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# Cognitive Control Across Adolescence: Dynamic Adjustments and Mind-Wandering

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Models of cognitive development suggest that cognitive control, a complex construct that ensures goal-directedness even in the face of distractions, is still maturing across adolescence. In the present study, we investigated how the ability to dynamically adjust cognitive control develops in this period of life, as indexed by the magnitude of the congruency sequence effect (CSE) in conflict tasks, and how this ability might relate to lapses of attention (mind-wandering [MW]). To these ends, participants from four age groups (12–13, 14–15, 18–20 and 25–27 years old) completed confound-minimized variants of the flanker and Simon tasks, along with a Go/No-Go task with thought probes to assess their frequency of mind-wandering. The CSE was present in both tasks, but was not affected by age in either of them. In addition, the size of the CSE in the flanker, but not in the Simon task was negatively associated with the frequency of MW with awareness. Trait MW and the probability of reporting MW during the task was found to increase with age in accordance with cognitive resource views of MW. Our findings suggest that at the behavioral level there are no substantial developmental changes through the adolescent period in control adjustment ability as measured by the CSE. Response inhibition performance in the Go/No-Go task, however, improved significantly with age. The implications of the present results for the conflict monitoring account of the CSE and extant theories of MW are discussed.

*Keywords:* adolescence, cognitive control, congruency sequence effect, mind-wandering

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Cognitive control refers to a collection of processes involved in setting and adjusting attentional biases to carry out goal-relevant actions (Gratton, Cooper, Fabiani, Carter, & Karayanidis, 2018). According to multiple models of development, these processes are still maturing and improving across adolescence (e.g., Casey, Getz, & Galvan, 2008; Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015; Luna & Wright, 2015; Steinberg, 2008; Steinberg et al., 2018); a period of life defined here as beginning around the age of 10 and lasting until one's midtwenties (Casey, 2015; Shulman et al., 2016). Neurobiological findings support the notion of protracted development as many control-related brain areas are still maturing and their activation patterns are still changing across this developmental period (for reviews, see Casey, Galvan, & Hare, 2005; Casey & Jones, 2010; Luna et al., 2015), such as those of the prefrontal cortex (PFC; Gogtay et al., 2004; Spear, 2000) or the anterior cingulate cortex (ACC; Eshel, Nelson, Blair, Pine, & Ernst, 2007).

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All data files and analysis scripts for this submission are available on the Open Science Framework website at https://osf.io/7vbtr/.

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At the behavioral level, aspects of cognitive control are often gauged with the help of response inhibition tasks. Response inhibition is a component process of cognitive control that involves overcoming prepotent but momentarily goal-irrelevant responses in favor of goal-relevant ones (Gratton et al., 2018). Some studies have shown protracted maturation of response inhibition across adolescence as indicated by the rate of successful performance on tasks that require participants to withhold a dominant response that temporarily becomes incorrect (e.g., stop-signal tasks, Vink et al., 2014, or Go/No-Go tasks, Braet et al., 2009; Carriere, Cheyne, Solman, & Smilek, 2010; Luna, Padmanabhan, & O'Hearn, 2010; Rubia et al., 2006; Somerville, Hare, & Casey, 2011; Stawarczyk, Majerus, Catale, & D'Argembeau, 2014). Studies using conflict tasks, on the other hand, have yielded somewhat inconsistent results. In these tasks, participants have to identify a task-relevant stimulus dimension while ignoring a task-irrelevant dimension. On congruent trials, the two dimensions prime the same response, whereas on incongruent trials, the irrelevant dimension primes an incorrect response. Performance is typically slower and less accurate on incongruent compared with congruent trials, a difference known as the interference or congruency effect. Some studies investigating adolescence found that the magnitude of the interference effect decreases with age (e.g., Huizinga, Dolan, & van der Molen, 2006; Marsh et al., 2006; at least up to a certain point, e.g., 14–15 years of age, Waszak, Li, & Hommel, 2010), others found that it increases in RTs (e.g., Duell et al., 2018; Rubia et al., 2006), but decreases in accuracy (e.g., Duell et al., 2018), whereas some found no change in the effect across adolescence at all (e.g., Adleman et al., 2002; Andrews-Hanna et al., 2011; Veroude, Jolles, Croiset, & Krabbendam, 2013). This heterogeneity across studies might be in part attributable to methodological differences, for example, the type of conflict task that was used, or the particular age ranges that were investigated.

Irrespective of the exact developmental pattern in behavioral interference resolution, it is clear that interference has an effect on performance in all age groups. One aspect of cognitive control that has received relatively little attention in the developmental literature thus far is how inhibitory control is adjusted dynamically in response to the occurrence of interference. It has been shown that the magnitude of the interference effect is modulated by the congruency of the previous trial, such that the congruency effect is smaller following incongruent compared with congruent trials (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014b; Gratton, Coles, & Donchin, 1992); a sequential modulation known as the congruency sequence effect (CSE). According to the most prominent account of the CSE, the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004), this effect reflects a dynamic, top-down adjustment of control levels after conflict is detected by a dedicated conflict monitoring unit. At the neural level, the effect is considered to be a consequence of communication between the ACC which is responsible for the detection of conflict, and the dorsolateral PFC which is thought to modulate control levels (Botvinick et al., 2001, 2004). Because maturation of the cognitive system across adolescence is characterized by the refinement of communication between different neural systems supporting cognitive control (Luna et al., 2015), the CSE might be particularly sensitive to developmental changes in this period.

Therefore, the present study was designed to investigate how the ability to dynamically adjust control in such a manner changes across adolescence at the behavioral level, if at all. However, certain regularities in the task sequence of typical conflict tasks can make it difficult to interpret the CSE purely as an indicator of dynamic control adjustments (Duthoo et al., 2014b; Egner, 2007; Schmidt, 2013). We will briefly outline these learning- and memory-related confounds, to illustrate their effect on the interpretation of the CSE, and to highlight the importance of controlling for them.

In standard two-alternative variants of conflict tasks, exact stimulus repetitions on congruent trials preceded by congruent trials (cC trials) and incongruent trials preceded by incongruent trials (iI trials) will speed responding via response priming compared with congruent trials preceded by incongruent trials (iC trials) and incongruent trials preceded by congruent trials (cI trials), generating a CSE-like pattern (Mayr, Awh, & Laurey, 2003). Furthermore, Hommel, Proctor, and Vu (2004) suggested that even partial stimulus repetitions on cI and iC trials can complicate interpretations, as the repeated stimulus feature can activate the event file associated with the previous trial (i.e., a representation that contains both stimulus and response characteristics). As this outdated event file then needs to be overwritten, performance is slowed on these trials, once again resulting in a CSE-like pattern.

Increasing the number of stimulus features and responses used in the task from two to four can solve the feature repetition problem because complete and partial stimulus repetitions can be removed from analyses or avoided altogether. However, this solution introduces a new confound (Mordkoff, 2012; Schmidt & De Houwer, 2011). In a four-alternative task, a 50% congruent trial sequence is typically generated by inflating the number of congruent trials compared with what would be expected if stimulus features were combined randomly. For example, to maintain 50% congruence in a four-arrow flanker task, a right-ward central arrow would have to be paired with right-ward distractors three times as often as with left-, up-, or downward arrows. This would mean that a rightward distractor is paired more often with a rightward response than with any other response; in other words, a contingency would exist between the distractor and the congruent response. This would result in the supposedly task-irrelevant dimension becoming informative. Importantly, Schmidt, Crump, Cheesman, and Besner (2007) found that not only do individuals respond faster to high-contingency trials compared with low-contingency trials in a nonconflict task, the size of this contingency effect is also modulated by previous trial contingency. Since contingency is perfectly confounded with congruency in four-alternative 50% congruent trial sequences, this sequential contingency modulation can account for the CSE-pattern as well. Therefore, it is important to control for the effects of stimulus repetitions and contingency learning if one wants to interpret the CSE in terms of control adjustments. Notably, recent studies have found the CSE pattern even after removing feature repetitions and target-distracter contingencies from the trial sequence, lending credence to the view that the CSE can occur in the absence of learning and memory confounds, presumably as a function of control adjustments (e.g., Aschenbrenner & Balota, 2017; Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a; Schmidt & Weissman, 2014; Weissman, Colter, Drake, & Morgan, 2015).

