age (young adults) and adults 65 to 75 years of age (older adults) with the reach-tracking version of the flanker task used by Erb and Marcovitch (2018a).

If initiation time and curvature can be used to target the functioning of the threshold adjustment process and controlled selection process in older adults, then both age groups should reveal patterns of effects similar to those shown in Figures 1B and 1C. Although relatively few studies have used hand-tracking methods to investigate cognitive control in older adults, a recent mouse-tracking study by Incera and McLennan (2018) indicates that adults over 60 years of age can successfully perform the flanker task and the Stroop task in hand-tracking contexts. The study did not investigate how performance was influenced by trial sequence effects, however. Consequently, it is unclear at present whether older adults' initiation times and reach curvatures exhibit similar effects to those observed in children and young adults.

As noted above, research with the flanker task has revealed inconsistent results regarding how inhibitory control changes across adulthood. Multiple studies have observed an increase in the size of the congruency effect between early and late adulthood (Gamboz et al., 2010; Waszak et al., 2010; Weintraub et al., 2013; Zeef & Kok, 1993; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996; Zelazo et al., 2014), whereas other studies have reported no significant developmental differences (Falkenstein et al., 2001; Kramer et al., 1994; Larson et al., 2016; Nieuwenhuis et al., 2002; Posthuma et al., 2002) or a significant decrease in the size of the congruency effect across adulthood (Fernandez-Duque & Black, 2006; Mathewson et al., 2005). In light of these discrepant findings, it is unclear whether age-related differences in inhibitory control will be observed in the current study. The majority of previous studies investigating the effects of aging on flanker performance have featured button-press tasks that encourage ballistic responses. In contrast, reach-tracking tasks allow participants to engage in online adjustments, resulting in relatively low error rates (e.g., Erb & Marcovitch, 2018a, 2018b). Given the interpretational issues raised by speed-accuracy trade-off effects (e.g., Lustig & Jantz, 2015; Salthouse, 1979; Starns & Ratcliff, 2010), a potential benefit of using reach tracking to study aging populations is that lower error rates may allow for more direct comparisons of performance between different age groups.

If age-related differences in inhibitory control are observed in the current study, a central question to be addressed concerns the specificity of these differences. Such differences could be process specific, in which case initiation times and curvatures would reveal different age-related effects. Alternatively, age-related differences could be driven by more general developmental changes that influence the threshold adjustment process and controlled selection process equally, in which case the measures would reveal similar age-related effects.

² Movement times generally show similar patterns to curvatures in reach tracking versions of congruency tasks (Erb et al., 2019; Erb & Marcovitch, 2018a, 2018b). Erb and colleagues focus on curvature as a measure for targeting the controlled selection process because the spatial characteristics of reaching movements provide a more direct measurement of how active competing responses are over the course of a trial relative to the temporal characteristics of reaching movements (see Erb et al., 2016).

