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Overshooting cognitive control adjustments in older age: Evidence from conflict- and error-related slowing in the Stroop, Simon, and flanker tasks

Mirela Dubravac, Beat Meier *

Institute of Psychology, University of Bern, Switzerland

A R T I C L E I N F O

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A B S T R A C T

Although humans gain considerable knowledge from young to older adulthood, aging is also associated with cognitive deficits. This study investigated age-related changes in dynamic cognitive control adjustments after cognitive conflicts and errors. Specifically, we compared younger and older adults' time courses of two established phenomena – post-conflict slowing and post-error slowing. Both age groups completed modified versions of three widely used cognitive conflict tasks (Stroop, Simon, and flanker task). In these tasks, occasional incongruent information triggered a conflict that had to be resolved accordingly but sometimes elicited errors. We tracked conflict- and error-related slowing across four trials after a correct conflict trial (i.e., post-conflict slowing) and an incorrect conflict trial (i.e., post-error slowing). Post-error slowing was generally stronger than post-conflict slowing. Older adults showed a disproportionally strong slowing on the first post-error trial compared to younger adults. In contrast, on subsequent trials, older adults showed a relatively stronger speed up. This pattern of results was consistent across all three tasks. The greater cross-trial response time changes in older adults suggests a deficit in fine-tuning cognitive control adjustments.

1. Introduction

In an era of rapid technological advancement, people do less repetitive but more unpredictable work that cannot easily be automated. On the one hand, the new technologies reduce the load on crystallized abilities such as storing knowledge about the world. On the other hand, however, the modern workplace increases the load on fluid abilities such as flexibly reacting to new information in unpredictable environments. While crystallized abilities increase from childhood to adulthood and tend to be well preserved in older age, fluid abilities follow an inverted U-shape across the lifespan as they decline steadily from age 20 to age 80 (Craik & Bialystok, 2006; Murman, 2015; Salthouse, 2010). Given the growing elderly population and the rising retirement age, these trends advocate the importance of investigating age-related cognitive changes, particularly in fluid abilities. Following this motivation, the present study investigated differences in younger and older adults' cognitive control. The study builds on recent work indicating that cognitive control gets more fine-tuned from childhood to adulthood (Dubravac et al., 2020, 2022). To test whether the fine-tuning is reversed in older age (i.e., the inverted U-shaped function hypothesis), in the present study, we compared younger and older adults' performance. We used the same cognitive conflict tasks as in our developmental studies (Stroop, Simon, and flanker tasks) and we tracked the dynamics of cognitive control adjustments after cognitive conflicts and errors across several subsequent trials.

Cognitive control refers to processes allowing flexible and goal-oriented information processing and behavior. Thus, cognitive control is particularly critical when the environment changes or gives conflicting information. For instance, cognitive control is involved in task switching by deactivating the previously relevant task set and activating the task set that is relevant for the current task. Typically, response times are slower in a mixed (task switching) block compared to a single task block. Studies showing stronger slowing in older adults compared to younger adults suggest that older adults have more difficulties juggling multiple tasks (Anderson & Craik, 2017; Craik & Bialystok, 2006; Reimers & Maylor, 2005). Increasing the need for cognitive control by presenting bivalent stimuli (relevant for two tasks) instead of univalent stimuli (relevant for only one task) leads to disproportionally larger switch costs in older adults (Hirsch et al., 2016; Lien et al., 2008). While younger adults show long-lasting slowing after bivalent trials across multiple subsequent univalent trials (Meier et al., 2009; Woodward et al., 2003), older adults, in contrast, show less persistent and only

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* Corresponding author at: Institute of Psychology, University of Bern, Fabrikstr. 8, 3012 Bern, Switzerland.
E-mail address: beat.meier@unibe.ch (B. Meier).

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sporadic slowing (Rey-Mermet & Meier, 2015). Older adults' coarser response time adjustments suggest difficulties sustaining optimal cognitive control.

Cognitive control adjustments have also been investigated with the flanker, Simon, and Stroop tasks (Braem et al., 2019; Eriksen & Eriksen, 1974; Simon & Small, 1969; Stroop, 1935). In these tasks, incongruent trials entail a conflict between the task-relevant and task-irrelevant stimulus dimensions. A correct response to a conflict requires focusing on the task-relevant dimension while ignoring the misleading task-irrelevant dimension (Hommel, 2011). Although the nature of the conflicts is not exactly the same, all three tasks entail a stimulus-conflict and a response-conflict leading to more errors and slower response times (*conflict slowing, congruency effect,* or *interference effect*). Moreover, the congruency effect can be modulated by conflict frequency and conflict sequentiality. More frequent conflicts (*frequency effect or proportion congruency effect*) and sequential conflicts (*sequential congruency effect* or *congruency sequence effect*) reduce the congruency effect (Gratton et al., 1992; Kerns et al., 2004; Stürmer et al., 2002), suggesting that cognitive control supports conflict resolution after adjusting to a high frequency of conflicts or a recent conflict (Botvinick et al., 2001; but see Hommel et al., 2004 for an alternative account, and see Egner, 2007 for an overview of different accounts and a mechanistic description of the cognitive processes involved in the three tasks).