Developmental studies of the CSE in children found that 5- to 7- and 6- to 8-year-olds already show sequential modulation (Ambrosi, Lemaire, & Blaye, 2016; Iani, Stella, & Rubichi, 2014), and Larson, Clawson, Clayson, and South (2012) found no difference in the size of the CSE between 9-year-old children and 22-year-olds. Smulders, Soetens, and van der Molen (2018) also found no significant age differences between children, preadolescents, and a group of late adolescents and young adults (18–25 years old) after controlling for baseline speed differences between groups. These studies, however, have all contained either feature repetition or both feature repetition and contingency learning confounds. Notably, using a confound-minimized flanker task, Cragg (2016) also found no age difference in the CSE between 7-, 10-, and 20-year-olds, groups that might correspond to children, preadolescents, and late adolescents, respectively. Similarly, Waxer and Morton (2011) who used a complex modified conflict task with an additional task-switching manipulation, found no difference in the size of the CSE between midadolescents (14–15 years old) and an older group consisting of both late adolescents and young adults (18–25). One empirical finding, however, that supports the idea that some control-related processes show protracted maturation comes from a study by Erb and Marcovitch (2018) who decomposed the CSE into a response threshold adjustment process and the controlled, top-down selection of the target response using reach tracking, and found that the latter process showed significant gains between preadolescents (10–12 years old) and a group of both late adolescents and young adults (18–24 years old). Their task, however, also contained confounds, further underlining the necessity to study potential age-related changes in the CSE using confound-minimized paradigms where control-related processes are isolated, and appropriate adult comparison groups that do not overlap with late adolescence.

Consequently, the present study was designed to investigate changes in dynamic control adjustments across adolescence using confound-minimized variants of two commonly used conflict tasks, the flanker (Eriksen & Eriksen, 1974) and the Simon task (Simon, 1969), in four age groups: early adolescence (12–13 years old), mid-adolescence (14–15), late adolescence (18–20), and young adulthood (25–27). These two tasks were chosen because a recent study (Aschenbrenner & Balota, 2017) concluded that the CSE in these two paradigms likely reflects a cognitive control adjustment mechanism, whereas the CSE found in the color-word Stroop task (Stroop, 1935) might reflect a priming-related mechanism.

Based on previous findings (Ambrosi et al., 2016; Cragg, 2016; Iani et al., 2014) we expected to find the CSE in every age group. Furthermore, based on models of cognitive control development (Shulman et al., 2016) the CSE was predicted to increase in magnitude across the age groups, reflecting greater deployment of top-down control in response to changing task demands as a function of age, in line with previous studies that interpreted larger CSEs in the Simon and flanker tasks as reflecting better control modulation (e.g., Aschenbrenner & Balota, 2017). An alternative interpretation of CSE magnitude could be that a larger modulation actually means that there is less cognitive control deployed to tackle conflict in the first place, leading to incongruence impacting performance to a greater extent, therefore smaller CSEs might be an indicator of optimal performance. This would lead to the alternative hypothesis that the CSE should decrease across age as control matures. Importantly, both interpretations suggest that (a) the CSE indexes some control related phenomenon, and (b) its magnitude should change across age. Challenging the latter prediction are previous empirical findings that suggest control adjustment abilities reach maturity in late childhood (Cragg, 2016; Larson et al., 2012; Waxer & Morton, 2011). If that is the case, we might see no substantial age differences in the CSE at all.

## Mind-Wandering, Cognitive Control, and Age

In addition to the control of attention across age groups, we also investigated lapses in attention in our sample, as captured by mind-wandering (MW). We aimed to explore the relationships between development and MW, and cognitive control and MW. MW is a multidimensional construct that includes a wide variety of subjective experiences (Seli et al., 2018), and in the present study, was defined as task unrelated thoughts occurring during goal-directed activities (e.g., Gyurkovics, Balota, & Jackson, 2018; Jackson & Balota, 2012). Flexible cognitive control may be imperative in refocusing attention to the task once the mind has wandered, as such, more flexible modulation of control may be associated with less time spent in MW during the task. Based on this notion, Drescher, Van den Bussche, and Desender (2018) investigated the relationship between the CSE in a flanker task, and MW frequency as captured by performance on the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), a Go/No-Go task often used in MW research because of its unengaging nature (e.g., Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Gyurkovics et al., 2018; Jackson & Balota, 2012). The authors expected a negative relationship in accordance with a "bigger means better control deployment" interpretation of the CSE. No reliable relationship was found, but numerically the coefficients were in accordance with predictions. We examined whether the association between the CSE and MW frequency was present in a larger sample using two different conflict tasks and generalized linear mixed-effects models to maximize the power of analyses.

Finally, we investigated age-related differences in MW across adolescence both at the state and the trait level. We formulated two competing hypotheses. Theories that consider MW to be a consequence of failures of executive control (e.g., McVay & Kane, 2010, 2012) would predict that MW decreases in frequency as a function of age as executive abilities mature. This is also in line with our previous hypothesis that better control regulation would be associated with less MW. However, there is another prominent view of MW which considers this type of cognition to be resource dependent (Smallwood & Schooler, 2006), and receives support from aging studies that find that older adults tend to report fewer instances of MW during a task (e.g., Giambra, 1989, 2000; Jackson & Balota, 2012; for a recent review see Maillet & Schacter, 2016), in everyday life (Maillet et al., 2018), or at the trait level (Seli, Maillet, Smilek, Oakman, & Schacter, 2017), than young adults, possibly because cognitive resources decline with age, thus older adults have fewer resources left over to maintain a task unrelated train of thought when already engaged in a task. This view would predict that the frequency of MW should increase as a function of maturation (and an associated increase in resources, e.g., Conklin, Luciana, Hooper, & Yarger, 2007; De Luca et al., 2003; Luna, Garver, Urban, Lazar, & Sweeney, 2004) in our study.

To our knowledge, thus far only one study has compared adolescent MW rates with adult MW rates to explore developmental changes in MW frequency (Stawarczyk et al., 2014). Based on their responses to probe questions embedded in the SART, mid-adolescents (14-to 16-year-olds) did not differ from a group of late adolescents and adults (19- to 26-year-olds) in how frequently they experienced MW, defined as task-unrelated thoughts while attention was decoupled from the environment, but they did report being distracted by external events more frequently during the task than did young adults. Consequently, in the current study, we explored whether age-related changes in MW frequency might become apparent if MW reports are differentiated based on the associated level of metacognition (i.e., were they aware that their mind had wandered before the probe question; Jackson & Balota, 2012; Smallwood, McSpadden, & Schooler, 2007). Furthermore, in this study we also investigated possible changes in MW across different stages of adolescence early, mid- and late; and contrasted these groups with young adults in their late twenties, above even the most liberal upper limit of adolescence (age 24; Shulman et al., 2016).