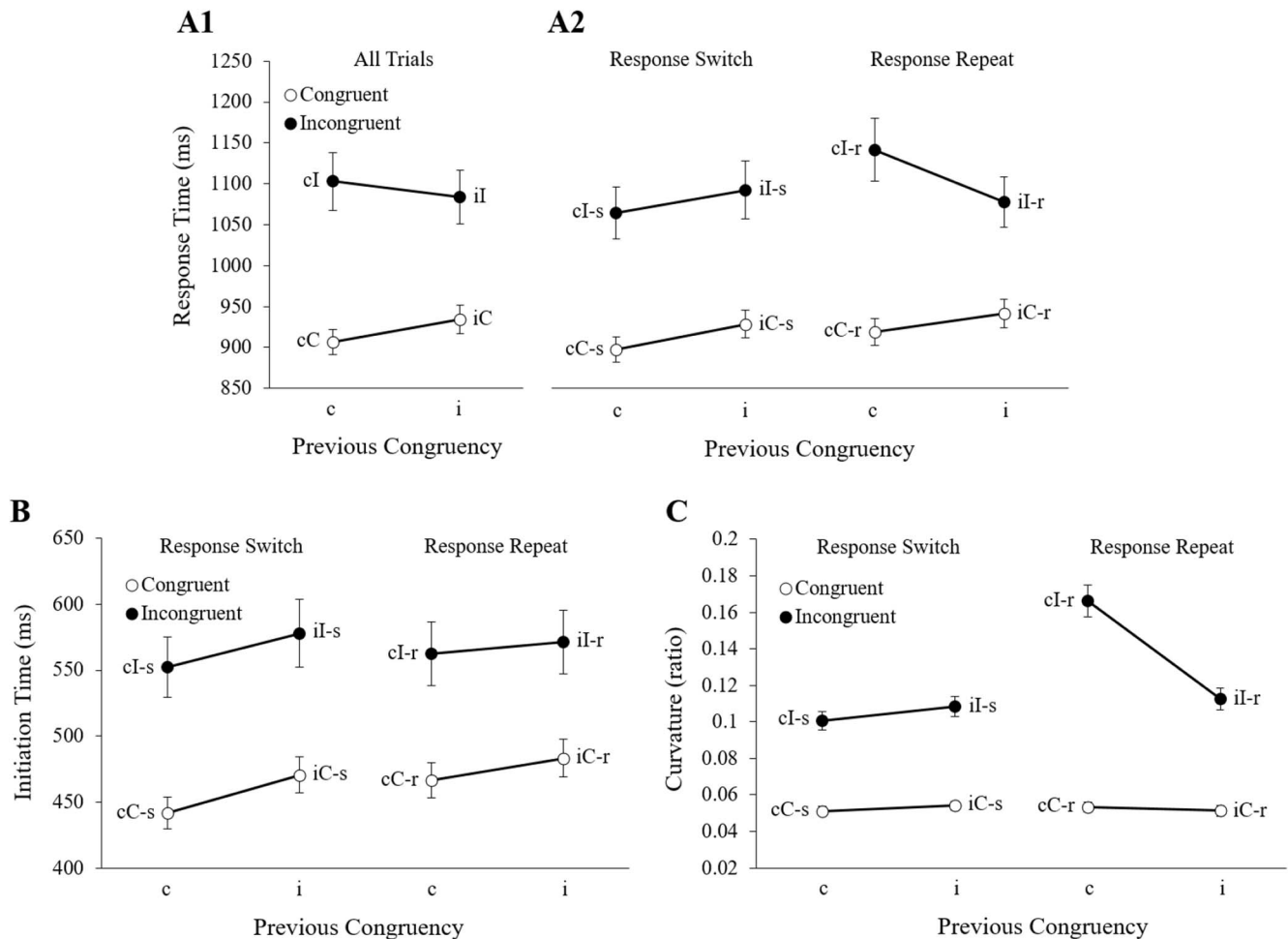


Figure 1. Results from a reach-tracking version of a two-alternative forced-choice flanker task collected by Erb and Marcovitch (2018a). The study featured 45 participants from each of three age groups: 6- to 8-year-olds, 10- to 12-year-olds, and 18- to 24-year-olds. A1: Average response time performance as a function of previous congruency (c vs. i) and current congruency (C vs. I), replicating the congruency sequence effect first reported by Gratton, Coles, and Donchin (1992) in a button-press version of the task. Average (A2) response time, (B) initiation time, and (C) reach curvature performance as a function of previous congruency, current congruency, and response type (switch vs. repeat). Error bars display standard errors. Adapted with permission from “Deconstructing the Gratton Effect: Targeting Dissociable Trial Sequence Effects in Children, Pre-Adolescents, and Adults,” by C. D. Erb and S. Marcovitch, 2018, *Cognition*, 179, p. 156. Copyright 2018 by Elsevier.

Method

Participants

The final sample was comprised of 45 young adults ($M = 19.0$ years, $SD = 2.5$; range = 18 to 34 years; 29 females, 16 males) and 45 older adults ($M = 69.0$ years, $SD = 2.8$; range = 65 to 75; 32 females, 13 males). The target sample size of 45 participants per age group was selected in light of research by Erb and Marcovitch (2018a) and is consistent with previous research investigating the dynamics of inhibitory control in early and late adulthood (e.g., Aschenbrenner & Balota, 2017). Participation in the study was limited to right-handed individuals capable of normal reaching movements with normal or corrected-to-normal vision. Testing took place at the University

of North Carolina at Greensboro. Young adults received course credit for participating, whereas older adults received \$10. The Institutional Review Board at the University of North Carolina at Greensboro approved the protocol.

Two older adults participated in the study but were excluded from the final sample due to an equipment malfunction ($n = 1$) and a failure to complete four blocks of the experimental task ($n = 1$). The sample of young adults included in the current study was collected as part of a separate study investigating individual differences in working memory capacity in college-aged adults. Participants in the study completed the same task presented to older adults in the current study with the exception that older adults in the current study completed four blocks of 48 trials whereas young adults in the individual differences study completed six blocks 48

of trials. To equate the groups in the current study, we restricted our analyses to the first four blocks of experimental trials.

Screening Older Adults

Older adult participants were screened during recruitment to ensure that they were capable of normal reaching behavior and did not have a history of cognitive or motoric impairment. Older participants also completed a vocabulary test (Zachary & Shipley, 1986) and processing speed measure (the digit-symbol substitution task; Wechsler, 1981) before performing the flanker task. Performance was in the typical range for these measures, with an average accuracy of 88.3% ($SD = 7.7\%$) on the vocabulary measure and an average score of 52.6 ($SD = 8.3$) correct responses in the digit-symbol substitution task.

Apparatus

The current experiment was based on previous research by Erb and Marcovitch (2018a) and, consequently, featured the same apparatus and task. The experiment was conducted using a rear-mounted projector to display the task on a Plexiglas screen. The projector, screen, and an electromagnetic source were affixed to a wooden board that was mounted to a 91.4 cm \times 152.4 cm (see Figure 2A). The projected display on the Plexiglas screen was 38 cm \times 50 cm. A 2 cm \times 2 cm square marker was placed 27 cm in

front of the screen. The square marker 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, Colchester, VT). 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, Natick, MA).

Participants were presented with a two-response version of the flanker task in which an array of five gray 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 gray squares that measured 1.7 cm \times 1.7 cm (see Figure 2B). The center of each gray 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

