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Developmental progression in children's and adolescents' cognitive control

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ABSTRACT

Background: Despite developmental progression in the ability to control behavior in service of goals during kindergarten period, little is known about cognitive control mechanisms in later childhood and adolescence.
Method: The present study provides detailed insights into children's and adolescents' ability to flexibly and efficiently adapt their speed of responding in the context of a multiple-trial spatial conflict task. Based on the dual mechanisms of cognitive control, variability in response times, response consistency, trial-by trial adjustments surrounding errors, and developmental differences thereof were investigated.
Results: Results showed that individuals become more reliable, more efficient, better adjusted, and thus of overall better in cognitive control with increasing age. Sequential adjustments of response times revealed that the participating 4th graders responded too fast when the task was running smoothly and slowed down too strongly after committing an error in comparison to 6th and 8th graders.
Conclusion: The results suggest that the fine-tuning of speeded responses are key mechanisms for developmental progression in cognitive control. Furthermore, the current study attempts to increase researcher's and practitioners' awareness that detailed analysis of cognitive control processes in typically developing children and adolescents is needed for a better understanding when evaluating these processes in individuals with deviant cognitive development.

Keywords: *Cognitive Control; Error-Monitoring; Typical Development*

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Introduction

Many learning and test situations, but also many everyday life situations contain some kind of interference calling for cognitive control processes to resolve the conflict. In many of these situations, individuals have to respond fast but also as accurate as possible for optimal performance. This requires the ability to – in a top-down manner – regulate behavior in a flexible way (i.e., slowing down under high conflict conditions to avoid errors). Self-regulatory deficits and a lack of moment-to-moment behavioral adaptations are being discussed to be at the root of cognitive control problems being observed in individuals with attention-deficit hyperactivity disorder (ADHD; Klein, Wendling, Huettner, Ruder, & Peper, 2006) and other vulnerable groups (e.g., institutionalized children, intellectual humility; Danovitch, Fisher, Schroder, Hambrick, & Moser, 2019; Troller-Renfree, Nelson, Zeanah, & Fox, 2016). Research on ADHD however, has produced mixed results in these atypically developing individuals (Shiels, Tamm, & Epstein, 2012). One reason for the inconsistent evidence may lie in the selection of control groups, typically including a wide age range, ignoring developmental improvements naturally occurring in cognitive control and performance monitoring (e.g., Schachar et al., 2004; Wild-Wall, Oades, Schmidt-Wessels, Christiansen, & Falkenstein, 2009). The present study therefore addresses moment-to-moment behavioral adjustments in a cognitive control task in typically developing children and adolescents that have received only very little attention in developmental literature. This study aims to gain a better understanding on the typically developing monitoring skills and to obtain a better basis for comparisons when addressing atypically developing individuals' behavioral adjustments under cognitive control demands.

Cognitive control processes (including inhibition, updating, switching but also monitoring and planning; Lee, Bull, & Ho, 2013; Lyons & Zelazo, 2011; Miyake et al., 2000; Roebers, 2017; Sergeant, 2000) allow the individual to adapt to continuously changing situations and to master challenging tasks by flexibly modulating the amount of cognitive control processes that are being recruited and invested (Botvinick, Braver, Barch, Carter, & Cohen, 2001). These processes are associated to the late maturation of prefrontal cortex and have a long-term impact on health-related outcomes (Moffitt et al., 2011; Wendelken, Munakata, Baym, Souza, & Bunge, 2012).

A central concept of cognitive control is monitoring, describing an individuals' online processing of his or her performance. The ability to monitor performance and adjust behavioral output according to set goals have mainly been researched in the context of *error monitoring* by using cognitive conflict paradigms with multiple-choice tasks (Danielsmeier & Ullsperger, 2011). However, research in this field focuses predominantly on neural signs attributable to the detection of committed errors (Wessel, 2012). The error-related negativity (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991) is an neuronal event-related potential that is believed to be functionally localized in the anterior cingulate cortex which alerts the cognitive control system for necessary adaption in occurrence of errors (van Veen & Carter, 2002; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). Despite the intense research on neuropsychological underpinnings of monitoring in cognitive control, behavioral measures of adaptive control that ideally lead to continuous and fine-tuned adaptations of the speed of responding haven't been examined in detail. Thereof, moment-by-moment modulations of speeded but controlled responses in a spatial cognitive conflict task and their developmental differences are the focus of the present contribution.