If cognitive control follows an inverted U-shape across the lifespan one would assume corresponding age differences in the congruency sequence effect (i.e., smaller congruency sequence effect in children and older adults compared to young adults). This, however, was not always observed. The mixed findings on age effects suggest that the congruency sequence effect emerges from different underlying cognitive processes that might have different developmental trajectories and that the effect depends on the specific task (Rey-Mermet & Gade, 2020; Smulders et al., 2018). Similarly, a recent meta-analysis testing the hypothesis of an inhibition deficit in older age concluded that the results support the hypothesis for some tasks (e.g., go/no-go) but not for other tasks (i.a., Stroop, flanker), while for the Simon task (i.a.) the results were inconclusive (Rey-Mermet & Gade, 2018). Thus, a more nuanced perspective on the investigation of dynamic cognitive control is needed. This can be reached by looking at *several* consecutive trials instead of only one. For example, studies with young adults showed slowing across several post-conflict trials in the Stroop, Simon, and flanker tasks (Dubravac et al., 2020; Rey-Mermet & Meier, 2017b). As these tasks involve a different kind of conflict than the bivalent trials in task switching, it is an open question whether we would find an age effect on subsequent trials in these tasks. Finding age differences in the time course of post-conflict slowing after incongruent trials would support the hypothesis of an age-related deficit in adjusting cognitive control after cognitive conflicts. Thus, one goal of the present study was to compare the time courses of **post-conflict slowing** between younger and older adults.

A second goal was to investigate age effects on the time course of **post-error slowing** and compare it to post-conflict slowing. An error can be seen as a conflict between the given incorrect response and the correct response (Botvinick et al., 2001; Verguts et al., 2011). Detecting an error usually leads to pronounced slowing on the following trial (Rabbitt, 1966; for a review see Danielmeier & Ullsperger, 2011). Studies examining age-related differences in post-error slowing suggest considerable changes across the lifespan, not only in the amount but also in the time course of post-error slowing (Brewer & Smith, 1989; Czernochowski, 2014; Dubravac et al., 2020, 2022; Dutilh et al., 2013; Rabbitt, 1979; Ruitenberg et al., 2014; Smith & Brewer, 1995; but see Masina et al., 2018). For instance, Smith and Brewer (1995) compared younger and older adults' response times on several trials before and after an error. They found stronger pre-error speeding and post-error slowing in older adults indicating more substantial variability in response times around errors (Smith & Brewer, 1995). Coarser response time adjustments around errors in older adults suggest an age-related deficit in sustaining cognitive control after errors. Complimentary, developmental studies showed a similar pattern when comparing children to young adults (coarser adjustments in children), supporting the hypothesis of an inverted U-shaped function of dynamic cognitive control (Brewer & Smith, 1989; Dubravac et al., 2020, 2022).

To test the inverted U-shape hypothesis and to compare slowing across several trials after conflicts and errors in the same experimental setup, we recruited younger and older adults and administered the same Stroop, Simon, and flanker tasks that we previously used in the developmental studies (Dubravac et al., 2020, 2022). In the Stroop task, the color of fruit and vegetables either matched their color in the real-world (congruent) or was an unrealistic color (incongruent), and the task was to indicate the real-world color (Archibald & Kerns, 1999; Roebers et al., 2011). In the Simon task, participants had to indicate the color of a starfish by pressing a button either with their right or left hand (Dubravac et al., 2020; Thaqi & Roebers, 2020). The presentation side of the starfish was either congruent with the required response side (i.e., left side presentation + left hand response) or was incongruent (i.e., left side presentation + right hand response). In the flanker task, a central target fish was presented among distracting fish that faced either in the same (congruent) or different (incongruent) direction, and the task was to respond according to the side the central fish was facing (Oeri et al., 2018; Roebers & Kauer, 2009).

All tasks comprised of a pure congruent block serving as a baseline and a critical mixed block. The mixed block comprised 24 incongruent trials evenly interspersed among 96 congruent trials (Meier et al., 2009). Every fifth trial was thus incongruent inducing conflict and occasionally errors. Having less frequent incongruent trials increases the error rate, which is essential for our purposes (Stürmer et al., 2002). This task structure with regular conflict trials has been shown previously to result in the same conflict adaptation effects as with random conflict presentation (Meier et al., 2009; Woodward et al., 2003). As predictability does not seem to affect the results in this line of research, we did not have any reason to suspect that predictability would affect potential age effects in the present study. Importantly, the regular task structure allowed us to compare response times on four congruent trials after correct and incorrect conflict trials, thus complementing our developmental studies (Dubravac et al., 2020, 2022).

We expected that both conflicts and errors would generally lead to slower responses, that is, post-conflict slowing and post-error slowing across several subsequent non-conflict trials (Brewer & Smith, 1989; Dubravac et al., 2020, 2022; Meier et al., 2009; Meier & Rey-Mermet, 2012, 2018; Notebaert & Verguts, 2011; Rey-Mermet & Meier, 2015, 2017a, 2017b; Smith & Brewer, 1995; Verguts et al., 2011; Woodward et al., 2003). Recent work with this paradigm showed that children had a stronger slowing than young adults suggesting that cognitive control adjustments get more fine tuned from childhood to adulthood (Dubravac et al., 2020, 2022). According to the inverted U-shaped function hypothesis, we expected coarser response time adjustments in older adults and more fine-tuned adjustments in younger adults. Coarse adjustments would be reflected in stronger slowing after conflicts and errors and greater response time changes across subsequent non-conflict trials. Fine-tuned adjustments, in contrast, would be reflected in relatively less slowing and less trial-by-trial changes.

2. Method

The tasks were adopted from a previous study (Dubravac et al., 2022). They were administered either on a laptop computer using *E*-prime (E-Prime 2.*0*, 2015) for the Simon task or on a tablet using Open Sesame (Mathôt et al., 2012) for the Stroop and flanker tasks. Data preparation, analysis, and visualization were conducted in RStudio 2021.09.0 (R Core Team, 2021), using the packages *tidyverse* (Wickham et al., 2019), *ez* (Lawrence, 2016), *schoRsch* (Pfister & Janczyk, 2020), *apa* (Gromer, 2020), and *car* (Fox & Weisberg, 2019). The data and analytic code are accessible on OSF (https://osf.io/wkx6z/?view_only=b81618a3a529418ba5adf9d1510073aa https://osf.io/wkx6z/).