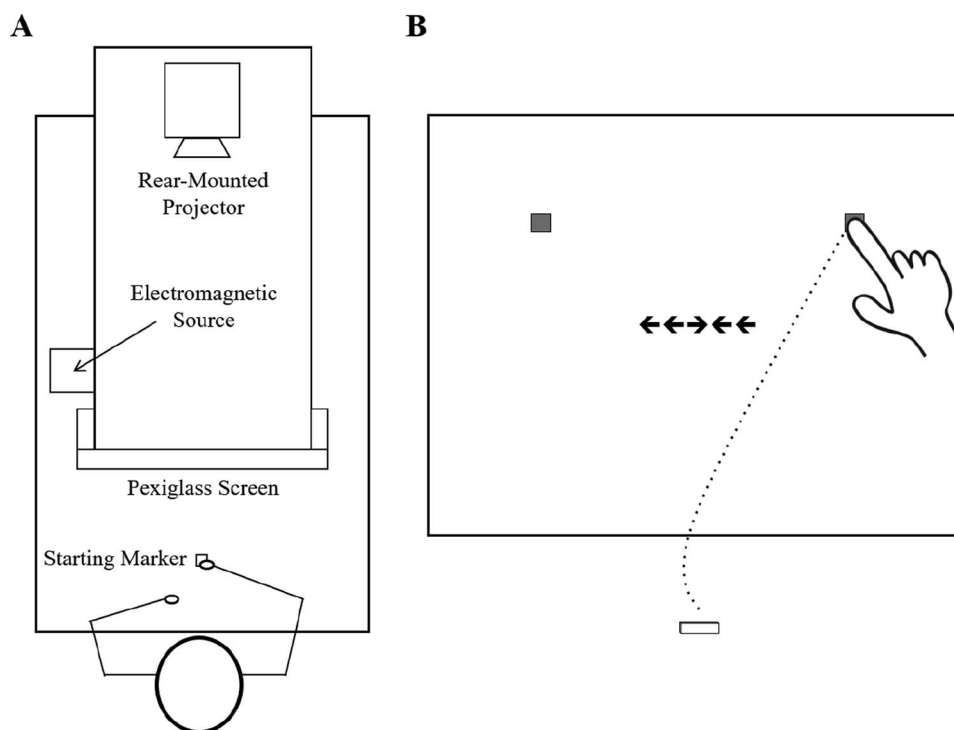


Figure 2. A: Diagram of experimental setup from aerial view. The task was displayed on a Plexiglas screen mounted upright on the table in front of the participant. All movements were initiated from a starting marker mounted on the table 27 cm in front of the screen. B: Illustration of an incongruent trial in the flanker task from the perspective of the participant. This figure was adapted with permission from "Deconstructing the Gratton Effect: Targeting Dissociable Trial Sequence Effects in Children, Pre-Adolescents, and Adults," by C. D. Erb and S. Marcovitch, 2018, *Cognition*, 179, p. 154. Copyright 2018 by Elsevier.

paused and did not resume until the participant returned their hand to the starting marker for 1 s. Participants had up to 10 s to respond following stimulus onset. The stimulus array remained on the screen until the participant responded or the time limit was reached. 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).

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. The experiment consisted of four blocks of 48 trials, for a total of 192 experimental 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.

Data Processing

The processing procedures used in the current study were largely adapted from Moher and Song (2013) and matched those reported by Erb and Marcovitch (2018a). 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 10 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). An average of 1.5% ($SD = 2.0\%$) of experimental trials were adjusted manually for each participant.

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).

Results

Error rates were low for both young adults ($M = 0.07\%$, $SD = 0.22\%$) and older adults ($M = 0.08\%$, $SD = 0.29\%$) and did not differ between the age groups, $F(1, 88) = 0.05$, $p = .83$. Consequently, error rates were not analyzed further. As in Erb and

Marcovitch (2018a), the first trial of each block was excluded from analysis given that these trials were not preceded by another trial. To control for posterror 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. Outliers were removed using a recursive trimming procedure (e.g., Van Selst & Jolicoeur, 1994) that identified outliers for congruent and incongruent trials separately. On average, this resulted in the exclusion of 0.31% ($SD = 0.34\%$) of congruent trials and 0.62% ($SD = 0.79\%$) of incongruent trials from each participant. Age group did not have a significant effect on the percentage of outliers removed from congruent trials, $F(1, 88) = 0.37$, $p = .55$, or incongruent trials, $F(1, 88) = 0.34$, $p = .56$. The average number of trials included from each participant in the analyses presented below was 183.8 ($SD = 3.0$).

Log transformations were applied to the response time, initiation time, movement time, and curvature data to minimize the effect of age-related differences in processing speed and to adjust for positively skewed distributions. Given that it is inappropriate to perform a log transformation on nonpositive values, a constant of 1 was added to each curvature value before the log transformation was applied. Performance on each measure was analyzed with an analysis of variance (ANOVA) featuring previous congruency (c, i), current congruency (C, I), and response type (switch, repeat) as within-subjects factors, and age group (young adults vs. older adults) as a between-subjects factor. Table 1 presents the ANOVA results for all significant effects with $\alpha = .05$. Corresponding results from the untransformed data are available in Supplemental Table S1 in Section 2 of the online supplementary materials and are consistent with the pattern of effects presented below. Select analyses revealing interactions with age group were also run on z-scored data. To aid interpretability, all figures and descriptive statistics presented in the following were generated using the untransformed data.

Response times revealed main effects of previous congruency, current congruency, and repetition type, and a significant three-way interaction among the factors. To account for this interaction, we evaluated the effects of previous and current congruency on response switch and response repeat trials separately. Consistent with the results of Erb and Marcovitch (2018a), response switch trials revealed significant main effects of previous and current congruency in response times, whereas response repeat trials revealed a significant CSE (see Figure 3A). Although response switch trials revealed a significant interaction between previous and current congruency, this interaction reflected a larger effect of previous congruency on congruent relative to incongruent trials rather than the pattern of effects associated with the CSE.

Average response times were faster in young adults ($M = 812$ ms, $SD = 81$) relative to older adults ($M = 931$ ms, $SD = 108$). The interaction between age group and current congruency was significant in response times, with a larger congruency effect (I-C) observed in older adults ($M = 86$ ms, $SD = 56$) than in young adults ($M = 54$ ms, $SD = 46$; see Figure 4). A significant interaction between age group, previous congruency, and current congruency was also observed, with a larger CSE in older adults ($\eta_p^2 = 0.44$) than in young adults ($\eta_p^2 = 0.10$). Follow-up tests revealed that response times were significantly slower on cI relative to iI trials for older adults, $F(1, 44) = 5.56$, $p = .023$, $\eta_p^2 = 0.11$, but not for young adults, $F(1, 44) = 0.001$, $p = .98$. The