Although the main focus of our study was self-reported MW, proposed behavioral indices of MW such as Go and No-Go accuracy, and reaction time (RT) variability to Go trials (Cheyne, Solman, Carriere, & Smilek, 2009) were also investigated, both across adolescence and with respect to cognitive control. Furthermore, age-related differences in SART performance were also examined because of the wealth of previous findings showing that Go/No-Go task performance improves with age (Braet et al., 2009; Carriere et al., 2010; Rubia et al., 2006; Stawarczyk et al., 2014).

## Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Data files and the analysis script for this study are available on the Open Science Framework at the following URL: https://osf.io/7vbtr.

### Participants

Participants with normal or corrected-to-normal vision were recruited from four different age groups: (a) early adolescents ($n$ = 30, 10 females, mean age = 12.43, $SD$ = .57, age range: 12–13, mean pubertal development score (Carskadon & Acebo, 1993): 2.17, $SD$ = .57), (b) midadolescents ($n$ = 25, 16 females, mean age = 14.36, $SD$ = .49, age range: 14–15, mean pubertal development score: 3.07, $SD$ = .51), (c) late adolescents ($n$ = 28, 19 females, mean age = 18.57, $SD$ = .57, age range: 18–20), and (d) young adults ($n$ = 25, 16 females, mean age = 25.76, $SD$ = .78, age range: 25–27). We aimed to collect 30 participants in each age group, as previous studies, and a pilot study conducted by the authors (data available on request), were able to detect the CSE with a sample of this size, and this number was attainable given other, practical constraints as well (time and funding available). Deviations from the target number are primarily attributable to the removal of some participants because of neurological or psychiatric problems undisclosed during recruitment. Participants were recruited through social media, via a volunteers' database maintained by the University of Sheffield, and from among the undergraduate and postgraduate students of the same University. Every volunteer received £10 as compensation for their time taking part. The study was approved by the Ethics Committee of the Department of Psychology, University of Sheffield.

### Materials

**Conflict tasks.** Participants completed two conflict tasks: the flanker task and the Simon task. In the flanker task, participants had to identify the direction the central target arrow was pointing in (left, right, up, or down) from a string of five arrows displayed in the center of the screen. On congruent trials, the arrows all pointed in the same direction, whereas on incongruent trials the target arrow in the middle pointed in a different direction from the other four, flanking arrows. In the Simon task, participants only saw a single arrow on each trial, and had to identify which direction it was pointing in, regardless of the location it was presented in. Arrows could be presented either above, below, to the left of, or to the right of fixation. On congruent trials the location and the direction of the arrow matched (e.g., an upward pointing arrow above fixation), whereas on incongruent trials they were the opposite (e.g., a downward pointing arrow below fixation).

Both tasks started with 24 practice trials which were extended with an additional 12 trials if the participant did not give at least 19 correct responses on the first 24 trials. Feedback was given after every trial during the practice session. Experimental sessions consisted of three blocks of 97 trials separated by short self-paced breaks, resulting in a total of 291 trials for both tasks. In each block, there were 24 trials in each condition (cC, iC, iI, cI). The first trial in each block had no previous congruency, and was not included in CSE analyses. The congruency of the first trial was determined randomly for each block.

The following measures were taken to control for both feature integration and contingency confounds: the four stimulus values (left, right, up, down) were divided into two pairs. In the flanker tasks, this was done randomly (any direction could be paired with any other), while in the Simon task, right was always paired with left, and up was always paired with down. Only values from one pair were used on odd trials, and values from the other pair on even trials to create the target (e.g., if right (R) was paired with up (U), and left (L) with down (D) in the flanker, incongruent trials could be RRURR or UURUU on odd/even trials, and LLDLL or DDLDD on even/odd trials, but never RRDRR, LLULL, and so forth). In other words, the trial sequence was alternating between two two-value variants of the same task. This guaranteed that no features were repeated, and ensured that the irrelevant stimulus feature was not disproportionately predictive of the correct answer. This method has been used in previous studies to control for these two confounds (Aschenbrenner & Balota, 2017; Jiménez & Méndez, 2013; Kim & Cho, 2014; Schmidt & Weissman, 2014; Weissman, Jiang, & Egner, 2014).

Following the design used by Aschenbrenner and Balota (2017), the following sequence of events occurred on each trial, in both tasks: a fixation cross was displayed for 500 ms, followed by a blank screen for 200 ms. After this, the target stimulus was presented for 3000 ms, or until a response was made. Participants had to indicate the direction of the target arrows by pressing the 2, 4, 6, or 8 keys on the numeric keypad to respond down, left, right, or up, respectively. Participants were asked to use the index finger of their dominant hand. Following the target stimulus, a blank screen was presented for 1,000 ms if the response to the target was correct. On incorrect trials an error message was displayed for 1,000 ms instead of the blank screen, saying either "ERROR" if the participant pressed an incorrect key, or "TOO SLOW" if the participant failed to respond within the response deadline. Finally, the message "Press 5 to continue" appeared on screen, until the participant pressed the 5 key on the number pad, and started the next trial. This was done to ensure that the participant's index finger was equal distances away from all four response buttons.

**Sustained Attention to Response Task (SART) with thought probes.** In the SART (developed by Robertson et al., 1997), the task of the participants was to press the SPACE bar every time a digit between 1 and 9 appeared on screen, except if that number was 3. In other words, digits 1, 2, and 4 to 9 were identified as Go stimuli, and the number 3 was identified as the No-Go stimulus. With the exception of number identity, Go and No-Go trials were identical. There were two blocks of 131 trials, resulting in a total of 262 trials. The two blocks were separated by a short self-paced break. Out of the 262 trials, 224 (85.5%) were Go trials, and 28 (10.69%) were No-Go trials. On the remaining 10 trials (3.82%) instead of a digit, participants saw the following probe question until they responded: "Please choose the one option below that best describes your experience with the task just now" (see Gyurkovics et al., 2018; Jackson & Balota, 2012). The options were "I was thinking about the task," "My mind was blank," "My mind drifted to things other than the task, but I wasn't aware of it until you asked me," and "While doing the task I was aware that thoughts about other things popped into my head," corresponding to on-task thoughts, space outs, zone outs, and tune outs, respectively (Smallwood et al., 2007). Trials were intermixed pseudorandomly, so that targets (No-Go trials) were never preceded or immediately followed by another target or a probe. Proportions of different trial types were identical across the two blocks. On digit trials (Go or No-Go trials), a digit in white was presented on black background in the center of the screen for 1,250 ms. The stimulus was then followed by an intertrial interval of 1,250 ms, during which a blank black screen was presented. No performance feedback was provided during the experimental blocks. The two experimental blocks were preceded by three practice blocks. In the first, participants completed nine trials (1 target), and received feedback on their performance after each one. In the second one, participants similarly completed nine trials with feedback; however, this time a probe question was also added. In the final practice block, nine trials and a probe appeared, with no feedback. As such, this practice block was identical to the experimental blocks. All tasks were programmed using the Psychtoolbox extension in MATLAB R2014b.