2.1. Participants

As part of a course in experimental methods taught at the local University, 96 participants (48 per age group) were recruited by word of mouth. Before testing the participants, written informed consent was obtained. The local ethics committee approved the study. For each task, we excluded participants who did not commit any errors on the critical conflict trials, who had 50 % or more errors, or who did not respond correctly to the following non-conflict trials (for details see Data preparation section). Table 1 presents the demographic characteristics of the final sample.

2.2. Task material

In the Stroop task, the stimuli were red, green, blue, and yellow quadrants and drawings of salad, strawberry, plum, and banana. In the Simon task, the stimuli were yellow and blue starfish. In the flanker task, the stimuli were left-facing and right-facing fish. Fig. 1 depicts example stimuli.

2.3. Procedure

Participants were tested individually and completed the Stroop, Simon, and flanker tasks in fixed order. All tasks comprised one practice block before the purely congruent block and one practice block before the mixed block. Four congruent warm-up trials not included in the analysis preceded the mixed block. No feedback was provided on performance. Participants were asked to respond as accurately and as fast as possible. After completing the tasks, participants of the older age group additionally completed the Mini Mental State Examination (MMSE) to control for age-related pathologies (Folstein et al., 1975; Meier et al., 2013). One person did not complete the MMSE, and one person just missed the required number of points to pass the test. As the exclusion of these participants did not change the results, we kept them in the analysis.

2.3.1. Stroop task

In the first practice block of the Stroop task, colored quadrants were presented in the middle of the tablet screen on 12 trials. Participants had to choose the corresponding color from four alternatives presented below the probe color quadrant. They gave the response by pressing directly on the touchscreen on the respective color quadrant. In the purely congruent block with 24 trials, a fruit was presented in the congruent color (i.e., typical color of the fruit). Participants had to choose the corresponding color from four alternatives presented below the probe. In the second practice block with four trials, the fruit was presented either in the congruent color (on two trials) or in one of the three incongruent colors (i.e., not a typical color of the fruit). Participants had to press on the color that is typical for the fruit (i.e., yellow for banana). The mixed block started with four congruent warm-up trials, after which followed the critical 120 trials. The 24 incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial started with a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by the probe stimulus (i.e., colored quadrant in the first block or fruit in subsequent blocks), which stayed on screen until response.

Table 1
Characteristics of the sample.

	M_{Age} (SD)	Age range	Women/men	n
Stroop task				
Young adults	23 (2)	20–30	23/14	37
Older adults	76 (5)	65–87	10/15	25
Simon task				
Young adults	23 (3)	20–32	24/20	44
Older adults	75 (6)	64–87	19/16	35
Flanker task				
Young adults	23 (3)	20–32	21/19	40
Older adults	75 (5)	64–87	19/23	42

2.3.2. Simon task

In the first practice block of the Simon task, two yellow starfish were presented on the left side of a laptop screen, and two blue starfish were presented on the right side. For yellow starfish, participants had to press the left mouse button with the left index finger. For blue starfish, participants had to press the right mouse button with the right index finger. In the purely congruent block, 12 yellow and 12 blue starfish appeared in random order, always on the congruent response side. In the second practice block with four trials, the starfish were presented either on the congruent (on two trials) or incongruent side (i.e., yellow starfish on the right side, blue starfish on the left side). Participants had to focus on the color of the starfish and ignore the presentation side. The mixed block started with four congruent warm-up trials, after which followed the critical 120 trials. The 24 incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial consisted of a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by a yellow or blue starfish, which appeared either on the left or right side and stayed on screen until response.

2.3.3. Flanker task

In the flanker task, seven fish were presented horizontally on a tablet screen to which response buttons were connected and placed on each side of the tablet. In the first practice block, all fish faced the same side (two times left, two times right). Participants had to indicate which side they were facing. For left-facing fish, participants had to press the left button with their left hand. For the right-facing fish, participants had to press the right button with their right hand. In the purely congruent block, the fish faced 12 times left and 12 times right in random order. In the second practice block, the central fish (target) did not face the same side as the other six fish (flankers) on two trials out of four. These trials were considered incongruent trials. Participants had to focus on the central fish and ignore the flanking fish. The mixed block started with four congruent warm-up trials, after which followed the critical 120 trials. The 24 incongruent trials were determined randomly with replacement and were evenly interspersed among the 96 congruent trials, occurring on every fifth trial. Each trial started with a fixation cross for 250 ms (= response-stimulus interval) in the middle of the screen, followed by six flankers and the target with a delay of 80 ms. The entire array (target and flanker fish) stayed on screen until response.

2.4. Design

To investigate the time course of post-conflict slowing and post-error slowing, response times on four congruent trials after a conflict (T + 0) were analysed as a function of the correctness of the conflict trial. From these trials we subtracted individual median response times of correct trials in the pure congruent block. This difference score reflects slowing due to occasional conflicts and errors in the mixed block and accounts for baseline response time differences between age groups. Another way to account for age differences in processing speed is to apply a natural logarithm (log) transformation to the raw response times. Thus, we calculated the difference score also with log transformed response times and run the same analyses. As the pattern of results was similar and the untransformed response times are more straightforward, we report the results with the transformed response times in the supplementary material. In both analyses the baseline-corrected response times were subjected to a 2 × 2 × 4 mixed analysis of variance (ANOVA). The