Table 1
Analysis of Variance Results From Log-Transformed Data

Effect	dfs	F	p	η_p^2	Description of effect
Response time					
ci	1, 88	10.59	= .002	.11	c < i
CI	1, 88	285.67	< .001	.76	C < I
SR	1, 88	49.73	< .001	.36	S < R
Age	1, 88	35.12	< .001	.29	Young < older
ci × CI	1, 88	29.67	< .001	.25	cC < iC < il < ci (CSE)
ci × SR	1, 88	18.48	< .001	.17	c-s < i-s < i-r < c-r
ci × CI × SR	1, 88	9.50	= .003	.10	
Switch					
ci	1, 89	28.77	< .001	.24	c-s < i-s
CI	1, 89	236.49	< .001	.73	C-s < I-s
ci × CI	1, 89	6.62	= .012	.07	cC-s < iC-s < ci-s < il-s
Repeat					
CI	1, 89	247.27	< .001	.74	C-r < I-r
ci × CI	1, 89	24.68	< .001	.22	cC-r < iC-r < il-r < ci-r (CSE)
CI × Age	1, 88	7.98	= .006	.08	Larger effect of CI in older adults
ci × CI × Age	1, 88	5.73	= .019	.06	
Young					
ci	1, 44	8.07	= .007	.16	c < i
CI	1, 44	97.98	< .001	.69	C < I
ci × CI	1, 44	5.06	= .030	.10	cC < iC < il = ci (CSE)
Older					
CI	1, 44	5.24	= .027	.11	c < i
CI	1, 44	186.08	< .001	.81	C < I
ci × CI	1, 44	34.44	< .001	.44	cC < iC < il < ci (CSE)
Initiation time					
ci	1, 88	79.72	< .001	.48	c < i
CI	1, 88	217.22	< .001	.71	C < I
SR	1, 88	28.13	< .001	.24	S < R
Age	1, 88	47.27	< .001	.35	Young < older
CI × SR	1, 88	26.28	< .001	.23	C-s < C-r < I-r = I-s
CI × Age	1, 88	7.26	= .008	.08	Larger effect of CI in older adults
ci × CI × Age	1, 88	6.08	= .016	.06	
Young					
ci	1, 44	33.79	< .001	.43	c < i
CI	1, 44	81.89	< .001	.65	C < I
Older					
CI	1, 44	54.53	< .001	.55	c < i
CI	1, 44	131.98	< .001	.75	C < I
ci × CI	1, 44	6.15	= .017	.12	Larger effect of ci on congruent trials
Movement time					
ci	1, 88	26.05	< .001	.23	i < c
CI	1, 88	83.15	< .001	.49	C < I
SR	1, 88	9.90	= .002	.10	S < R
ci × CI	1, 88	24.33	< .001	.22	cC = iC < il < ci (CSE)
ci × SR	1, 88	19.90	< .001	.18	i-r = i-s; c-s < c-r
CI × SR	1, 88	40.98	< .001	.32	C-r = C-s < I-s < I-r
Curvature					
ci	1, 88	51.16	< .001	.37	i < c
CI	1, 88	177.17	< .001	.67	C < I
SR	1, 88	36.87	< .001	.30	S < R
ci × CI	1, 88	69.24	< .001	.44	cC = iC < il < ci (CSE)
ci × SR	1, 88	33.89	< .001	.28	i-r = i-s; c-s < c-r
CI × SR	1, 88	71.00	< .001	.45	C-r = C-s < I-s < I-r
ci × CI × SR	1, 88	23.71	< .001	.21	
Switch					
CI	1, 89	142.41	< .001	.62	C-s < I-s
ci × CI	1, 89	5.82	= .018	.06	cC-s = iC-s < il-s < ci-s (CSE)
Repeat					
ci	1, 89	70.52	< .001	.44	i-r < c-r
CI	1, 89	178.54	< .001	.67	C-r < I-r
ci × CI	1, 89	70.56	< .001	.44	cC-r = iC-r < il-r < ci-r (CSE)

Note. ci = previous congruency; CI = current congruency; SR = response type (switch vs. repeat); Age = age group (young vs. older); CSE = congruency sequence effect.