Developmental improvements in the ability to monitor and adjust behavior when necessary have consistently been observed in typically developing children (e.g., Carlson, 2005; Cragg & Nation, 2008; Diamond, 2013; Hughes & Ensor, 2007; Jones, Rothbart, & Posner, 2003). The most prominent advancements in cognitive control that are observed once children are in school-age concern *quantitative* changes, that is, a continuously increasing speed of responding in multiple-trial tasks (Diamond, 2002). So far often overlooked are *qualitative* aspects of cognitive control driving the developmental progresses into adulthood (e.g., Chevalier, 2015; Chevalier, Huber, Wiebe, & Espy, 2013; Gonthier, Zira, Colé, & Blaye, 2019). These concern an increasing ability to efficiently handle the accuracy-speed trade-off inherent in many cognitive control situations, an ability that seems heavily impaired and thus obvious in children with ADHD (e.g., Best, Miller, & Jones, 2009; Geburek, Rist, Gediga, Stroux, & Pedersen, 2013; Keute, Stenner, Müller, Zähle, & Krauel, 2019; Somsen, 2007; van Meel, Helsenfeld, Oosterlaan, & Sergeant, 2007). In other words, these qualitative aspects in cognitive control concern sequential adjustments of speed of responding in the course of a conflict task, well observable before, on, and after an error (Fernandez-Duque, Baird, & Posner, 2000; Roebers, 2017). Their behavioral correlates are pre-error speeding, impulsive errors, and post-error slowing.

The theoretical background for the above noted qualitative aspects of cognitive control is provided by Braver's framework on dual mechanisms of cognitive control (DMC; Braver, 2012; Braver, Gray, & Burgess, 2007; Chevalier et al., 2013). According to this view, cognitive control entails two primary aspects, one being the ability to monitor the amount of conflict and occurring errors, signaling to what extent cognitive control is needed. The other, for the present study more important aspect, is the *recruitment* of cognitive control resources that can be further broken down into *proactive* and *reactive* cognitive control. Thereby, proactive control is needed before a response is given, and depends on the amount of cognitive conflict that is perceived. It entails the monitoring of conflict (or interference) that may change over the course of a multiple-trial task. Reactive control, in contrast, concerns post-response processing in that committed errors are detected, calling for more cognitive control resources to be recruited in anticipation of the next conflict, behaviorally quantifiable through post-error slowing, that is, increased reaction times following an error (Dutilh et al., 2012; Rabbitt, 1966; Rabbitt & Rogers, 1977).

Qualitative changes in proactive cognitive control may thus be found with respect to an individual's ability to define the most efficient basic speed of responding to achieve a maximum accuracy and at the same time, react at the fastest possible speed without increasing errors (i.e., handling the accuracy-speed trade-off; see Diamond, 2013). Insufficient *proactive* control may consequently be observable by (a) a generally more pronounced variability in response times when comparing different age groups or when comparing healthy individuals with patients (e.g., Brewer & Smith, 1989; Leth-Steensen, Elbaz, & Douglas, 2000; Hervey et al., 2006), (b) stronger intra-individual variability of response times as a function of age groups or diagnosis (e.g., Castellanos & Tannock, 2002; MacDonald, Nyberg, & Bäckman, 2006), (c) increasingly speeded responses after correct responses (indicative of an exaggerated adjustments of reaction times; i.e., pre-error speeding; e.g., Allain, Burle, Hasbroucq, & Vidal, 2009; Dudschig & Jentzsch, 2009; Hajcak & Simons, 2008), and (d) so-called impulsive errors (i.e., faster responses on error trials compared to correct trials; e.g., Davies, Segalowitz, & Gavin, 2004; Simpson et al., 2012; Wiersema, van der Meere, & Roeyers, 2007). Efficient *reactive* control may be observable concerning response time adjustments after an error occurred (i.e., post-error slowing; e.g., Rabbitt, 1966; Rabbitt & Rogers, 1977; Schroder et al., 2017; Smulders, Soetens, & van der Molen, 2016).

Unfortunately, the majority of developmental studies addressing transitions in cognitive control has focused on response times for correct responses only, disregarding sequential effects and strategic up- and down regulations of cognitive control processes surrounding incorrect responses (but see Ambrosi, Lemaire, & Blaye, 2016). This renders direct comparisons with clinical sample very difficult. The current study represents an attempt to address this gap in literature with new additional findings that may provide a more comprehensive view of developmental improvements. The developmental pattern of these control processes also enable implications for developmental disorder such as ADHD that are characterized by error-processing deficits (e.g., Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; Wiersema, van der Meere, & Roeyers, 2005).

However, the very few existing developmental studies on sequential response time adjustments in the context of cognitive conflict tasks of typically developing children confirm the assumed qualitative changes. Fairweather (1978) was among the first to document increasingly efficient modulations of response times from childhood to adulthood. Brewer and Smith (1989) followed up on this and reported increasingly smooth modulations of response speed with age. That is, in comparison to adults, 9-year-old children were found to more strongly speed up their responses after a correct response (pre-error speeding) and also to more strongly slow down after an error (post-error slowing).

Although the evidence is not entirely unambiguous (e.g., Gupta, Kar, & Srinivasan, 2009; van de Laar, van den Wildenberg, van Boxtel, & van der Molen, 2012; Wiersema et al., 2007), it appears that with increasing age, trial-by-trials modulations of response times become more fine-tuned, subtle and thereby more efficient (e.g., Brewer & Smith, 1989; Schachar et al., 2004; Smulders et al., 2016). A differentiated picture of developmental improvements in qualitative aspects of cognitive control in the age range of 10 to 14 years, however, is still missing and needed to understand driving forces for developmental progression in cognitive control.