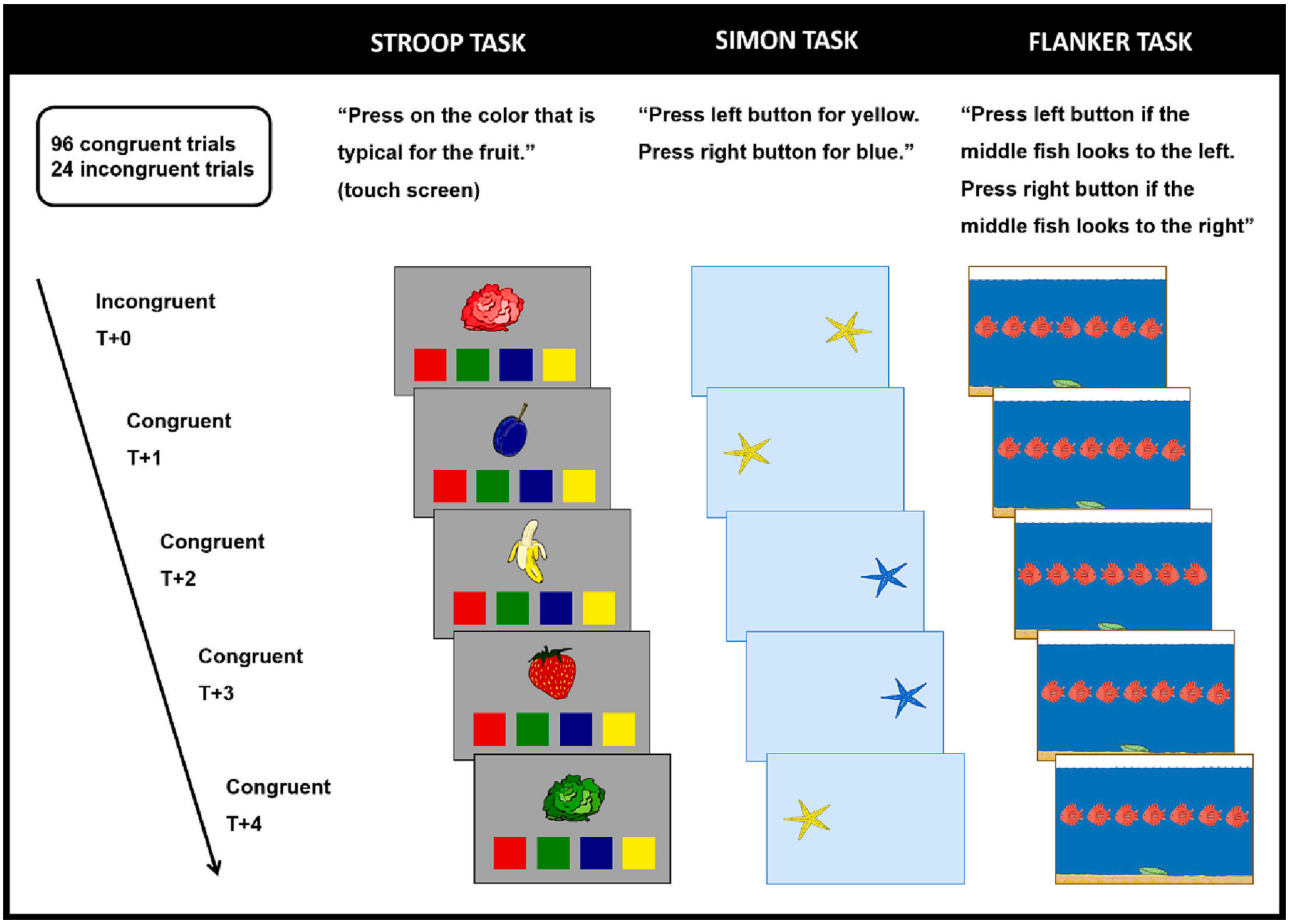

Fig. 1. Example stimuli and trial sequence for the three tasks.

between-subjects factor was age group (younger vs. older adults). The within-subject factors were slowing type (post-conflict vs. post-error) and trial (T + 1, T + 2, T + 3, T + 4). An alpha level of 0.05 was set. Where appropriate, corrected Greenhouse-Geisser values are reported.

2.5. *Data preparation*

Before analyzing the data, we conducted a similar data cleaning procedure as in previous studies (Dubravac et al., 2020, 2022). Data were excluded if participants did not commit any errors on incongruent trials (Stroop younger: 11, Stroop older: 23; Simon younger: 1; Simon

Table 2

Response times in ms in the pure congruent block (baseline) and in the mixed block on incongruent conflict trials (T + 0) and subsequent correct congruent trials (T + 1, T + 2, T + 3, and T + 4) as a function of age group and correctness on T + 0.

Age group	Trial	T + 0		T + 1		T + 2		T + 3		T + 4		Baseline	
		M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Stroop task													
Younger	Correct	789	14	574	7	573	8	556	9	552	8	532	10
	Error	682	37	730	32	608	16	609	18	602	21		
Older	Correct	1431	89	969	60	943	52	934	50	928	48	1032	60
	Error	1134	55	1829	205	1103	88	1016	70	1157	184		
Simon task													
Younger	Correct	507	9	427	9	390	10	377	9	376	10	318	9
	Error	334	9	583	34	433	20	401	16	423	15		
Older	Correct	784	30	659	33	581	23	576	22	568	21	503	33
	Error	608	44	1083	79	693	44	633	33	618	33		
Flanker task													
Younger	Correct	452	5	349	6	327	6	349	6	323	6	308	6
	Error	294	5	390	7	339	7	348	5	333	8		
Older	Correct	647	31	539	18	519	18	530	18	509	18	570	40
	Error	460	22	769	69	560	26	553	23	563	45		

older: 10; Flanker younger: 1, Flanker older: 6), or if they committed too many errors on incongruent trials (i.e., ≥ 50 %; Stroop younger: 0, Stroop older: 0; Simon younger: 2, Simon older: 1; Flanker younger: 7; Flanker older: 0). Furthermore, participants' data was excluded if there were missing values in in at least one cell (Stoop younger: 0, Stroop older: 0; Simon younger: 1, Simon older: 2; Flanker younger: 0, Flanker older: 0). This could be due to an error on a congruent trial. For example, if an error occurred on T + 2, this trial was excluded as well as the following four trials. Notably, the preceding trials were kept in the analysis to maximize the number of available trials. This resulted in