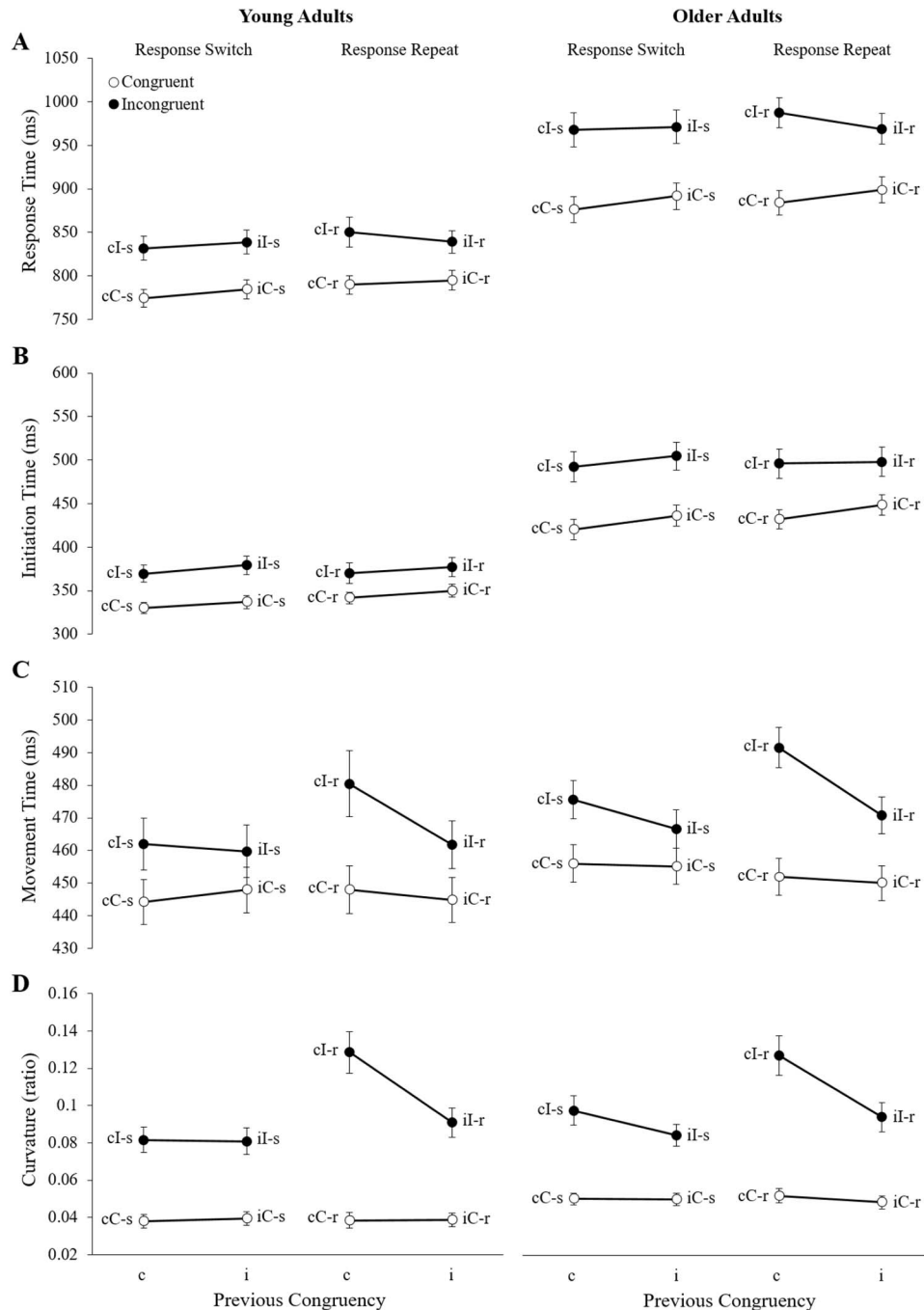


Figure 3. Average (A) response time, (B) initiation time, (C) movement time, and (D) curvature performance as a function of previous congruency (c vs. i), current congruency (C vs. I), and response type (switch vs. repeat) for young adults (left panel) and older adults (right panel). Error bars display standard errors. [Supplemental Figure S1](#) in the online supplementary materials presents average performance across both age groups.

interaction between age group and current congruency and the interaction between age group, previous congruency, and current congruency remained significant when this analysis was performed on z-scored response times (see [Section 3](#) of the online supplementary materials).

Initiation times revealed significant main effects of previous congruency, current congruency, and response type, replicating the

results of [Erb and Marcovitch \(2018a\)](#); see [Figure 3B](#)). The interaction between current congruency and response type was significant, with congruent trials revealing significantly slower initiation times on response repeat trials ($M = 393$ ms, $SD = 79$) relative to response switch trials ($M = 381$ ms, $SD = 79$) but no effect of response type on incongruent trials ($p = .404$). Average initiation times were faster in young adults ($M = 357$ ms, $SD = 58$) relative

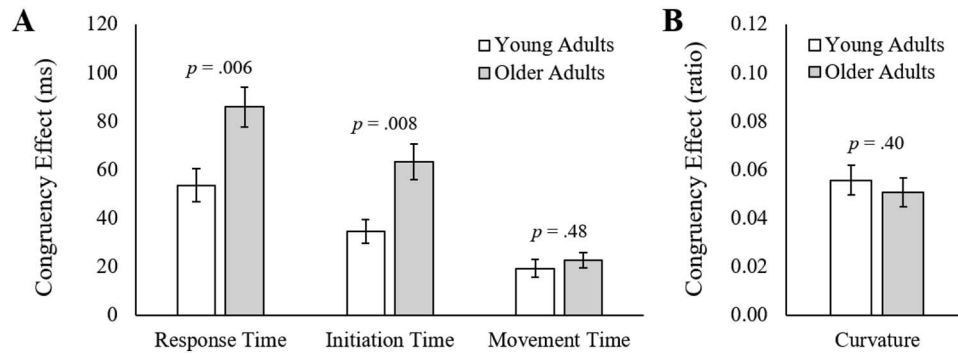


Figure 4. Average congruency effect (I - C) observed in (A) response times, initiation times, movement times, and (B) curvatures as a function of age group. Error bars display standard errors. Note that the significance values reflect analysis of the log-transformed data.

to older adults ($M = 466$ ms, $SD = 91$). The congruency effect was larger in older adults ($M = 34$ ms, $SD = 33$) relative to young adults ($M = 63$ ms, $SD = 50$), as indicated by a significant Age Group \times Current Congruency interaction (see Figure 4). The interaction between age group, previous congruency, and current congruency also reached significance. Follow-up tests revealed a significant interaction between previous and current congruency in older adults alone, with a larger effect of previous congruency on congruent trials (iC - cC: $M = 17$ ms, $SD = 15$) relative to incongruent trials (iI - cI: $M = 8$ ms, $SD = 18$). The interaction between age group and current congruency and the interaction between age group, previous congruency, and current congruency remained significant when this analysis was performed on z-scored initiation times (see Section 3 of the online supplementary materials).