The current study

The present approach focuses on a widely understudied aspect of cognitive control development, that is, on developmental improvements in the ability to flexibly modulate cognitive control processes in the context of a multiple-trial task. Although age-related increases in cognitive control have repeatedly been documented (see above), the literature mainly focuses on correct responses only, thereby neglecting sequential effects and response times before, on, and after erroneous responses. With respect to efficient modulations in proactive and reactive cognitive control, however, these effects may be especially informative for a better understanding of cognitive control improvements beyond the age of 8 years that are crucial for perception and actions. Moreover, an in-depth and detailed exploration on improvements in cognitive control in typically developing children and adolescents will allow to better evaluate performance and moment-to-moment adjustments of speeded responses in atypically developing individuals within the same age range. It was expected that individual's behavior in cognitive control during late childhood and adolescence will be characterized by continuous qualitative changes.

Given the very limited evidence on proactive and reactive cognitive control in children and adolescents, the present study will first explore whether, as theoretically assumed, response times in a cognitive conflict task vary more strongly in younger (4^{th} graders) than in older (6^{th} and 8^{th} graders) on the group level. It will be examined whether also on the individual level there are age-related decreases in response time variations, as Brewer and Smith's study (1989) suggested. The main focus of the present study lies on sequential effects of response times surrounding errors. Using the Simon task and applying a fixed sequence of congruent and incongruent trials (Rey-Mermet & Meier, 2017), we will provide detailed insights into typically developing children's and adolescents' ability to flexibly and efficiently adapt their speed of responding. We expect that 4^{th} graders will speed up after a correct response, will commit errors by responding (too) fast, and will slow down more extremely after having committed an error than 6^{th} and 8^{th} graders. These analyses will help to gain a better understanding of the qualitative changes in the ability to flexibly and adaptively recruit and invest cognitive control processes and may underline the necessity of age-specific norms when evaluating young individuals with deviant development.

Method

Participants

The sample consisted of N = 209 typically developing children and young adolescents (46% females) from three different grades (4th, 6th, and 8th grade school). They were recruited from 13 public primary and secondary schools situated in different urban and rural regions. They were predominately of Caucasian origin and from middle-class families, representing the average characteristics of the local communities and free from neurological disorders (e.g., ADHD). All participants were fluent in the local language to follow verbal task instructions easily. Of the 209 children and adolescents, the group of 4th graders consisted of 71 children (35% females) with a mean age of 10.5 years (SD_{months} = 6.6). The group of 6th graders consisted of 67 children (52% females) with a mean age of 12.2 years (SD_{months} = 6.7). Finally, the group of 8th graders consisted of 71 young adolescents (51% females) with a mean age of 14.3 years (SD_{months} = 8.6). The initial pool included in total N = 222 participants. Data of 13 participants were omitted due to missing data or technical failures.

Procedure and Measures

The objectives of the present project were approved by the Faculty's Ethics Committee of the Faculty of Humanities of the University of Bern, Switzerland (Approval No. 2017-09-00002). For all participants, parents provided written informed consent. Additionally, verbal assent from children and young adolescents was obtained prior to testing. Participants were tested individually in a quiet room in their school. The tasks were administered by trained experimenters. After completing the tasks, children and young adolescents were thanked for their participation, praised for their effort, and rewarded with a small present.

One task that has been extremely useful for the examination of cognitive control-related adjustments is the classical Simon task (Simon, 1969). This spatial cognitive conflict task includes strong spatial compatibility manipulation and moreover triggers adjustments in the face of response conflicts and errors (Notebaert & Verguts, 2011). A computerized (E-Prime 2.0 Psychological Tools, Pittsburgh, PA) version of this spatial standard two-choice conflict task was accomplished. Participants completed two different experimental blocks: congruent block: 24 congruent trials; mixed block: 96 congruent and 24 incongruent trials in a fixed sequence order in which every fifth trial was incongruent to make the task sufficiently difficult (to avoid floor effects in errors; Rey-Mermet & Meier, 2017). Each trial consisted of the presentation of one out of two target stimuli (a blue and a yellow starfish), appearing either on the right or on the left side on the screen, and a response that was given by pressing one of two pre-defined keys on the laptop. Participants were instructed to press (with their index fingers) the left side key for the yellow starfish and the right side key for the blue starfish, independent of its presentation side. In congruent trials, the yellow and blue starfish appeared on the same side as their corresponding key. In the incongruent trials, the yellow and blue starfish appeared on the opposite side to where their corresponding key was (i.e., a spatial conflict). Please note that within the congruent and incongruent trials yellow and blue starfish appeared in random order. No participant ever indicated during the briefing to have noticed the fixed pattern of congruent and incongruent trials. Participant's responses (accuracies [ACC] and reaction times [RT]) were recorded. The inter-stimulus interval (ISI) – the interval between any given response and the onset of the next experimental trial – was 250 milliseconds (ms), with a fixation cross in the center of the screen, preparing for the next trial. Presentation and response times were not time limited. In each of these two experimental blocks, participants completed first a practice session with four practice trials and were instructed to perform as quickly and correctly as possible. Practice sessions were repeated if three (or more) out of four answers were incorrect.