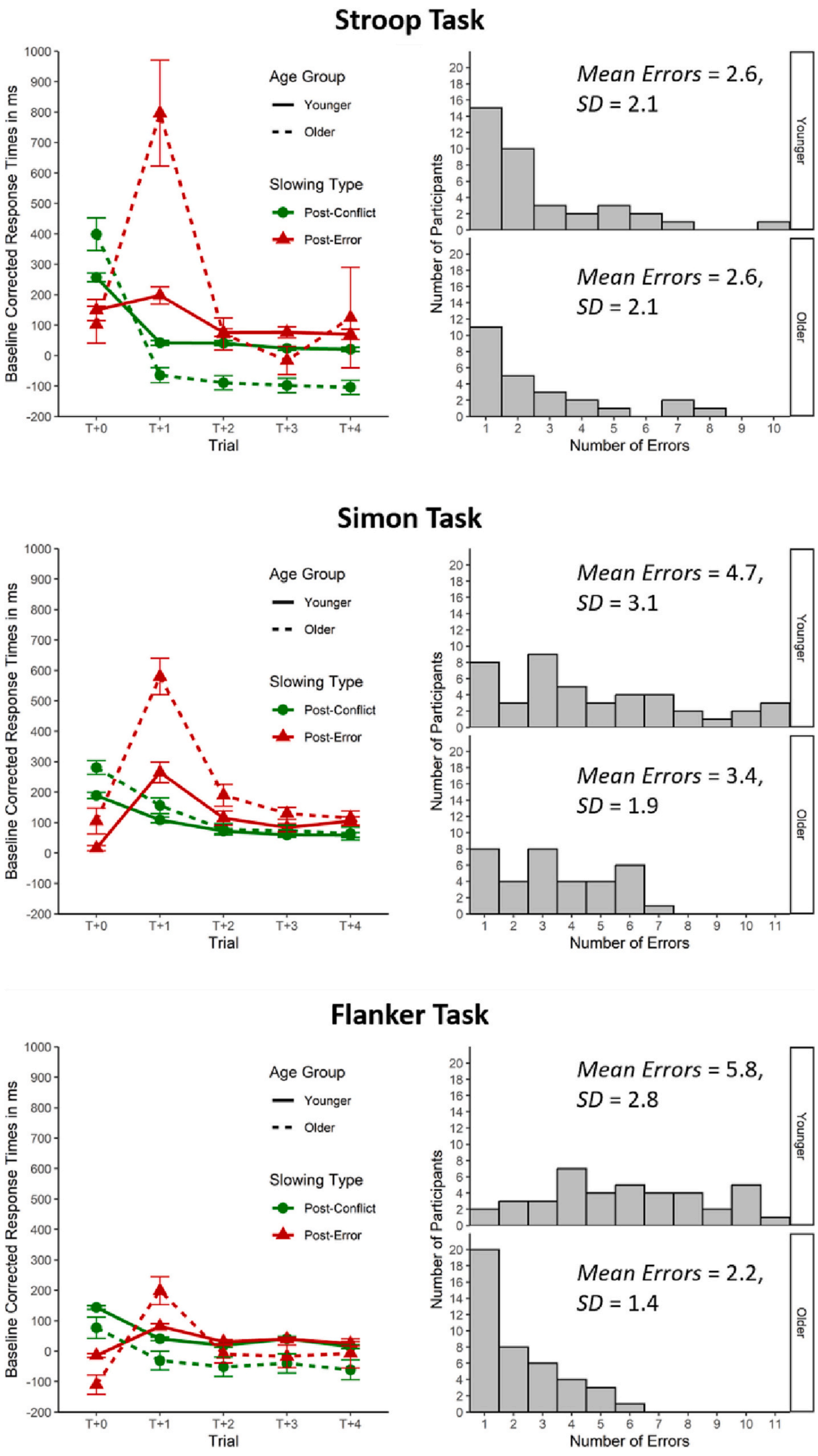

Fig. 2. Post-conflict slowing and post-error slowing across four trials and distributions of the number of errors across participants for younger and older adults.

Note. Response times in the baseline block (pure congruent block) were subtracted from response times on conflict trials (T + 0) and subsequent non-conflict trials (T + 1 to T + 4) in the mixed block to reflect slowing due to conflicts (post-conflict slowing; green lines, dots) and errors (post-error slowing; red lines, triangles). Thus, positive values indicate slowing, negative values indicate speeding, and a value of 0 ms means that response times were the same as in the baseline block. Error bars represent standard errors of the mean.

slightly different number of trials per cell (cf. Appendix A).

3. Results

Table 2 shows response times on correct and incorrect incongruent trials (T + 0) and the subsequent trials (T + 1, T + 2, T + 3, T + 4). It also shows response times in the pure congruent block serving as a baseline. Fig. 2 shows post-conflict slowing and post-error slowing across trials (baseline-corrected response times) and the distribution of the number of errors on incongruent trials in the mixed block across participants. Table 3 shows the results of the 2x2x4 ANOVA on baseline corrected response times.

Fig. 2 reflects the general pattern of the three main effects: When detecting a conflict or error (on T + 0 or T + 1, respectively), older adults slowed down more than young adults. Post-error slowing was stronger than post-conflict slowing. Trials in temporal proximity to the conflict/error on T + 0 (i.e., T + 1) produced larger slowing than later trials (i.e., T + 3 and T + 4). Most importantly, the three-way interaction indicates age-related differences in the time course of conflict- and error-related slowing. As we were mainly interested in the age differences on the time courses of conflict- and error-related adjustments, we approached the three-way interaction by conducting follow-up age group comparisons of response time differences on the four trials following a correct or incorrect conflict trial (post-conflict slowing vs. post-error slowing). The first set of analyses involves the age group comparison of the difference between post-conflict and post-error response times, reflecting age-related differences in response time adjustments after conflicts versus errors. The second set of analyses involves the age group comparison of the response time change from T + 1 to T + 2, T + 2 to T + 3, and T + 3 to T + 4, reflecting age-related differences in response time adjustments across trials.