Movement times revealed main effects of previous congruency, current congruency, and response type (see Figure 3C). A significant CSE was observed in movement times, as reflected by the significant interaction of previous and current congruency. Notably, the interaction between age group and current congruency did not approach significance, $F(1, 88) = 0.51$, $p = .48$ (see Figure 4). The interaction between previous congruency and response type was significant, with no effect of response type on trials preceded by an incongruent trial but significantly slower movement times on response repeat trials preceded by a congruent trial ($M = 468$ ms, $SD = 45$) relative to response switch trials preceded by a congruent trial ($M = 459$ ms, $SD = 43$). Similarly, the interaction between current congruency and response type was significant. Follow-up tests revealed that the effect of response type did not reach significance in congruent trials but was significant in incongruent trials, with slower movement times on incongruent trials featuring a response repeat ($M = 476$ ms, $SD = 46$) relative to incongruent trials featuring a response switch ($M = 466$ ms, $SD = 46$).

Curvatures revealed significant main effects of previous congruency, current congruency, and response type, as well as a number of significant interactions among the factors, including a three-way interaction (see Figure 3D). To account for this interaction, we evaluated the effects of previous and current congruency on response switch and response repeat trials separately. Follow-up analyses revealed a significant CSE in both response

switch and response repeat trials; however, the CSE observed in response repeat trials was considerably larger ($\eta_p^2 = 0.44$) than the effect observed in response switch trials ($\eta_p^2 = 0.06$). The interaction between age group and current congruency did not approach significance, $F(1, 88) = 0.70$, $p = .40$.

To evaluate the extent to which young adults and older adults may have differentially traded off slower initiation times for more direct reach movements, we calculated the correlation between each participant's initiation time and curvature values. The average correlation for young adults ($M = -.166$, $SD = .142$) and older adults ($M = -.147$, $SD = .125$) did not differ significantly between the two groups, $F(1, 88) = 0.44$, $p = .51$. This finding indicates that participants in both age groups tended to be more direct in their reach movements on trials featuring relatively slower initiation times.

Discussion

The current study aimed to address two central questions: Can initiation time and curvature be used to target the functioning of the threshold adjustment process and the controlled selection process in adults 65 to 75 years of age? If so, how does the functioning of these processes contribute to putative age-related differences in inhibitory control between early and late adulthood? We address each of these questions in turn in the following sections.

Targeting Dissociable Processes in Older Adults

Consistent with the results of Erb and Marcovitch (2018a), participants' initiation times and curvatures presented distinct patterns of effects. Initiation times revealed main effects of previous congruency and current congruency on both response switch and response repeat trials, indicating that conflict from the previous and current trials resulted in heightened response thresholds, longer periods of global inhibition, and, consequently, slower initiation times. Conversely, reach curvatures revealed a substantial CSE in response repeat trials, with larger curvatures on cI-r relative to iI-r trials and no difference between cC-r and iC-r trials. Thus, the results of the current study indicate that initiation time and curvature can be used to target the functioning of the threshold adjustment process and controlled selection process in older adults.

The response time effects observed in the current study were also consistent with those observed in Erb and Marcovitch (2018a). Response times on response switch trials revealed main effects of previous and current congruency ($cC < iC < cI < iI$), whereas response repeat trials revealed the pattern of effects most closely associated with the CSE ($cC < iC < iI < cI$). These findings provide further evidence that the response time CSE observed in 2AFC versions of the flanker task results from the combination of two distinct patterns of effects that impact dissociable processes underlying inhibitory control (for a detailed discussion, see Erb & Marcovitch, 2018a). Notably, the CSEs observed in reach curvatures and movement times were not specific to response switch trials, in contrast to the results of Erb and Marcovitch (2018a).

Targeting Age-Related Differences in the Congruency Effect

Previous studies investigating the development of inhibitory control in button-press versions of the flanker task have revealed discrepant results concerning how the size of the congruency effect changes between early and late adulthood (Falkenstein et al., 2001; Fernandez-Duque & Black, 2006; Gamboz et al., 2010; Kramer et al., 1994; Larson et al., 2016; Mathewson et al., 2005; Nieuwenhuis et al., 2002; Posthuma et al., 2002; Weintraub et al., 2013; Zeef & Kok, 1993; Zeef et al., 1996; Zelazo et al., 2014). Response times in the current study revealed a significantly larger congruency effect in older adults than in young adults. Notably, this effect was driven by initiation times, with neither movement times nor curvatures revealing significant age-related differences in the size of the congruency effect. Thus, our findings indicate that aging negatively impacts inhibitory control in the flanker task in a process-specific manner, with impairments observed in the functioning of the threshold adjustment process but not the controlled selection process. Specifically, conflict on incongruent trials appears to result in higher threshold adjustments and, consequently, slower initiation times in older adults.

Why might the threshold adjustment process function differently in older adults than in young adults? One potential explanation comes from a study by Coxon, Van Impe, Wenderoth, and Swinnen (2012) that used diffusion tensor imaging to investigate the association between motor inhibition and the structural integrity of white matter tracts in young and older adults. The study involved a two-handed stop-signal task that featured three trial types: *go trials* that required participants to generate both a left-handed and a right-handed response, *selective stop trials* that required participants to generate a response with one hand and inhibit responding with the other, and *nonselective stop trials* that required participants to inhibit both a left-handed and a right-handed response. Measures of inhibition were then correlated with measures of white matter integrity, specifically the fractional anisotropy as well as the tract strength as derived from probabilistic tractography. Coxon et al. observed a stopping interference effect in which participants took longer to generate the appropriate response with a particular hand on selective stop trials relative to go trials. Notably, the size of the stopping interference effect was significantly larger in older adults than in young adults.

Coxon et al. (2012) attributed the stopping interference effect to a global inhibition process involving the STN. Consistent with this

interpretation, larger stopping interference effects were found to correlate with lower measures of white matter integrity, particularly in tracts connecting the presupplementary motor area with the STN. Further, this effect was more pronounced in older adults, indicating that decreasing white matter integrity could be a neural correlate of the observed age-related difference in the size of the stopping interference effect. As noted by Coxon et al., this interpretation is consistent with theories of cognitive aging that emphasize the role of age-related impairments in inhibitory processing (e.g., Hasher & Zacks, 1988; Hasher et al., 1999; Lustig et al., 2007). With regard to the current study, the results of Coxon et al. suggest that age-related reductions in the integrity of white matter tracts projecting to the STN may have contributed to the size of the congruency effect observed in older adults' initiation times. Future research could explore this possibility by investigating how the initiation time effects observed in conflict tasks relate to tractography measures across the life span.