Results

Statistics and data analysis

On trial level, RT below 150 ms and above 2000 ms were considered as outliers and therefore excluded (< 1% of the N = 25'080 trials were removed). For the congruent and incongruent trials, and overall, mean RT (for correct responses only) and the accuracy (ACC; proportion correct) were calculated.

All statistical procedures were performed using the statistical package for the social sciences (SPSS; Version 25). One-way analysis of variance (ANOVA) were realized to test the effect of age group on response speed distributions, consistency, and performance ACC on incongruent trials. To address the relationship between response consistency and overall performance, a bivariate as well as a partial correlation (controlling for age) were calculated. The effect of varying interference as well as the sequential effects surrounding errors (i.e., pre-error speeding, impulsive errors, and post-error slowing) were investigated by conducting a series of separated mixed ANOVAs with different trial types as within-subjects factor and age group as a between-subjects factor. For the multiple comparisons of specific response latencies related to the trial types, p-value adjustments for multiple group comparisons were made by Bonferroni corrections. An alpha level of $\alpha = .05$ was set for significance tests.

To confirm the assumption of higher levels of interference on incongruent compared to congruent trials (monitoring of conflict or interference; Ridderinkhof, van der Molen, Band, & Bashore, 1997; Rueda et al., 2004), substantial *congruency effects* in all three age groups had to be confirmed first. Analysis found in all age groups the expected substantial congruency effect, with prolonged RT and decreased ACC for the incongruent compared to the congruent trials, F_{RT} (1, 206) = 550.30, p <.001, η_p^2 = .73 (incongruent trials: M = 699.05, SE = 7.86 > congruent trials: M = 585.17, SE = 10.30); F_{ACC} (1, 206) = 485.31, p <.001, η_p^2 = .70 (incongruent trials: M = .79, SE = .01 < congruent trials: M = .97, SE = .00).

Response speed distributions and consistency

First, we investigated age-related group differences in response speed distribution of all correct responses (including congruent and incongruent trials) across the entire cognitive conflict task (see Figure 1). A one-way ANOVA was conducted to assess the effect of age group on response latencies for all correct trials across the entire mixed task. Results revealed a statistically significant main effect of Age group, F(2, 206) = 55.37, p <.001, η_p^2 = .35, with all three age groups differing significantly from each other (4th graders: M = 685.21, SE = 11.81 > 6th graders: M = 594.73, SE = 10.30 > 8th graders: M = 533.25, SE = 8.76), with the oldest being the fastest responding. There was a trend towards substantial heterogeneity of variance (Levene's test, p = .08), indicating different variances of response time distributions across the three age groups.

Following up on this, intra-individual variability was assessed to explore age-related differences in consistencies of responding (intra-individual coefficient of variation; ICV; see Wojtowicz, Berrigan, & Fisk, 2012). This coefficient mirrors an individual's ratio between individual SD and mean RT for all correct responses, providing an interesting, often-overlooked measure of within-person variability. A main effect of Age group in response consistency was found, F(2, 206) = 4.37, p <.05, η_p^2 = .04, with 4th graders exhibiting significantly higher ICV compared to 8th graders, p <.05, (6th graders, in contrast, did not differ from either age group). This suggests that 4th graders engaged in coarser, and 8th graders in more fine-tuned sequential adjustment of response times. Furthermore, the result of a Pearson correlation indicated that there was a significant negative association between ICV and ACC performance in the mixed block (including congruent and incongruent trials), r (209) = -.435, p <.05. Next, a partial correlation controlled for age revealed a substantial correlation between these two variables, r (206) = -.414, p <.05. These results underline that independent of age higher response variability during the whole task (i.e., low response consistency; high ICV) is associated to higher error rates, thus, low performance in ACC.