3.1. Stroop task

The 2 × 2 ANOVA with the factors age group (younger vs. older adults) and slowing type (post-conflict vs. post-error) yielded a significant interaction on T + 1, $F(1, 60) = 20.81$, $p < .001$, $\eta_p^2 = 0.26$, as well as on T + 2, $F(1, 60) = 7.58$, $p = .008$, $\eta_p^2 = 0.11$. As Fig. 2 already suggests, this interaction was not significant on subsequent trials T + 3, $F(1, 60) = 0.54$, $p = .463$, $\eta_p^2 < 0.01$, and T + 4, $F(1, 60) = 1.75$, $p = .191$, $\eta_p^2 = 0.03$. Thus, we went on with two-sided post-hoc *t*-tests comparing the age groups on the first two trials after a conflict/error. On both trials the difference between post-conflict slowing and post-error slowing was substantially greater in older adults than in younger adults [T + 1: 860 ms vs. 156 ms, $t(25.13) = 3.79$, $p < .001$; T + 2: 160 ms vs. 35 ms, $t(26.09) = 2.31$, $p = .029$]. This result suggests a stronger impact of trial type on older adults' response times.

In the next step, we examined slowing across trials by conducting 2 × 4 ANOVAs with age group (younger vs. older adults) and trial (T + 1, T + 2, T + 3, T + 4) separately for post-conflict slowing and post-error slowing. For post-conflict slowing, the interaction was not significant, $F(1.85, 110.97) = 0.95$, $p = .385$, $\eta_p^2 = 0.02$. This suggests that after a successful conflict resolution, there is no age effect in the time course of post-conflict slowing. In contrast, for post-error slowing, the interaction was highly significant, $F(1.82, 109.40) = 11.01$, $p < .001$, $\eta_p^2 = 0.16$, suggesting age-related differences in the time course of post-error slowing. To examine the age effect on the course of post-error slowing, we compared the age groups with respect to the change in response times from T + 1 to T + 2, T + 2 to T + 3, and T + 3 to T + 4. Two-sided *t*-tests indicated that older adults (726 ms) showed a significantly steeper decline in post-error slowing from T + 1 to T + 2 than younger adults (122 ms), $t(24.97) = 3.57$, $p = .001$. However, there was neither an age effect between T + 2 and T + 3, $t(33.15) = 1.70$, $p = .099$, nor between T + 3 and T + 4, $t(60) = -1.26$, $p = .214$.

Table 3
Results of the 2 × 2 × 4 ANOVA on baseline corrected response times.

Effect	*Df*	*F*	*p*	η_p^2
Stroop task				
Age group	1, 60	0.06	0.805	< 0.01
Slowing type	1, 60	37.98	< 0.001	0.39
Trial	1.86, 111.58	24.45	< 0.001	0.29
Age group × Slowing type	1, 60	15.46	< 0.001	0.20
Age group × Trial	1.86, 111.58	12.15	< 0.001	0.17
Slowing type × Trial	1.79, 107.68	17.86	< 0.001	0.23
Age group × Slowing type × Trial	1.79, 107.68	9.73	< 0.001	0.14
Simon task				
Age group	1, 77	12.50	< 0.001	0.14
Slowing type	1, 77	91.47	< 0.001	0.54
Trial	1.70, 131.09	78.55	< 0.001	0.50
Age group × Slowing type	1, 77	15.33	< 0.001	0.17
Age group × Trial	1.70, 131.09	14.29	< 0.001	0.16
Slowing type × Trial	1.86, 142.85	32.75	< 0.001	0.30
Age group × Slowing type × Trial	1.86, 142.85	8.28	< 0.001	0.10
Flanker task				
Age group	1, 80	1.62	0.207	0.02
Slowing type	1, 80	23.66	< 0.001	0.23
Trial	1.62, 129.84	21.50	< 0.001	0.21
Age group × Slowing type	1, 80	11.40	< 0.001	0.12
Age group × Trial	1.62, 129.84	6.74	0.003	0.08
Slowing type × Trial	1.63, 130.34	12.07	< 0.001	0.13
Age group × Slowing type × Trial	1.63, 130.34	5.82	0.007	0.07

3.2. Simon task

The 2 × 2 ANOVA with the factors age group (younger vs. older adults) and slowing type (post-conflict vs. post-error) yielded a significant interaction on T + 1, $F(1, 77) = 14.33$, $p < .001$, $\eta_p^2 = 0.16$. In contrast to the Stroop task, this effect missed significance on T + 2, $F(1, 77) = 3.40$, $p = .069$, $\eta_p^2 = 0.04$. As Fig. 2 already suggests and in line with the Stroop task, this interaction was not significant on subsequent trials T + 3, $F(1, 77) = 2.16$, $p = .146$, $\eta_p^2 = 0.03$, and T + 4, $F(1, 77) = 0.04$, $p = .851$, $\eta_p^2 < 0.01$. On T + 1 the difference between post-conflict slowing and post-error slowing was substantially greater in older adults (423 ms) than in younger adults (156 ms), $t(49.35) = 3.55$, $p < .001$. This result suggests a stronger impact of trial type on older adults' response times.

In the next step, we examined slowing across trials by conducting 2 × 4 ANOVAs with age group (younger vs. older adults) and trial (T + 1, T + 2, T + 3, T + 4). The interaction was significant for post-error slowing, $F(1.77, 136.36) = 11.93$, $p < .001$, $\eta_p^2 = 0.13$, but not for post-conflict slowing, $F(1.73, 133.23) = 3.17$, $p = .052$, $\eta_p^2 = 0.04$. This is in line with the Stroop task and suggests that age affects response time adjustments across post-error trials but not across post-conflict trials. To examine the age effect on the course of post-error slowing, we compared the age groups with respect to the change in response times from T + 1 to T + 2, T + 2 to T + 3, and T + 3 to T + 4. Two-sided *t*-tests indicated that older adults (390 ms) showed a significantly steeper decline in post-error slowing from T + 1 to T + 2 than younger adults (150 ms), $t(49.92) = 2.94$, $p = .005$. There was neither an age effect between T + 2 and T + 3, $t(77) = 0.70$, $p = .487$, nor between T + 3 and T + 4, $t(40.90) = 1.09$, $p = .281$.