## Procedure

After obtaining informed consent from participants and their parents in the case of participants who were under 18, they first completed the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) for the first time (PANAS1) to measure their baseline emotional state prior to the start of the session. Then the experimenter administered the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999). This took approximately 15–20 min. After this, the participant was seated at a computer, and the two conflict tasks (the flanker and the Simon tasks) were completed. Their order was counterbalanced across participants. The two tasks together took approximately 30–40 min to complete. As the next step, the PANAS was completed for the second time (PANAS2), followed by the State–Trait Anxiety Inventory (STAI; Spielberger, 1989), and the Mind-Wandering Questionnaire (MWQ; Carriere, Seli, & Smilek, 2013) that measures the everyday frequency of deliberate and spontaneous MW. Early and midadolescents also completed a self-rated measure of pubertal development (Carskadon & Acebo, 1993). Finally, the SART was run, which lasted approximately 10–15 min. Altogether one experimental session lasted about 75–90 min. Descriptive data for the individual difference measures can be found in Supplemental Table 1 in the online supplemental materials. With the exception of the MWQ individual difference measures were collected as part of standard practice in our lab to enable better characterization of each age group but no hypotheses were formulated regarding these variables and their association with cognitive control.

## Statistical Analysis

Before statistical analyses, RTs shorter than 150 ms were removed. This resulted in the removal of only 0.05% of trials in the flanker, 0.08% of trials in the Simon, and 1.60% of trials that had RTs in the SART. Then outliers, identified as trials with RTs beyond 3 SDs of the participant's mean were also removed. This resulted in the removal of 1.55%, 1.69%, and 1.44% of trials in the flanker, Simon, and SART, respectively. For RT analyses in the conflict tasks, error trials and trials immediately following error trials were also removed. For accuracy analyses, these trials were retained.

Age effects in behavioral performance on the tasks were investigated with linear mixed-effects modeling using the "lme4" package in R (Bates, Maechler, Bolker, & Walker, 2015). For the flanker and the Simon tasks, predictors Current Trial Congruency (coded as 0 and 1 for congruent and incongruent, respectively), Previous Trial Congruency (coded as 0 and 1 for congruent and incongruent, respectively), Age Group (with young adults serving as reference category), and all their interactions were specified as fixed effects, with RT as an outcome variable, and a random effect of participants. The random effects structure was determined by examining the Akaike Information Criterion (AIC) values of models containing no random slopes, only random intercepts per participant; random slopes for Current Congruency, and random slopes for the Current Congruency × Previous Congruency interaction. The model with the lowest AIC value was selected. The Type II ANOVA table of the final model generated by the Anova() function from the "car" package (Fox & Weisberg, 2019) is reported. Follow-up pairwise analyses for interactions containing group were conducted using the "emmeans" R package (Lenth, 2018). For accuracy analyses similar generalized linear mixed-effects models were run. For the sake of brevity, accuracy analyses are only reported if they in any way contradict or complement RT findings. Descriptive accuracy data is presented in Supplemental Table 2 in the online supplemental materials. Furthermore, the code for supplementary models containing different control variables that may affect findings (e.g., baseline mood, IQ, or sex) is available on the project's OSF page at https://osf.io/7vbtr/.

Accuracy and RT data from the SART was analyzed using a strategy identical to the one outlined above, with the exception that the variables included in these models were Trial Type (Go or No Go, coded as 0 and 1, respectively) and Age Group. Reaction time variability changes as a function of age were investigated with a between-subjects ANOVA. The outcome variable was the Go stimulus coefficient of variation (CV; Go RT *SD*/*M* Go RT).

To investigate the relationship between self-reported MW and cognitive control (i.e., the size of the CSE), generalized linear mixed-effects models were used. In these analyses, binary dummy variables indicating whether a given thought report category was chosen in response to a probe question or not were the outcome variables. The magnitude of the CSE for each participant was calculated using the formula (cI − cC) − (iC − iI) where each letter combination corresponds to the mean RT of that condition. Random intercepts per participants were specified to account for multiple observations (i.e., probe questions) by individual. This strategy is similar to the one used by Van den Driessche et al. (2017). This same strategy was used to analyze group differences in MW frequency. Generalized linear mixed-effects models were also used to examine the relationship between SART accuracy—a proposed behavioral indicator of MW—and cognitive control. The results of the Anova() function are reported, along with exponentiated coefficients (odds ratios [*OR*s]) where appropriate. Pearson correlations were used to investigate whether cognitive control and behavioral variability (Go trial CV) are related. Finally, Kendall rank correlation was used to investigate the relationships between SART accuracy and self-reported MW, and behavioral variability and self-reported MW.

The α level was set at .05 in all analyses.

## Results

### Conflict Tasks

**Reaction time analyses.** Raw RTs were analyzed first (for means and *SD*s, see Supplemental Table 3 in the online supplemental materials). Table 1 contains the relevant terms of the various models run. In the flanker task, a model with random slopes for the Previous Congruency × Current Congruency interaction was selected over a model with only random intercepts, and a model with random slopes for the effect of Current Congruency only. A main effect of Congruency was found, indicating slower responses on incongruent compared with congruent trials. This was modulated by Previous Congruency, in other words, a reliable CSE was found. However, the CSE by Age Group interaction did not approach significance. Figure 1 shows the CSE by age groups.

In the Simon task, similarly to the flanker, the model with random slopes for the Previous Congruency × Current Congruency interaction was preferred, as opposed to the model with only random intercepts, or the model with random slopes for the effect of Current Congruency only. A significant Congruency effect and a CSE were found in this task too. The CSE was not significantly modified by Age. Figure 2 depicts the CSE by age groups in the Simon task.

The same pattern of results emerged for the terms of interest after controlling for baseline speed differences across groups by standardizing RTs on each participant's mean and *SD* (Supplementary Figures 1–2, for descriptive data, see Supplementary Table 3). As can be seen in Table 1, the Age Group × Current Congruency interaction was significant in these analyses in both tasks. Early adolescents showed smaller congruency effects than late adolescents and adults in both tasks (all $ps < .05$). Midadolescents also differed from the two older groups in the flanker task.

**Exploratory analyses.** We conducted additional cross-task analyses, examining the two conflict tasks together. These analyses were run to explore whether the CSE interacts with Task, and whether the CSE by Age Group interaction interacts with Task. A significant Previous Congruency × Current Congruency × Task interaction was found, both in raw and standardized RT, $\chi^2(1) = 12.19$, $p < .001$, and $\chi^2(1) = 17.33$, $p < .001$, respectively, reflecting the fact that the CSE was bigger in the Simon compared with the flanker task. The Previous Congruency × Current Congruency × Task × Age Group interaction did not reach significance.

### Sustained Attention to Response Task (SART)

**Behavioral performance.** Indices of behavioral performance on the SART are summarized in Table 2. For RT analyses, the model with random slopes for Trial Type per participant was preferred over a model that only contained random intercepts (AIC values: 299341.3 and 299364.4, respectively). The main effects of Trial Type and Age Group were significant, $\chi^2(1) = 183.90$, $p < .001$, and $\chi^2(3) = 45.75$, $p < .001$, respectively. Participants were faster on incorrect No-Go trials than on correct Go trials, and early adolescents were generally slower than any other group (all $ps < .01$). When standardized RTs were examined to control for the baseline speed difference across groups, only the random intercepts model converged. Trial Type still had a main effect, $\chi^2(1) = 208.63$, $p < .001$, but neither of the other effects approached significance.

When accuracy was analyzed, main effects of Trial Type and Age Group were found, $OR = .012$, 95% CI [.006, .024], $\chi^2(1) = 552.09$, $p < .001$, and $\chi^2(3) = 17.97$, $p < .001$, respectively. As would be expected, participants were more error-prone on No-Go trials than on Go trials, and early adolescents were more error-prone than late adolescents or adults (all $ps < .05$). The Trial Type × Age Group interaction was significant in this analysis, $\chi^2(3) = 10.07$, $p = .018$, with a bigger difference between the two conditions in early adolescents compared with young adults ($p = .011$).