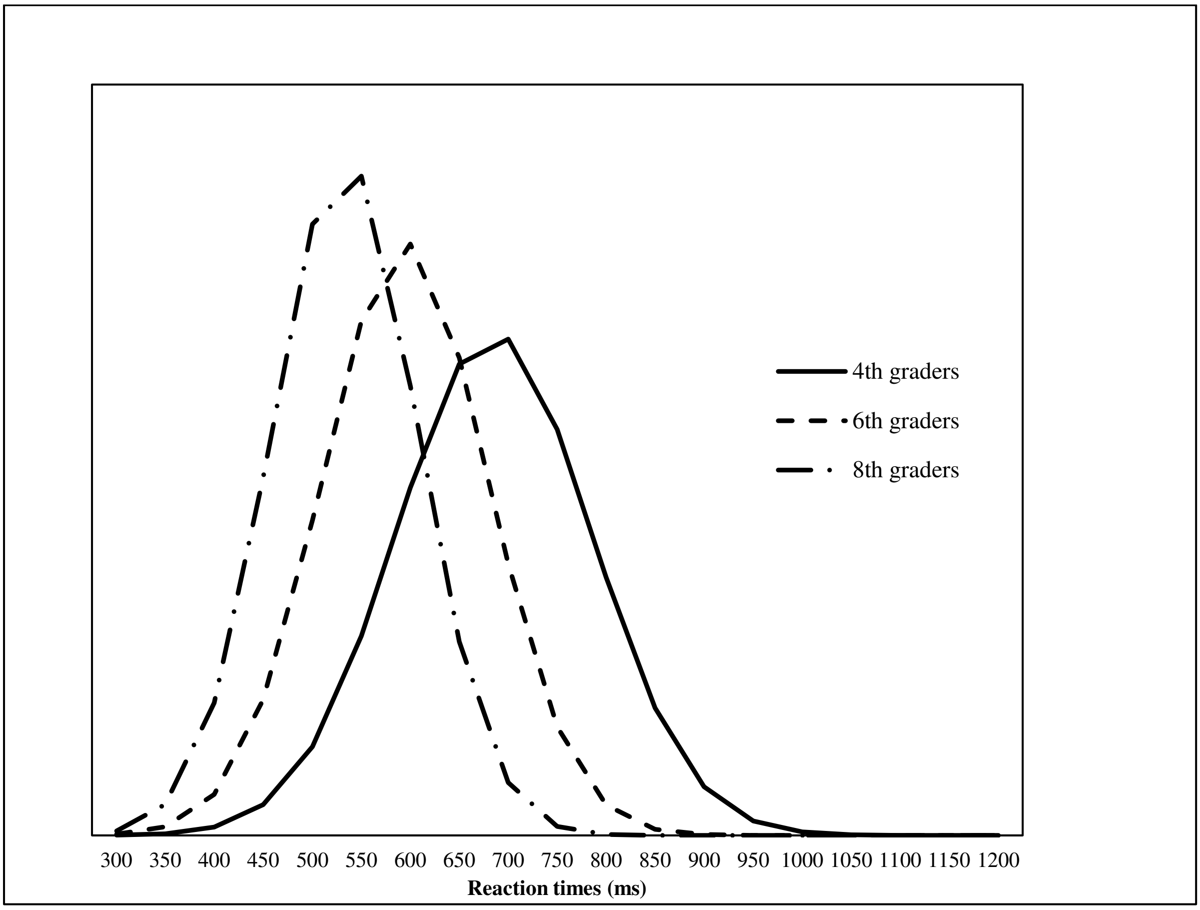

Figure 1. Response speed distributions - Distribution of reaction times for all correct trials (including congruent and incongruent trials) in the Simon task (mixed block) across the three age groups (4^{th}-, 6^{th}, and 8^{th}-graders).

Sequential effects surrounding errors. Trials following errors on congruent trials were excluded due to low trials counts (i.e., very few errors occurred on congruent trials). Trials surrounding an error on the incongruent trials were compared with trials surrounding a correct response to the incongruent trial. However, the number of sequential adjustment observations differed as a function of correctness (Schroder et al., 2019). That is, as performance was relatively accurate, there were more sequences surrounding a correct responses on an incongruent trial than surrounding an incorrect response on an incongruent trial. Further, to exclude the influence of double-errors, only correct congruent trials that preceded and followed incorrect and correct incongruent trials were included to explore sequential effects (Hajcak & Simons, 2008). On average, participants across all age groups made between 4 and 5 errors on incongruent trials in the course of the spatial conflict task, thus, there was no effect of Age group on the number of errors, $F(2, 206) = 1.61$, $p = .32$, $\eta_p^2 = .01$. Hence, response latencies surrounding errors across the three age groups are comparable. Figure 2 gives an overview over RT for correct and incorrect responses surrounding the incongruent trials, as a function of age. The different sequential effects were addressed by computing a series of separated mixed ANOVAs with different trial types and their corresponding responses latencies across the three age groups (see below). Adjustments for multiple group comparisons were made with Bonferroni corrections.