It is important to note that the age-related difference in the size of the congruency effect observed in initiation times in the current study may have reflected a number of different factors beyond white matter integrity. For instance, the effect may have resulted from strategic performance modulations in which older adults were particularly motivated to avoid errors or large reach curvatures and, consequently, were more cautious when signals of conflict were detected (e.g., Lustig & Jantz, 2015; Yee & Braver, 2018). Alternatively, the effect may have stemmed from a calibration of the threshold adjustment process that occurred with experience. On this view, performance was not modulated strategically but was shaped through a learning process that ensures performance remains within certain parameters (e.g., that errors and large reach curvatures are minimized). Consequently, it is possible that the controlled selection process functions differently in older adults than in young adults but the current study failed to observe an effect of age group in reach curvatures because this difference was offset by a difference in the functioning of the threshold adjustment process.

This possibility is consistent with research indicating that older adults often exhibit larger speed-accuracy trade-off effects than young adults (e.g., Ghisletta, Joly-Burra, Aichele, Lindenberger, & Schmiedek, 2018; Salthouse, 1979; Starns & Ratcliff, 2010). Although average correlations between initiation times and reach curvatures did not differ significantly between the two age groups in the current study, slower overall initiation times in older adults may nevertheless have enabled older adults to maintain reach curvatures at a level comparable to those of young adults. Future research should therefore investigate whether age-related differences in reach curvatures would be observed in older participants if they were encouraged to initiate their movements earlier by, for example, implementing an initiation deadline (e.g., Incera & McLennan, 2018).

As noted above, previous research investigating the effects of aging on flanker performance has generated inconsistent results (Falkenstein et al., 2001; Fernandez-Duque & Black, 2006; Gamboz et al., 2010; Kramer et al., 1994; Larson et al., 2016; Mathewson et al., 2005; Nieuwenhuis et al., 2002; Posthuma et al., 2002; Waszak et al., 2010; Weintraub et al., 2013; Zeef & Kok, 1993; Zeef et al., 1996; Zelazo et al., 2014). Although a detailed comparison of each of these studies extends beyond the scope of the current article, three general observations are worth

noting. First, many of the previous studies comparing young adults and older adults featured relatively small sample sizes, with 16 participants or fewer in each age group (e.g., Falkenstein et al., 2001; Fernandez-Duque & Black, 2006; Mathewson et al., 2005; Nieuwenhuis et al., 2002; Zeef & Kok, 1993; Zeef et al., 1996). Second, the age ranges collected vary substantially between studies, with the average age of older adult participants in some studies under 60 years (e.g., Falkenstein et al., 2001; Posthuma et al., 2002) and in other studies over 70 years (e.g., Fernandez-Duque & Black, 2006). Third, average error rates varied widely across the studies, as did the number of trials excluded due to participants failing to respond within a specified time frame (e.g., Larson et al., 2016; Posthuma et al., 2002; Waszak et al., 2010). These observations, along with the results of the current study, indicate that age-related differences in the size of the congruency effect are more likely to be observed when (a) larger sample sizes are collected, (b) participants in the older age group are 68 years of age or older (see Waszak et al., 2010), and (c) error rates are low in each age group.

Age-Related Differences in the Congruency Sequence Effect

Response times revealed a significantly larger CSE in older adults than in young adults. This effect appears to have been driven by the interaction of current congruency, previous congruency, and age group in initiation times. Specifically, the effect of the previous trial's congruency was significantly larger on congruent trials ($cC < iC$) than on incongruent trials ($cI < iI$) in older adults' initiation times. Conversely, the effect of the previous trial's congruency was descriptively smaller on congruent trials than on incongruent trials for young adults' initiation times. Consequently, the response time difference between cC and iC trials was more pronounced in older adults, whereas the difference between iI and cI trials was less pronounced in young adults. This finding is consistent with the interpretation that aging impacts flanker performance in a process-specific manner, with initiation times but not movement times or curvatures revealing a significant three-way interaction among current congruency, previous congruency, and age group.

The CSE has been at the center of recent debates concerning the cognitive and neural underpinnings of controlled cognition (for reviews, see Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007, 2017; Schmidt, 2019). Consequently, a number of studies have investigated the extent to which the CSE is modulated by age (e.g., Aisenberg, Sapir, d'Avossa, & Henik, 2014; Aschenbrenner & Balota, 2015, 2017; Larson et al., 2016; Puccioni & Vallesi, 2012). For instance, Aschenbrenner and Balota (2017) presented participants with a modified version of the flanker task designed to minimize overlap between the stimulus and response features of the current trial (trial n) and the previous trial (trial $n - 1$). In contrast to the results of the current study, the researchers reported an age-related decrease in the size of the CSE observed in response times. However, a recent reanalysis of the young adult data from Aschenbrenner and Balota's (2017) study indicates that their task allowed feature integration effects to occur between alternating trials (i.e., between trial n and trial $n - 2$) rather than between consecutive trials (i.e., trial n and trial $n - 1$), thereby

complicating a direct comparison of their results with the results of the current study (Erb & Aschenbrenner, 2019).

Larson et al. (2016) also investigated the extent to which the CSE observed in the flanker task is modulated by aging. Neither response times nor error rates revealed significant differences between the size of the CSE observed in young adults and older adults in their study. Although the button-press version of the flanker task used by Larson et al. was similar to the task used in the current study, the average error rate on incongruent trials for older adults was higher than 20%. In addition, overall error rates were significantly higher for older adults than young adults. Consequently, it is possible that age-related differences in the size of the CSE were obscured by the relatively high rate of errors observed in older adults.