To examine RT variability, the coefficient of variation (CV) was calculated for each participant (correct Go trial RT *SD*/correct Go trial RT *M*). This was significantly different across groups, $F(3, 102) = 8.60$, $p < .001$. The CV in early and midadolescents was significantly different from late adolescents and adults (all $ps < .05$), suggesting that intraindividual variability in RT on correct Go

Table 1
*Terms of Interest From the Four General Linear Mixed-Effects Models Investigating the Conflict Task Performance Across Age Groups*

| Model (AIC value) | Flanker—Raw RT (373188.6) | | | Flanker—*z*-scored RT (82204.5) | | | Simon—Raw RT (377831.5) | | | Simon—*z*-scored RT (78557.6) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Effect | $\chi^2$ | *df* | *p* | $\chi^2$ | *df* | *p* | $\chi^2$ | *df* | *p* | $\chi^2$ | *df* | *p* |
| Age group | 33.52 | 3 | <.001 | .40 | 3 | .940 | 38.93 | 3 | <.001 | .15 | 3 | .985 |
| Congruency (C) | 314.52 | 1 | <.001 | 572.26 | 1 | <.001 | 588.52 | 1 | <.001 | 1130.92 | 1 | <.001 |
| Previous congruency (PC) | 2.57 | 1 | .109 | 8.98 | 1 | .003 | 14.36 | 1 | <.001 | 10.56 | 1 | .001 |
| C × Age Group | 6.33 | 3 | .096 | 20.28 | 3 | <.001 | 2.24 | 3 | .524 | 14.50 | 3 | .002 |
| PC × Age Group | .22 | 3 | .975 | 1.04 | 3 | .792 | 6.94 | 3 | .074 | 6.00 | 3 | .112 |
| PC × C (CSE) | 13.20 | 1 | <.001 | 17.25 | 1 | <.001 | 62.92 | 1 | <.001 | 105.39 | 1 | <.001 |
| PC × C × Age Group | 1.55 | 3 | .671 | 4.57 | 3 | .206 | 7.54 | 3 | .057 | 4.79 | 3 | .188 |

*Note*. CSE = congruency sequence effect; AIC = Akaike information criterion. For raw RT analyses, models with random slopes for the PC × C interaction were selected over models with a slope only for C, or no random slopes at all. The AIC values of the competing models in the flanker were: 37,3209.4 for C slope model, and 37,3525.9 for no slope model. In the Simon: 37,7837.7 for C slope model, and 37,8317.3 for no slope model. For *z*RT analyses, the C slope models were favored. The AIC value of competing models in the flanker: 82,214.5 for PC × C slope model (failed to converge), and 82,394.6 for no slope model. In the Simon: 78,562.6 for PC × C slope model (failed to converge), and 78,777.8 for no slope model.

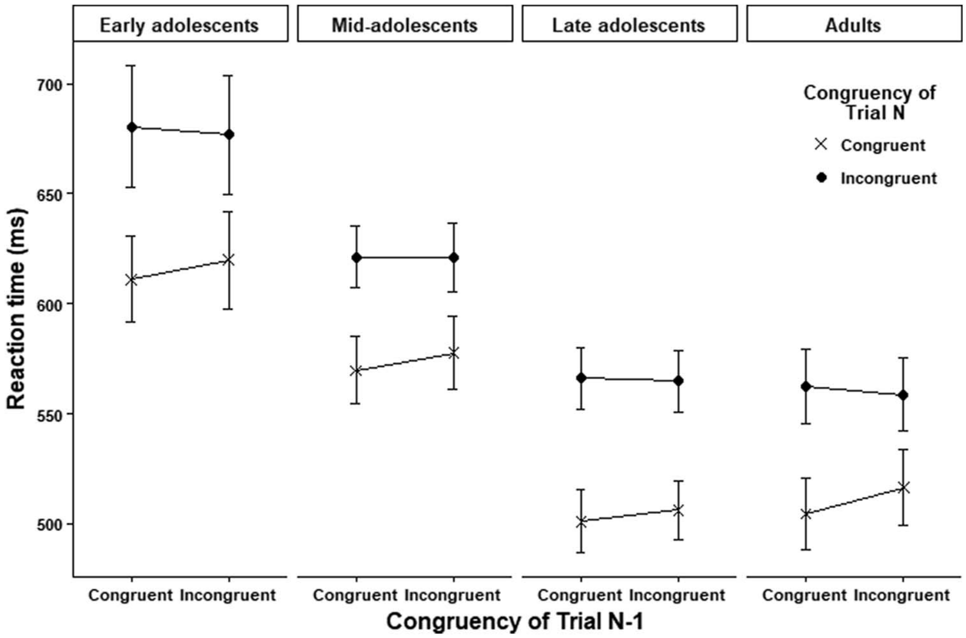


*Figure 1.* The effect of congruency as a function of previous trial congruency, or the congruency sequence effect in raw RT in the flanker task. Error bars represent ±1 *SE*.

trials was higher in the two under-18 compared with the over-18 age groups.

**Mind-wandering and age.** First, we investigated age differences in self-reported MW frequency during the SART (see Table 3). The frequency of each thought content category across groups is illustrated in Figure 3. A significant difference was found in the probability of reporting tune outs (MW with awareness) across age groups. Post hoc tests suggested this was due to early adolescents reporting fewer tune outs than late adolescents, *OR* = .375, 95% CI [0.158, 0.888], $z = -2.92$, Tukey adjusted $p = .018$. No reliable age effects were found in the other thought content categories. To explore the data further, MW with and without aware-

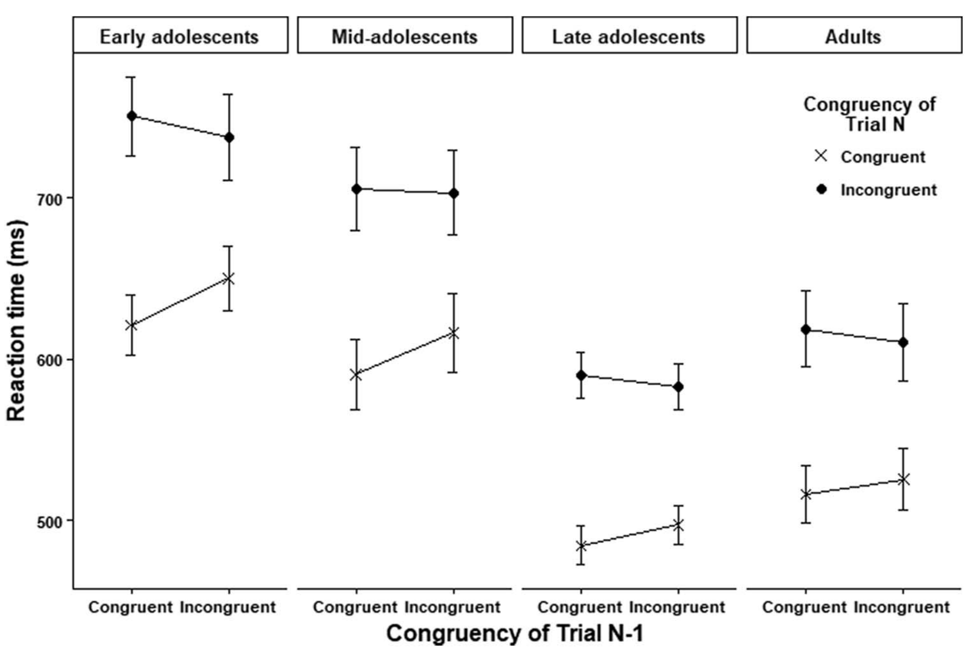


*Figure 2.* The effect of congruency as a function of previous trial congruency, or the congruency sequence effect in raw RT in the Simon task. Error bars represent ±1 *SE*.