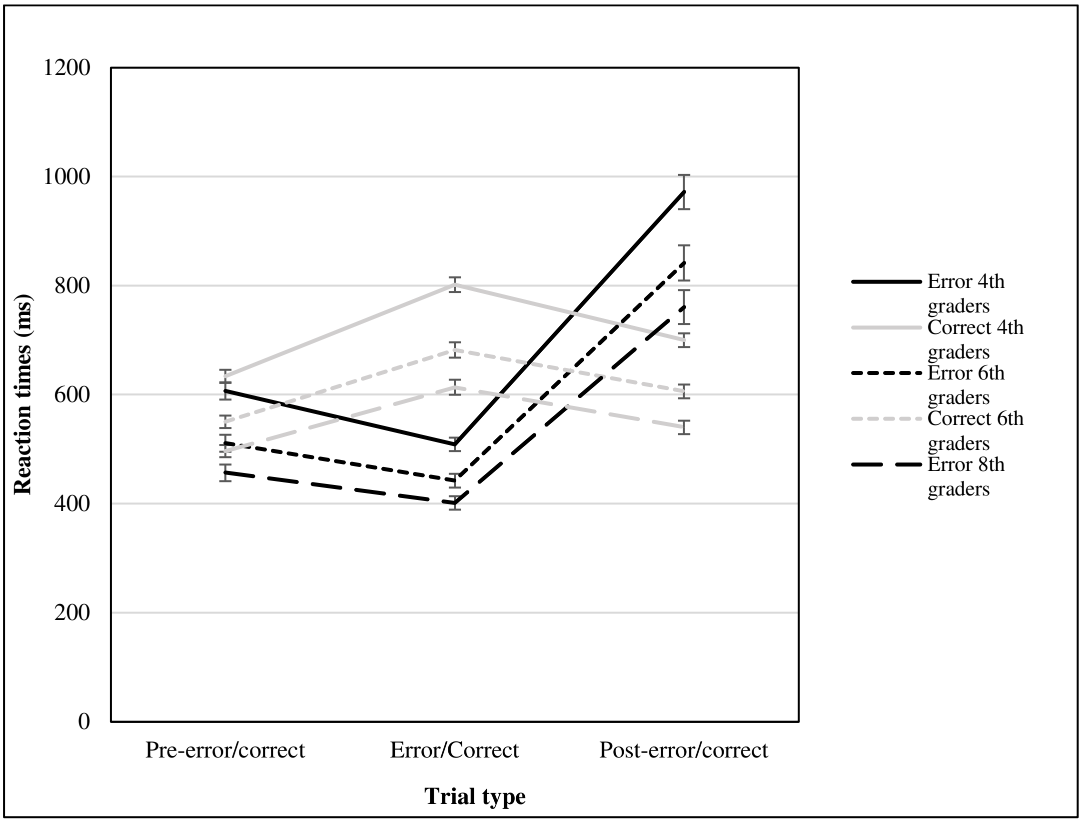

Figure 2. Sequential effects surrounding errors - Mean reaction times for pre-error/correct (correct congruent), error/correct (incongruent), and post-error/correct (correct congruent) trials in the Simon task (mixed block) across the three age groups (4th-, 6th, and 8th-graders). Standard errors of the means (SEM) are presented by the error bars. Separated mixed ANOVAs for sequential effects surrounding errors are reported in the result section.

Pre-Error Speeding. On the trial level, cognitive control tasks including the instruction to respond as fast and as accurate as possible allow investigating whether individuals tend to speed up their responses when the task is running smoothly, that is, when they are responding correctly (also called the "win-stay strategy"; Brewer & Smith, 1989). As speeded responses increase the risk of an error, this is also called pre-error speeding (Allain et al., 2009). To analyze whether children and young adolescents are using the "win-stay" strategy before committing an error, mean RT before (i.e., congruent trials with correct responses) and on incorrect incongruent trials were compared. [Readers are reminded that there was a substantial congruency effect (see above), that is, that congruent trials normally were responded to faster than incongruent trials]. A mixed ANOVA was conducted with Trial type (pre-error correct congruent vs. incorrect incongruent) as within-subject factor and Age group (4th vs. 6th vs. 8th grade) as between-subjects factor. Results revealed a significant main effect of Trial type, $F(1, 206) = 57.24$, p <.001, $\eta_p^2 = .22$, indicating that incorrect responses on incongruent trials were given substantially faster than on pre-error trials. Thus, individuals speeded up towards an error. Further, a significant main effect of Age group emerged, $F(2, 206) = 34.24$, $p < .001$, $\eta_p^2 = .25$, with all three age groups differing significantly from each other (4th graders: $M = 557.46$, $SE = 11.10$ > 6th graders: $M = 476.58$, $SE = 11.43$ > 8th graders: $M = 428.92$, $SE = 11.10$). The interaction between the within-subject factor Trial type and Age group was not significant, $p > .05$, suggesting that the pre-error speeding effect was comparable in the three age groups.

Impulsive Errors. We wanted to establish that errors occurred because participants reacted too fast. For this, mean RT on the incongruent trials were compared for correct versus incorrect responses. A mixed ANOVA was conducted with Response accuracy (correct vs. incorrect on the incongruent trials) as within-subject factor and Age group (4th vs. 6th vs. 8th grade) as between-subjects factor. Results revealed a significant main effect of Response accuracy, $F(1, 206) = 817.82$, $p < .001$, $\eta_p^2 = .80$, indicating that – indeed - incorrect responses were given substantially faster than correct responses on these incongruent trials. Further, a significant main effect of Age group emerged, $F(2, 206) = 49.40$, $p < .001$, $\eta_p^2 = .32$, with all three age groups differing significantly from each other (4th graders: $M = 655.07$, $SE = 10.62$ > 6th graders: $M = 562.16$, $SE = 10.93$ > 8th graders: $M = 507.38$, $SE = 10.62$). Interestingly, the interaction between Response accuracy and Age group was also significant, $F(2, 206) = 7.57$, $p < .001$, $\eta_p^2 = .07$. Following up on this interaction, results revealed that the difference between correct and incorrect responding on the incongruent trials was larger in the 4th graders compared to both, the 6th and 8th graders (who did not differ from one another), $F(2, 206) = 7.57$, $p < .01$, $\eta_p^2 = .07$. Thus, we found evidence for impulsive errors in all three age groups of typically developing participants, with the youngest age group being disproportionally susceptible for too fast responding, leading to impulsive errors on the incongruent trials.