3.3. Flanker task

The 2 × 2 ANOVA with the factors age group (younger vs. older adults) and slowing type (post-conflict vs. post-error) yielded a significant interaction on T + 1, $F(1, 80) = 10.18$, $p = .002$, $\eta_p^2 = 0.11$. The interaction was not significant on T + 2, $F(1, 80) = 3.24$, $p = .076$, $\eta_p^2 = 0.04$, on T + 3, $F(1, 80) = 3.59$, $p = .062$, $\eta_p^2 = 0.04$, or on T + 4, $F(1, 80) = 1.81$, $p = .182$, $\eta_p^2 = 0.02$. On T + 1 the difference between post-conflict slowing and post-error slowing was substantially greater in older adults (229 ms) than in younger adults (41 ms), $t(42.12) = 3.27$, $p = .002$. This result is in line with the Stroop and Simon tasks suggesting a stronger impact of trial type on older adults' response times immediately after the event.

In the next step, we examined slowing across trials by conducting 2 × 4 ANOVAs with age group (younger vs. older adults) and trial (T + 1, T + 2, T + 3, T + 4). For post-conflict slowing, the interaction was not significant, $F(2.73, 218.75) = 1.29$, $p = .280$, $\eta_p^2 = 0.02$. This is in line with the Stroop and Simon tasks and suggests that there is no age effect in response time adjustments after successful conflict resolution. In contrast, for post-error slowing, the interaction was significant, $F(1.60, 128.29) = 6.38$, $p = .004$, $\eta_p^2 = 0.07$, suggesting age-related differences in response time adjustments after errors. To examine the age effect on the course of post-error slowing, we compared the age groups with respect to the change in response times from T + 1 to T + 2, T + 2 to T + 3, and T + 3 to T + 4. Two-sided *t*-tests indicated that older adults (209 ms) showed a significantly steeper decline in post-error slowing from T + 1 to T + 2 than younger adults (50 ms), $t(42.67) = 3.02$, $p = .004$. There was neither an age effect between T + 2 and T + 3, $t(48.78) = 1.01$, $p = .315$, nor between T + 3 and T + 4, $t(44.11) = -0.90$, $p = .375$.

4. Discussion

The present study investigated differences in cognitive control adjustments between young and older adults after detecting cognitive conflicts and errors. Cognitive conflicts were induced by occasional incongruent trials in the Stroop, Simon, and flanker tasks. Slowing after correct conflict trials (post-conflict slowing) was compared to slowing after incorrect conflict trials (post-error slowing) on four non-conflict trials. Across all three tasks, we found evidence for conflict and error related slowing in both age groups. Most slowing happened immediately after conflict detection (on T + 0) or error detection (on T + 1) and diminished across trials. Critically, older adults showed stronger slowing than younger adults, especially on the first trial after an error. In sum, older adults were more affected, that is, they showed stronger slowing and greater response time changes across trials than younger adults. Our findings align with previous research and suggest coarser cognitive control adjustments with aging (Hsu & Hsieh, 2021; Rey-Mermet & Meier, 2015; Smith & Brewer, 1995).

When discussing the comparability of the cognitive processes involved in conflict- and error-related slowing, one must keep in mind that the processes producing the two slowing types are displaced in time (Dubravac et al., 2020). *Correct* conflict trials involve the successful detection and resolution of conflict on T + 0. These processes might have produced the strong conflict-related slowing on T + 0. As a matter of fact, however, conflict detection and/or resolution failed for *incorrect* trials. The strong slowing on the first post-error trial (T + 1) indicates that multiple processes were initiated, producing a disproportionately strong slowing, especially in older adults. After error detection, an orienting response toward the source of the error might co-occur with a strong response inhibition on the first post-error trial (Marco-Pallarés et al., 2008; Notebaert et al., 2009; Ridderinkhof, 2002). Thus, while conflict is processed on T + 0 for correct responses, conflict+error are processed on T + 1 for incorrect responses, leading to a strong slowing on the respective trial. After the peak, slowing decreased across trials, in line with previous studies (Brewer & Smith, 1989; Dubravac et al., 2020, 2022; Rey-Mermet & Meier, 2017b; Smith & Brewer, 1995; Smulders et al., 2016).

The relatively stronger slowing after errors might reflect a greater challenge for cognitive control. Errors require cognitive control to resolve post-error conflict between the correct and incorrect response on the first post-error trial and to balance various processes across subsequent trials. More importantly, the effect of slowing type interacted with age group in that older adults were more strongly affected by errors than younger adults, in line with previous research (Dutilh et al., 2013; Smith & Brewer, 1995). Previous research showed that higher cognitive control demand leads to more post-error slowing (Regev & Meiran, 2014). Thus, older adults' exaggerated slowing on the first trial after an error could be explained by assuming that error-related processes pose a relatively higher load on older adults' cognitive control. On subsequent trials, older adults speeded up, leading to greater trial-by-trial changes in response times, consistent with previous studies with different tasks (Hultsch et al., 2002; Rey-Mermet & Meier, 2015). Younger adults, in contrast, showed more balanced cognitive control adjustments across trials. Thus, coordinating the multiple processes initiated by an error challenges older adults' cognitive control to a greater extent than younger adults', which is reminiscent of the task switching literature suggesting an age-related deficit in juggling multiple tasks (Anderson & Craik, 2017; Craik & Bialystok, 2006; Reimers & Maylor, 2005).