Table 2

*SART Task Performance Indices—Means (SDs)—for Early, Mid-, and Late Adolescents and Young Adults*

| Index | Early adolescents | Mid-adolescents | Late adolescents | Young adults |
|---|---|---|---|---|
| Accuracy | | | | |
| *N* | 30 | 24 | 28 | 24 |
| Go accuracy | .98 (.02) | .99 (.02) | .99 (.01) | .99 (.01) |
| No-go accuracy | .70 (.19) | .72 (.18) | .78 (.15) | .82 (.15) |
| Go reaction time | | | | |
| *N* | 30 | 24 | 28 | 24 |
| Go RT | 552.34 (81.90) | 473.24 (64.95) | 442.67 (87.24) | 425.85 (51.96) |
| Go *z*RT | .02 (.01) | .02 (.02) | .01 (.01) | .01 (.01) |
| No-go reaction time | | | | |
| *N* | 29 | 24 | 27 | 24 |
| No-go RT | 438.20 (82.10) | 380.83 (71.50) | 363.81 (51.73) | 349.51 (58.34) |
| No-go *z*RT | −.62 (.37) | −.65 (.39) | −.59 (.35) | −.69 (.48) |
| Intraindividual variability | | | | |
| *N* | 30 | 24 | 28 | 24 |
| Go RT CV | .31 (.06) | .30 (.06) | .26 (.06) | .25 (.04) |

*Note*. Accuracy reflects the proportion of correct responses. CV = coefficient of variation (Go RT *SD*/Go RT *M*); SART = sustained attention to response task.

ness were collapsed into a new category, “overall MW.” There was an age effect in this category too (Table 3, bottom row), which closely mirrored the pattern of the age effect in tune outs: early adolescents reported MW less frequently than late adolescents, $OR = .406$, 95% CI [0.181, 0.910], $z = -2.87$, Tukey adjusted $p = .022$.

Next, we analyzed self-reported trait MW, as measured by the two subscales, Deliberate and Spontaneous, of the Mind-Wandering Questionnaire. In a 2 (MW Type: Deliberate, Spontaneous) × 4 (Age Group) ANOVA, a main effect of Group was found, $F(3, 102) = 5.09$, $p = .003$. This was attributable to early adolescents reporting less MW ($M_{\text{Deliberate}}$: 3.91 ± 1.11; $M_{\text{Spontaneous}}$: 3.35 ± 1.37) than late adolescents ($M_D$: 4.94 ± 1.22; $M_{Sp}$: 4.63 ± 1.22) and young adults ($M_D$: 4.79 ± 1.43; $M_{Sp}$: 4.36 ± 1.39, all $ps < .05$). Midadolescents did not significantly differ from any other group ($M_D$: 4.72 ± 1.30; $M_{Sp}$: 4.06 ± 1.54). Participants in every age group reported less spontaneous MW than deliberate, $F(1, 102) = 21.71$, $p < .001$. The MW Type × Age Group interaction did not approach significance ($F < 1$).

Neither of the potential, performance based behavioral indices of MW (Go accuracy, No-Go accuracy, Go RT CV in the SART) were significantly related to self-reports of MW, either state or trait level. The two levels of self-reports, however, were correlated in our sample: both deliberate and spontaneous trait-MW predicted the probability of on task reports, $OR = .687$, 95% CI [.562, .831], $\chi^2(1) = 14.93$, $p < .001$, and $OR = .708$, 95% CI [.593, .839], $\chi^2(1) = 15.88$, $p < .001$, respectively; and tune out reports during the task, $OR = 1.426$, 95% CI [1.186, 1.733], $\chi^2(1) = 14.12$, $p < .001$, and $OR = 1.299$, 95% CI [1.093, 1.560], $\chi^2(1) = 8.77$, $p = .003$, respectively.

**Mind-wandering and cognitive control.** We next examined whether the magnitude of the CSE was related to the self-reported frequency of MW during the SART (see Table 3). The frequency of MW with awareness (tune outs) was negatively related to the magnitude of the CSE in the flanker in both raw and standardized RT, $OR = .986$, 95% CI [.975, .996], and $OR = .236$, 95% CI [.069, .775], respectively. Similar associations were found using overall MW as the outcome in both raw and standardized RT:

Table 3

*Terms From the Generalized Linear Mixed-Effects Models Investigating the Frequency of Different Thought Content Reports Across Age and as a Function of CSE Magnitude in the Two Tasks*

| | Age | | Flanker CSE (RT) | | Flanker CSE (*z*RT) | | Simon CSE (RT) | | Simon CSE (*z*RT) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Measure | $\chi^2(3)$ | *p* | $\chi^2(1)$ | *p* | $\chi^2(1)$ | *p* | $\chi^2(1)$ | *p* | $\chi^2(1)$ | *p* |
| On-task reports | 6.92 | .074 | 7.53 | .006* | 3.39 | .066 | 0.39 | .535 | <0.01 | .964 |
| Space outs | 6.59 | .086 | 0.07 | .786 | 0.45 | .504 | 0.78 | .377 | 0.45 | .503 |
| Zone outs | 0.58 | .902 | 0.26 | .607 | 0.2 | .658 | 0.04 | .843 | 0.05 | .821 |
| Tune outs | 10.29 | .016* | 7.34 | .007* | 5.71 | .017* | 0.09 | .769 | 0.61 | .436 |
| Overall MW | 10.21 | .017* | 8.32 | .004* | 4.52 | .034* | 0.02 | .892 | 0.33 | .567 |

*Note*. In the RT models, the predictor variable was the magnitude of the congruency sequence effect (CSE) in raw, unstandardized RT, whereas in the *z*RT models the CSE was based on standardized RT. MW = mind-wandering.
* $p < .05$.