Post-Error Slowing. In tasks as the Simon task used here, individuals can – theoretically –reactively control cognition. By means of accurate error monitoring, ideally, individuals can slow down *after* having committed an error to avoid future errors. In other words, the error itself is also processed and signals to the individual that the chosen task strategy needs to be adapted towards slower responding for optimizing accuracy of performance (Botvinick et al., 2001). To analyze whether children and young adolescents slowed down after committing errors, mean RT on incorrect incongruent trials (errors) and the following trial were compared with each other. A mixed ANOVA was conducted with Trial type (incorrect incongruent vs. post-error correct congruent) as within-subject factor and Age group (4th vs. 6th vs. 8th grade) as between-subjects factor. Results revealed a significant main effect of Trial type, $F(1, 206) = 582.82$, $p < .001$, $\eta_p^2 = .74$, indicating that incorrect responses ($M = 450.67$, $SE = 7.20$) were given substantially faster than responses on post-error trials ($M = 858.02$, $SE = 18.22$).

Further, a significant main effect of Age group emerged, $F(2, 206) = 18.17$, $p < .001$, $\eta_p^2 = .15$, with 8th graders ($M = 580.90$, $SE = 18.85$) responding significantly faster than both 6th graders ($M = 641.98$, $SE = 19.4$) and 4th graders ($M = 740.161$, $SE = 18.85$). [There was no significant difference between 6th graders and 8th graders, $p = .08$.] Interestingly, the interaction between Trial type and Age group was significant, $F(2, 206) = 3.27$, $p < .05$, $\eta_p^2 = .03$. Follow-up analyses on the interaction revealed that the difference in RT between error and the corresponding post-error trials was significant larger in the 4th graders compared to 8th graders, $F(2, 206) = 3.27$, $p < .05$, $\eta_p^2 = .03$. [The 6th graders did not differ from either age group.] Thus, while all three age groups were found to specifically and substantially slow down after having committed an error, indicative of efficient error monitoring, the magnitude of the RT adjustment was found to be substantially larger in the youngest compared to the two older age groups.

As we have shown that participants were especially fast responding on error trials, the post-error slowing reported in the previous paragraph may mirror a "back-to-normal-speed" RT adjustment rather than a specific processing of the error itself. It may suggest that there is a reactive action-taking on that error to avoid future ones. Therefore, we also addressed RT after committing an error on incongruent trials with RT after correct responses on an incongruent trial (e.g., Schroder et al., 2017). A mixed ANOVA was conducted with Trial type (post-error correct congruent vs. post-correct correct congruent) as within-subject factor and Age group (4th vs. 6th vs. 8th grade) as between-subjects factor. Results revealed a significant main effect of Trial type ($F(1, 206) = 236.65$, $p < .001$, $\eta_p^2 = .54$). This indicates that responses after an error on an incongruent trial were significantly slower ($M = 858.02$, $SE = 18.22$) than responses after a correct response on an incongruent trial ($M = 615.29$, $SE = 7.25$). This points towards a substantial, *specific* post-error slowing. Further, a significant main effect of Age group emerged, $F(2, 206) = 22.78$, $p < .001$, $\eta_p^2 = .18$, with all three age groups differing significantly from each other (4th graders: $M = 835.79$, $SE = 19.56$ > 6th graders: $M = 723.85$, $SE = 20.14$ > 8th graders: $M = 650.34$, $SE = 19.56$). The interaction between Trial type and Age group was not significant, $F(2, 206) = .95$, $p = .388$, $\eta_p^2 = .01$, suggesting that post-error slowing is independent of age, at least in this age range.

Discussion

The main goal of the present was to shed light on age-dependent qualitative changes in cognitive control based on typically developing children's and adolescents' ability to flexibly modulate the amount of cognitive control processes in presence of errors. The present study is one of the first studies to systematically and empirically investigate the developmental differences of speeded and controlled responses during an often understudied developmental period, that is, the transition from late childhood to young adolescence. Our results allow to better understand key mechanisms for developmental progression in cognitive control and to evaluate performance of atypically developing youths, as disproportional developments are rarely taken into account in studies including, for example, children and adolescents with ADHD.

A first hint that qualitative changes in cognitive control (Ambrosi et al., 2016; Chevalier, 2015; Chevalier et al., 2013; Gonthier et al., 2019) may be crucial when addressing top-down regulation in children and adolescents beyond the early primary school years was found when considering the distributions of RT across the entire task. The present study clearly revealed developmental progress in the ability to master the task with smaller fluctuations in RT, as became visible in the RT distributions for the three included age groups (see Figure 1). The narrower distribution of the older compared to the younger participants on the group level was confirmed in the smaller intra-individual variability on the individual level when younger and older participants were compared. Thus, in the course of development, individuals increasingly engage in proactive control, that is, increasingly learn to select and maintain a well-fitting speed of responding, allowing them to give speeded responses without disproportionally increasing the risk of errors. 4th graders' performance can be considered as less effective, as their RT fluctuated in a more pronounced way compared to 8th graders. For comparisons with clinical samples, these age differences in typically developing youth are highly relevant as they call for age-dependent comparisons. Further, the consistency of response latencies was also found to be substantially and negatively related to overall task accuracy independent of age, suggesting a sensitive behavioral marker of cognitive control dysfunction in clinical samples, such as children and adolescents with ADHD (e.g., Castellanos & Tannock, 2002).