The Role of Processing Speed

Although age-related differences in congruency effects are commonly attributed to declines in inhibitory control, it is important to note that these differences can result from more general developmental differences, including declines in processing speed or motor speed. That is, performance on inhibitory control tasks can decline with age but such declines need not index developmental differences specific to the processes underlying inhibitory control (Verhaeghen, 2011). To reduce the contribution of age-related differences in processing speed or motor speed, we applied log transformations to the response time, initiation time, movement time, and curvature data. However, it is important to note that these transformations may have failed to remove age-related differences in processing speed or motor speed entirely.

Researchers often assess individual differences in processing speed in order to remove variation associated with these differences from performance on other tasks of interest (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Salthouse, 1991; Salthouse, Hancock, Meinz, & Hambrick, 1996). Future research could therefore attempt to control for age-related differences in processing speed by collecting additional measures. However, Cepeda, Blackwell, and Munakata (2013) noted that many of the tasks used to assess processing speed correlate with executive control to differing degrees at different points in development, thereby complicating the interpretation of age-related differences. Consequently, addressing the role of processing speed when evaluating age-related differences in inhibitory control remains a challenge. Nevertheless, the results of the current study present an important step forward in identifying how the dynamics of inhibitory control differ across adulthood by localizing the effect of age group to initiation times.

Relation to Previous Hand-Tracking Findings and Future Directions

The congruency effect observed in reach curvatures did not differ significantly between young and older adults in the current study. This finding is consistent with the results of a mouse-tracking study by Incera and McLennan (2018) that also failed to reveal a significant effect of age on the congruency effect observed in movement trajectories in the flanker task. The researchers did, however, find a significant age-related

difference in the size of the congruency effect in the Stroop task. This finding highlights the importance of considering how different congruency tasks can differentially tax inhibitory control across the life span (see also Aschenbrenner & Balota, 2017).

An important direction for future research to explore therefore concerns how age-related differences in the dynamics of inhibitory control might vary across different tasks. For instance, Erb and Marcovitch (2018b) found that the curvature effects observed in the Simon task differ substantially from those observed in the flanker task, with curvatures revealing large CSEs ($cC < iC < iI < cI$) on both response switch and response repeat trials. Given that the Simon and flanker tasks appear to place different demands on the controlled selection process, future research should investigate if age-related differences in the functioning of the controlled selection process are observed in the Simon task during adulthood.

Future research should also use electroencephalography (EEG) to explore the extent to which the effects observed in reaching dynamics are reflected in neural dynamics at different points in the life span (see Erb & Cavanagh, 2019). As noted by Erb and colleagues (2016), the pattern of effects observed in initiation times ($cC < iC < cI < iI$) in the Stroop task matches the pattern of effects observed in single-unit recordings of dACC neurons during performance of a Stroop-like conflict task (Sheth et al., 2012), whereas reach curvatures in the task presented the same pattern of effects observed in dACC activation in an fMRI investigation of the Stroop task by Kerns et al. (2004). Given the invasiveness of collecting single-unit recording data and the restricted temporal resolution of fMRI, neither of these methods are ideally suited for targeting the functioning of the threshold adjustment process and controlled selection process simultaneously. EEG, on the other hand, is noninvasive and presents a high temporal resolution, making it particularly well suited for investigating the neural dynamics of control across the life span (e.g., Baniqued, Low, Fletcher, Gratton, & Fabiani, 2018; Gajewski, Ferdinand, Kray, & Falkenstein, 2018; Larson et al., 2016).

Limitations

To verify that older participants in the current study were cognitively healthy for their age group, we presented them with brief vocabulary and processing speed measures before the experimental task. Given that young adults did not complete these additional tasks, it is possible that the age-related differences observed in the current study were impacted by the additional tasks. For instance, the tasks may have facilitated older adult performance by providing participants the opportunity to become accustomed to the testing environment. Alternatively, the tasks may have impaired older adult performance by causing cognitive fatigue. Although the current study cannot rule out the possibility that the additional tasks presented to older adults influenced the results, it is important to note that the age-related difference in inhibitory control observed in response times is consistent with a number of previous studies (e.g., Gamboz et al., 2010; Waszak et al., 2010; Weintraub et al., 2013; Zelazo et al., 2014), suggesting that the age-related effects observed in the current study were not driven by the vocabulary and processing speed tasks alone. Nevertheless, future research should either present all age groups with the same tasks or

present additional screening tasks to older adults after experimental tasks are completed.

Conclusion

The results of the current study provide further evidence that different components of reaching behavior—namely, initiation time and curvature—reveal distinct patterns of effects that have been linked to the functioning of two dissociable processes proposed to underlie inhibitory control: a threshold adjustment process involving the global inhibition of motor output and a controlled selection process involving competitive inhibition among coactive responses (Erb & Marcovitch, 2018a, 2018b; Erb et al., 2016, 2017, 2018, 2019). Age-related differences in inhibitory control, as assessed by the size of the congruency effect, were specific to initiation times, indicating that the threshold adjustment process functions differently in later adulthood than in early adulthood. However, it is important to emphasize that this finding comes from a specific inhibitory control task and, consequently, it is unclear whether the age-related differences observed in the current study will generalize to other tasks and testing conditions. Future research should therefore build on the current study by investigating how the threshold adjustment process and controlled selection process are impacted by healthy aging as well as age-related disorders and diseases known to impair inhibitory control (Bokura, Yamaguchi, & Kobayashi, 2005; Gauggel, Rieger, & Feghoff, 2004; Obeso et al., 2011).

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