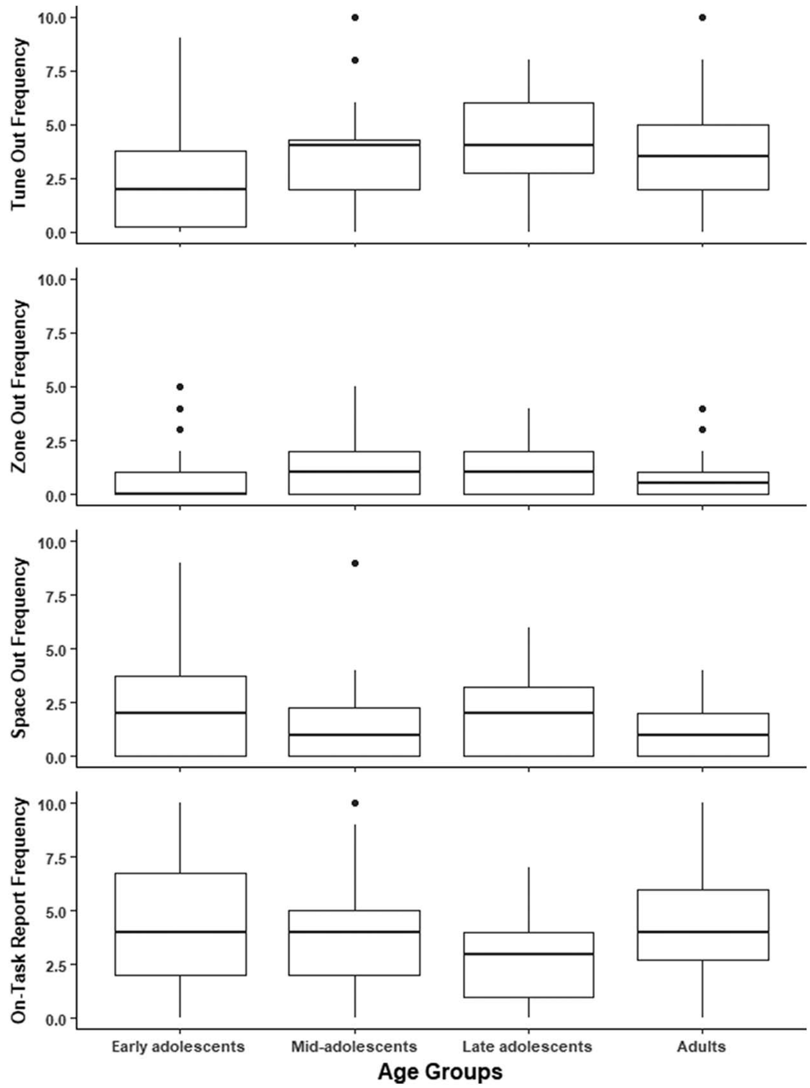


*Figure 3.* Box-plots of the frequencies of different categories of thought reports across age groups during the Sustained Attention to Response Task (SART).

*OR* = .986, 95% CI [.976, .995], and *OR* = .296, 95% CI [.093, .915], respectively. A positive relationship of similar magnitude was also found between raw RT CSE in the flanker and on-task thought report frequency, *OR* = 1.015, 95% CI [1.004, 1.026]. These relationships did not interact with age. No significant relationships were found in the Simon task or with other thought report categories. The magnitude of the CSE was also not a significant predictor of any of the potential behavioral indices of MW (Go accuracy, No-Go accuracy, Go RT CV; all $ps > .05$), and was not related to trait MW (all $ps > .05$).

## Discussion

In the present study, we investigated different aspects of the cognitive control system across early, mid-, and late adolescence, and young adulthood. Confound-minimized versions of two classic conflict tasks, the Simon task and the flanker task, were used to examine whether adolescents show evidence of dynamic modulations of cognitive control as indicated by the presence of the congruency sequence effect (CSE), and whether the magnitude of this modulation changes across adolescence. Furthermore, we also investigated self-reported mind-wandering (MW) in a Go/No-Go task in these age groups, and the relationship between MW and cognitive control.

### Cognitive Control Across Adolescence

The main focus of this study was to investigate age-related changes in dynamic adjustments of cognitive control as indexed by the CSE. The typical CSE pattern in RT was observed in both tasks and was larger in the Simon compared with the flanker task, replicating an effect reported by Weissman et al. (2014). The authors suggested that this difference might be because distractor information is translated into a response more rapidly than target information in the Simon task compared with the flanker task, giving a "head start" for the inhibition of the distractor-related response (Weissman, Egner, Hawks, & Link, 2015). This inhibition is then further amplified after incongruent trials, generating a larger CSE. Our results support this account.

Contrary to our prediction, age did not interact with the CSE in either one of the tasks. This is consistent with previous developmental work involving children (Cragg, 2016; Larson et al., 2012; Waxer & Morton, 2011), that also found no significant age differences in the size of the CSE across different age groups. Numerically, the CSE increased slightly across age groups in the flanker task, and decreased in the Simon task. Such a divergence, coupled with the fact that there was no correlation in the CSE across tasks ($r = -.10$ in raw RT, $r = -.05$ in standardized RT) could hint at a difference between the mechanisms, or in the implementation of the same mechanism, underlying the CSE in the two tasks. This is in line with recent findings that suggest that conflict signals and/or control mechanisms are specific to a given task (Funes, Lupiáñez, & Humphreys, 2010; Whitehead, Brewer, & Blais, 2019, for a review see Braem, Abrahamse, Duthoo, & Notebaert, 2014), or even that the mechanism generating the CSE might differ from task to task (Aschenbrenner & Balota, 2015, 2017).

Similar to the CSE and consistent with some previous studies (Adleman et al., 2002; Andrews-Hanna et al., 2011; Veroude et al., 2013), the congruency effect observed in this study did not differ between age groups when examining raw RT scores. However, when baseline speed differences between groups were controlled for in the analyses, participants under 18 (early and midadolescents) showed smaller congruency effects compared with both over-18 groups. This was most likely an effect of the standardization procedure as adolescents showed higher intraindividual variability in accordance with previous studies showing that adolescent performance is more variable than adult performance (Montez, Calabro, & Luna, 2017). Hence, when RTs were standardized based on *SD*s, the effect appeared to be smaller compared with the high intraindividual variance in that group than in the less variable adult group.

Taken together, our findings suggest that on the behavioral level conflict resolution, as measured by the congruency effect, matures quickly and reaches adult-like levels by or before the age of 12. Similarly, patterns typically associated with conflict-induced dynamic adjustments of control levels are already present at the same age. This is in line with the conclusions of Ambrosi et al. (2016); Cragg (2016); Iani et al. (2014), and Stins, Polderman, Boomsma, and de Geus (2008) who tested children at or under the age of 12. Sequential modulations did not show substantial changes as a function of age in our sample in accordance with previous studies using confounded or more complex paradigms (Larson et al., 2012; Smulders et al., 2018; Waxer & Morton, 2011). Our results complement those of Cragg (2016) who used a confound-free flanker task in children and late adolescents, by showing a similar lack of substantial age differences in a confound-free Simon task between adolescents and adults. It is, however, important to bear in mind that we cannot draw the conclusion that there are *no* age effects in the CSE from null findings as our study and previous studies may simply have been underpowered to detect them. If so, our findings suggest that any age-related changes in CSE magnitude are likely to be extremely subtle, especially after controlling for age differences in response speed.

## Go/No-Go Performance and Mind Wandering

Patterns consistent with age-related improvements in cognitive control were found in the SART, both in behavioral performance and self-reported MW with the biggest differences emerging between participants under and over 18. Early adolescents were slower and more error prone than the other groups. Furthermore, the performance of early and midadolescents on Go trials was more variable compared with the two older groups. This pattern of results is consistent with previous findings that adolescents show impaired performance in Go/No-Go tasks both in terms of speed and accuracy (Carriere et al., 2010; Stawarczyk et al., 2014) and behavioral variability (Braet et al., 2009; Stawarczyk et al., 2014). These findings are also in line with models of adolescent cognitive development that posit that control abilities are still maturing at this stage of life (Iselin & DeCoster, 2009; Shulman et al., 2016). According to our results, however, this improvement is more evident in certain abilities than in others, as the inhibition of prepotent but momentarily incorrect responses in the SART did show age-related changes while conflict resolution and adaptation to conflict in the flanker and the Simon tasks did not.