Addressing the sequential effects with the aim to uncover reasons for the narrower RT distributions and the higher consistency of RT in older compared to younger participants revealed disproportionally coarser response time adjustments in the 4th graders as compared to the 6th and 8th graders. This was true for the errors themselves and for post-error slowing. Although all three age groups adjusted their speed of responding when the task was running smoothly, the uncovered sequential effects were stronger in the younger compared to the older participants when both RT of errors and post-error trials were considered. Thus, it seems safe to assume that the fine-tuning of speeded responses in the face of perceived cognitive conflict (infrequent incongruent trials: proactive cognitive control) or committed errors (error monitoring: reactive cognitive control) are key mechanisms for developmental progression in cognitive control in typically developing children. At the same time, these results call for age-matched samples when researching cognitive control in atypically developing individuals.

Concerning RT of error trials, it appears that younger compared to older participants adjusted their response threshold too easily and too liberally when the task was running smoothly, leading to an increased risk of erring (Brewer & Smith, 1989; Dudschig & Jentzsch, 2009), similar to what has been reported for ADHD children (Weigard, Heathcote, Matzke, & Pollock, 2019). As there were no age-dependent effect of pre-error speeding, results can be interpreted that even the 4th graders engaged in proactive control, but the efficiency of this process appeared yet less well developed. The alignment of their speed of responding was too strong, leading to impulsive behavior. Thus, 4th graders seemed to be susceptible for too fast responses and therefore may have committed more impulsive errors (e.g., double-errors, errors on congruent trials – not analyzed here). These findings are in line with studies showing that differences between correct and incorrect responding typically becomes smaller with increasing age (see Davies et al., 2004). From that perspective, ADHD children's impulsive reactions leading to often to unwanted behavior might be interpreted as a developmental delay in cognitive control.

Once an error had occurred, younger compared to older children also adjusted their RT more coarsely. All three age groups were found to substantially slow down after having committed an error (e.g., Brewer & Smith, 1989; see overview Smulders et al., 2016), but the amount of the recruitment of reactive control resources in anticipation of the next trial was found to be larger in the youngest compared to the two older age groups. While the metacognitive development literature suggests that typically developing 4th graders are relatively well able to monitor their performance, including errors (Roebers, 2017; Schneider & Löffler, 2016), the stronger post-error slowing in this age group suggests that yet, monitoring errors absorbs a substantially larger amount of cognitive resources in this than in older age groups, which in turn slows down the processing of the next trial more strongly. Moreover, RT after committing an error compared to RT after correct responses confirmed the interpretation of *specific* processing of the error itself (i.e., post-error vs. post-correct; Rabbitt, 1966; Rabbitt & Rogers, 1977; Schroder et al., 2017). Thus, besides impulsive responding, age-related changes in the efficiency of error monitoring and processing were uncovered contributing to developmental progression in cognitive control.

Conclusion

To conclude, the present study offers detailed insights into key mechanisms contributing to developmental progression in typically developing youth's cognitive control in a strongly understudied age range. As has been put forward in the developmental literature (Best, Miller, & Naglieri, 2012; Diamond, 2013), the handling of a task-inherent speed-accuracy trade-off appears to drive continuous improvements in the top-down regulation of cognitive conflict and may thus also be vulnerable to deficits. These ongoing developmental improvements align nicely with structural and functional changes on neural substrate through childhood and adolescence (Moffitt et al., 2011;

Wendelken et al., 2012). Our study shows that typically developing individuals become more reliable, more efficient, better adjusted, and thus overall better in cognitive control with increasing age. Healthy children and adolescents in this age range are increasingly achieving a well-balanced coordination of proactive and reactive modes of cognitive control. These abilities are visible and needed in many everyday life situations which call for fast and accurate behavior (e.g., traffic, social interactions, academic achievements).

These results offer not only new insights to a neglected cognitive domain but also offer practical implications that may be of great clinical relevance: they may help to better evaluate cognitive control and error monitoring in atypically developing individuals. The current findings of developmental trajectories in cognitive control and error monitoring may help to better understand behavioral correlates in vulnerable groups (such as ADHD) for whom impaired performance is relatively consistently documented (e.g., Liotti et al., 2005). These insights allow to better circumscribe the degree of deviation that would still be considered as within "the typical range". Methodologically, the narrowly defined age groups are a major strength of the current study as they enable confident comparisons when addressing atypically developing individuals' behavioral adjustments under cognitive control demands. Taken together, our findings may increase the awareness and comprehension of age-dependent cognitive control processes. In future work, researchers and practitioners may examine how to foster cognitive control, both in healthy and vulnerable youths.

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