Notably, the stronger slowing in older adults might reflect general slowing with age (Salthouse, 2000, 2010; West & Moore, 2005). Assuming that activation due to priming for congruent trials is the same for younger and older adults (Rey-Mermet & Gade, 2018), subtracting individual response times in the first pure congruent baseline block from the response times in the subsequent critical mixed block is a way to account for age-related differences in processing speed. In addition to the baseline correction, we conducted the same analyses with log transformed response times (cf. supplementary materials) and found the same pattern of results. Moreover, the processing speed theory does not fully explain older adults' larger inter-trial variability in response times (Hultsch et al., 2002; Masina et al., 2018). In this sense, our results are in line with theories of a cognitive control deficit in older age, as older adults showed deficient fine-tuning of cognitive control when encountering cognitive conflicts and especially after errors (Braver et al., 2001; Braver & Barch, 2002; Hämmerer et al., 2014).

The main pattern of results generalized across the Stroop, Simon, and flanker tasks, which is remarkable as the tasks varied not only in the type of conflict (response conflict, perceptual conflict) but also in presentation media (tablet, laptop) and response modalities (touch screen, mouse buttons, response buttons). However, there were also differences between tasks. Most obvious are the differences in the amount of older adults' post-error slowing on T + 1 (cf. Fig. 2, left side). This could be due to different error rates, as previous research showed that lower error rates are associated with higher post-error slowing (Steinborn et al., 2012). Considering older adults error rates (cf. Fig. 2, right side), the argument explains the larger post-error slowing in the Stroop task ($M = 2.6$ errors) compared to the Simon task ($M = 3.4$ errors). However, the flanker task had the lowest post-error slowing and the lowest error rate ($M = 2.2$ errors). Thus, the different error rates cannot fully explain the different amounts of slowing across tasks. Similarly, the age effect on T + 1 (i.e., stronger post-error slowing in older adults) could be explained by differing error rates between age groups, as older adults had lower error rates than younger adults in the Simon and flanker tasks. However, in the Stroop task, error rates were equal and older adults still showed stronger post-error slowing than younger adults. Moreover, it was in the Stroop task where the age effect on the difference between post-error slowing and post-conflict slowing (i.e., pure post-error slowing) was also significant on T + 2, providing further support for a true age-effect on post-error slowing.

Previous research comparing age groups on only one trial, usually the conflict trial (i.e., congruency effect) or the first trial after a conflict (i.e., congruency sequence effect), produced mixed findings regarding age effects. Meta-analytic overviews of the studies investigating age effects on a wide variety of cognitive tasks, including the Stroop, Simon, and flanker tasks, suggest that after controlling for general slowing, there are no age effects in conflict slowing in the Stroop task (Verhaeghen & Cerella, 2002; Verhaeghen & de Meersman, 1998) and that the effects are task-specific, calling into question that there is a global inhibition deficit in older adults (Rey-Mermet & Gade, 2018; see also Rey-Mermet et al., 2018). In the present study, the effect even reversed in that older adults outperformed younger adults on the flanker task in terms of error rates ($M_{older} = 2.2$ errors vs. $M_{younger} = 5.8$ errors, cf. right side of Fig. 2) and slowing on T + 0 ($M_{older} = 77$ ms vs. $M_{younger} = 144$ ms, cf. left side of Fig. 2 and see Table 2 for the numbers). Focusing only on one trial (e.g., the conflict trial T + 0) would thus have produced an inconsistent picture across tasks. Moreover, older adult's larger intertrial variability might actually conceal potential deficits in fluid abilities when measured on a single trial. The present design, though, does not offer the observation of a facilitatory effect of incongruent trials post-conflict (i.e., congruency sequence effect), which is also an aspect of dynamic cognitive control adjustments. Our cross-trial perspective can thus be seen as complementing previous research. Together these lines of research provide a more nuanced window into age-related cognitive differences.

Behavior is never isolated from previous responses and experiences or intentions and plans for the future. Tracking the dynamics of cognitive control adjustments across multiple trials thus offers a more comprehensive understanding of age-related cognitive differences than average single-trial comparisons alone. Together, our results suggest that older adults' difficulties in adapting to fast-changing environments might come from the declining fluid ability to make flexible and fine-tuned cognitive control adjustments (for a similar argument regarding fluid abilities for development and the lifespan see also Erb et al., 2018; Hommel et al., 2011). Supporting the reversed U-shaped function hypothesis our results suggest that it is the dynamic alternation between the up-and-down regulation of cognitive control that seems most vulnerable to the aging process. The generality of this pattern across different error rates, tasks, conflict types, presentation media, and response modalities strengthens our conclusions. To further investigate age-related changes in the time scale of cognitive control, future research could investigate the effect of different task contingencies on performance on multiple trials across the lifespan.

Declaration of competing interest

We have no conflicts of interest to disclose. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The data and analytic code are accessible on OSF (https://osf.io/wkx6z/).

Appendix A

Table showing the average number of trials per cell for each age group.

Age group	Trial	T + 0	T + 1	T + 2	T + 3	T + 4
Stroop task						
Younger	Correct	21.2	21.2	21.2	21.2	21.1
	Error	2.6	2.5	2.5	2.5	2.5
Older	Correct	21.2	21.2	21.3	21.3	21.3
	Error	2.6	2.6	2.6	2.6	2.6
Simon task						
Younger	Correct	18.4	18.3	18.3	18.3	18.4
	Error	4.7	4.3	4.3	4.2	4.2
Older	Correct	19.5	19.5	19.4	19.6	19.6
	Error	3.4	3.2	3.2	3.1	3.1
Flanker task						
Younger	Correct	17.6	17.6	17.7	17.6	17.7
	Error	5.8	5.7	5.7	5.7	5.6
Older	Correct	21.0	21.0	21.0	21.0	21.0
	Error	2.2	2.1	2.1	2.1	2.1

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2023.103874.

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