Turning to mind-wandering, age differences were also found in the reported frequencies of MW during the SART. Early adolescents reported significantly fewer episodes of overall MW (MW episodes with or without awareness, combined) than late adolescents, and numerically fewer episodes than adults. One explanation of this observation could be that MW, or certain aspects of MW (e.g., the maintenance of off-task thought), are resource-dependent (Smallwood, 2013; Smallwood & Schooler, 2006) and early adolescents just do not have enough cognitive resources at their disposal yet to generate and/or maintain off-task thoughts during task performance. Our finding that late adolescents reported the highest levels of MW, however, could also be explained in terms of the "Control Failures $\times$ Current Concerns" account of MW (McVay & Kane, 2010). This posits that MW is a consequence of the cognitive system's failure to defend task performance from the interference of intrusive thoughts, triggered by the current concerns of an individual. It is possible, although speculative, that late adolescents who were primarily undergraduate students had more university related current concerns that were activated by the university setting in which they were tested than any other group, leading to a disproportional increase in MW in that specific age group. Furthermore, as this age effect was driven by differences in the frequency of MW episodes with awareness, it could be due to differences in metacognitive ability across the groups (Weil et al., 2013), as opposed to differences in the actual amount or duration of MW episodes. Future studies are needed to replicate these findings and to disentangle potential mechanisms.

Our results complement the findings of Stawarczyk et al. (2014) who found no difference in self-reported MW frequency between 14- and 16- and 19- to 26-year-olds. Importantly, that study did not distinguish between different types of MW and used broader age ranges, both of which factors might have contributed to the lack of age-related differences in MW. They did, however, find that their adolescent group were on-task less frequently than adults, unlike in our sample. This is seemingly at odds with the cognitive resource account of MW; however, their findings suggested that this effect was a result of an increase in external distractions (not measured in our study), and not in spontaneous thoughts in adolescents. This is consistent with the idea that adolescents have less developed attention regulation abilities (e.g., Polizzotto, Hill-Jarrett, Walker, & Cho, 2018).

We also investigated trait level MW using a brief mind-wandering questionnaire developed by Carriere et al. (2013). This questionnaire measures the frequency of MW episodes engaged deliberately (intentional MW) and spontaneously (unintentional MW) in everyday life. This is an important distinction, as the two types of MW can show dissociation (Golchert et al., 2017; Seli, Carriere, & Smilek, 2015; Seli, Risko, & Smilek, 2016) and the intentionality dimension has also been shown to be different from the metaawareness dimension (Seli, Ralph, et al., 2017). In our sample, both intentional and unintentional trait-level MW was positively correlated with MW with awareness during the SART, but not with MW without awareness. This pattern of results provides further indirect support for the idea that intentionality and metaawareness are not identical constructs. However, it is worth noting that MW without awareness was reported very infrequently in our sample, and low variability in its incidence may have limited our ability to detect meaningful associations involving this type of MW. Finally, both deliberate and spontaneous MW were found to increase with age, paralleling our state-level results, and the findings of Seli, Maillet, et al. (2017) in older adults (Exp. 1).

## Cognitive Control and MW

We also investigated the possible relationship between mind-wandering and cognitive control adjustments, as indicated by the CSE. Across all age groups, we found a reliable negative relationship between the size of the CSE in the flanker task and the frequency of overall MW during the SART which was driven by tune outs, similarly to the age effect described above. This finding suggests that participants who were better at dynamically adjusting their attention to the demands of the task reported fewer task-unrelated thoughts. This is consistent with the findings reported by Drescher et al. (2018), and might reflect that these individuals show better reactive control of their attention; for example, they may be better able to redirect their attention to the task after it has wandered away, possibly resulting in shorter MW episodes. In support of this interpretation, Stawarczyk et al. (2014) also found that reactive control was negatively associated with MW frequency.

The negative relationship between CSE magnitude and MW frequency is seemingly inconsistent with our previous conclusion that people with more mature cognitive resources MW more. However, previous findings suggest that CSE magnitude is largely independent of cognitive resources (e.g., working memory capacity, Meier & Kane, 2013; Unsworth, Redick, Spillers, & Brewer, 2012), thus the CSE-MW relationship is probably tapping a different aspect of the cognitive system (such as reactive control efficiency) than the MW-age relationship (amount of cognitive resources available).

There are two caveats that make the interpretation of the CSE-MW relationship less straightforward. First, as mentioned in the Introduction, an argument could be made that if the level of proactive, preparatory control is high, adjustments in response to conflict should be smaller, thus smaller CSEs might reflect better control allocation. Our developmental findings do not help adjudicate between this, and a “larger is better” interpretation, as young adult CSEs did not differ in size substantially from younger CSEs that are probably generated by less mature cognitive systems. However, if we assume that smaller CSEs reflect better control, the negative relationship between CSE and MW becomes harder to interpret. It is also possible that both the “larger is better” and “smaller is better” interpretations of the CSE could be viable depending on the approach a given participant takes to the task, and this approach might be fluctuating within an individual too, over the course of the task. These limitations must be taken into account in any individual difference study focusing on the CSE. Second, even though we controlled for learning and memory confounds in our design, it is still possible that the CSE reflected some noncontrol related process, such as temporal learning (Schmidt, 2013; Schmidt & Weissman, 2016), and that this process is related to MW frequency or duration in some way. Further complicating this is the finding that this association was only found for the flanker task, and not for the Simon. This observation provides additional support to the idea outlined above that the CSE reflects different mechanisms in these two tasks as they have different correlates. How exactly the CSE differs between the Simon and the flanker tasks and what exactly it reflects in each, however, can only be determined through further investigation. For instance, the proportion of reactive versus proactive elements, or the additional contribution of noncontrol related processes in the CSE might be different in the two tasks.

The results from the current study need to be considered in light of the following limitations. First, for practical reasons, the study did not include any measures of working memory capacity. In future studies, such measures could help explore how working memory changes across adolescence, and whether these changes are related to attentional control adjustments and reports of MW. Furthermore, although the order of the conflict tasks was counterbalanced across participants, the SART always came last, thus it is possible that the more pronounced age effects in that task are due to greater fatigue effects in younger participants compared with adult participants. This, however, does not substantially change our interpretation of the MW age effect finding in terms of the cognitive resource account of MW. Finally, future studies might benefit from including secondary measures of MW (such as eye-tracking and pupillometry) to help establish the validity of self-reports (e.g., Frank, Nara, Zavagnin, Touron, & Kane, 2015) as it is possible that participants—especially from younger age groups—were unable to report their thought contents accurately in our study.

## Conclusion

We investigated how the sequential modulation of the congruency effect changes across adolescence in two, confound-minimized conflict tasks. The CSE did not interact with age in either of the tasks, strongly suggesting that if there are any age-related changes in the size of the effect, they are not substantial. More pronounced age effects were found in response inhibition performance in the SART (performance improved with age) and self-reports of MW (reports of MW increased with age and peaked in late adolescence). Differences were biggest between participants under 18 (early and midadolescents) and participants 18 or older (late adolescents and young adults). Both findings imply that certain aspects of the cognitive system are still maturing in adolescence. Finally, our results that the CSE in the flanker task but not in the Simon task was associated with MW frequency during the SART, and that there was no relationship between the CSEs in the two tasks, suggest that the CSE may not reflect the same mechanism (i.e., conflict-induced control adjustments, temporal learning) in the flanker and Simon tasks.

## Context

The current study was conducted by Máté Gyurkovics as part of his doctoral program. The work was supervised by coauthors Drs. Liat Levita and Tom Stafford. Dr. Levita's lab focuses on the investigation of cognitive and affective changes in adolescence using behavioral and electrophysiological methods. Within this program of research, Máté's dissertation studies seek to learn more about the development of the cognitive control system, response inhibition in particular, across adolescence on both the behavioral and the neural level. As a next step, the authors are currently working on an EEG study based on the findings of the present experiment aiming to see whether the neural mechanisms supporting performance in a similar conflict task are comparable across age groups. In the future, they would like to follow up on the implications these findings have for the nature of the CSE in different tasks, to understand what exactly the age-related changes (or lack thereof) in this particular effect tell us about the development of human cognition.

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