A cross-sectional examination of response inhibition and working memory on the Stroop task

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ARTICLE INFO

ABSTRACT

The authors examined the association between working memory and response inhibition on the Stroop task using a cross-sectional, international sample of 5099 individuals (49.3% male) ages 10–30 ($M = 17.04$ years; $SD = 5.9$). Response inhibition was measured using a Stroop task that included "equal" and "unequal" blocks, during which the relative frequency of neutral and incongruent trials was manipulated. Competing stimuli in incongruent trials evinced inhibitory functioning, and having a lower proportion of incongruent trials (as in unequal blocks) placed higher demands on working memory. Results for accuracy indicated that age and working memory were independently associated with response inhibition. Age differences in response inhibition followed a curvilinear trajectory, with performance improving into early adulthood. Response inhibition was greatest among individuals with high working memory. For response time, age uniquely predicted response inhibition in unequal blocks. In equal blocks, age differences in response inhibition varied as a function of working memory, with age differences being least pronounced among individuals with high working memory. The implications of considering

the association between response inhibition and working memory in the context of development are discussed.

1. Introduction

Adolescence is a period during which individuals must learn to navigate the increasing academic, social, and personal challenges they face. The ability to regulate behavior in favor of short- and long-term goals is one skill critical to mastering these challenges. Response inhibition and working memory are two executive processes that facilitate the ability to engage in such goal-directed behavior (DeLuca et al., 2003; Miller & Cohen, 2001). Research on adults indicates that response inhibition and working memory are psychologically distinct (e.g., Friedman & Miyake, 2004), yet functionally concomitant processes (Davidson, Amso, Anderson, & Diamond, 2006; Engle & Kane, 2004). Further, findings from some studies suggest that working memory facilitates response inhibition, such that individuals with high working memory demonstrate better performance on measures of response inhibition compared to individuals with low working memory (e.g., Egner & Hirsch, 2005; Long & Prat, 2002; Miller & Cohen, 2001; Weldon, Mushlin, Kim, & Sohn, 2013). However, such findings have not been replicated in samples that include adolescents. Understanding the relation between these two processes at a time during which they are still developing (e.g., Huizinga, Dolan, & van der Molen, 2006) affords a more comprehensive picture of adolescent executive functioning. In the present study, we explored whether inter-individual variation in working memory contributed to variation in response inhibition across different periods of development, using a cross-sectional sample of individuals between the ages of 10 and 30 years.

Response inhibition − the ability to deliberately inhibit automatic or prepotent responses (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000) – is part of a family of functionally similar inhibitory processes responsible for regulating thoughts and actions (Andrews-Hanna et al., 2011; Braver, 2012; Nigg, 2000). Cross-sectional studies of response inhibition indicate that inhibitory skills continue maturing into the early twenties (Davidson et al., 2006; Luna et al., 2001; Velanova, Wheeler, & Luna, 2009), with evidence to suggest that these age patterns are relatively consistent among individuals from various countries across the world (Steinberg et al., 2017). Thus, adolescence is a time when individuals are still developing self-regulatory abilities. Understanding how to facilitate inhibitory functioning during this sensitive period is important given the observed link between inhibitory function and academic achievement, occupational success, law-abiding behaviors, and psychological well-being (Moffitt, Poulton, & Caspi, 2013).

Working memory, which also continues maturing into the early twenties (DeLuca et al., 2003; Huizinga et al., 2006; Luciana, Conklin, Hooper, & Yarger, 2005), entails a set of cognitive processes responsible for the maintenance and manipulation of mentally represented information, as well as attentional control (Cowan et al., 2005; Kane, Bleckley, Conway, & Engle, 2001). In many conceptions of working memory, one of the crucial functions subserved by this system is the ability to hold current task goals in an active, quickly retrievable state (Engle, 2002) and it is this domain-general facet of working memory that has been linked to inhibitory functioning (Kane & Engle, 2003). Researchers who advocate this view postulate that successful response inhibition requires active maintenance of task goals in memory, which is achieved via efficient attentional control (Conway et al., 2005; Diamond, 2013; Engle & Kane, 2004; Kuo, Stokes, & Nobre, 2012; Miyake et al., 2000). From this vantage point, working memory *capacity* refers to the extent of an individual's ability to control attention and actively maintain goals in mind (Engle, 2002).

One task well-suited for examining response inhibition in relation to goal maintenance in working memory is the Stroop task (Kane & Engle, 2003; Long & Prat, 2002). On this standard measure of response inhibition (Friedman & Miyake, 2004; Huizinga et al., 2006; MacLeod, 1991; Nee, Wager, & Jonides, 2007; Veroude, Jolles, Croiset, & Krabbendamn, 2013), participants are asked to quickly and accurately indicate the color in which a word is displayed while ignoring its semantic meaning. On incongruent trials, a color word is displayed in an incongruent color (e.g., the word 'blue' displayed in green font), requiring that participants inhibit the prepotent response to read the word and instead respond on the basis of the word's physical color. Response inhibition and the resolution of cognitive conflict on incongruent trials not only requires efficient self-regulatory abilities, but also relies on attentional resources and the active maintenance, in working memory, of the task goal (Kane & Engle, 2002; Marsh et al., 2006).

Response inhibition on the Stroop task is typically operationalized as the *Stroop interference effect* (Stroop effect) (Adleman et al., 2002; Andrews-Hanna et al., 2011; Long & Prat, 2002; MacLeod, 1991; Morey et al., 2012) wherein performance on incongruent trials is compared to performance on some variation of a baseline trial (e.g., Huizinga et al., 2006) such as congruent trials, in which the color of the word matches its meaning (e.g., the word 'blue' displayed in the color blue) or neutral trials, where the presented word is a non-color word (e.g., 'math' displayed in any color). Lower accuracy scores and slower response times on incongruent trials relative to baseline trials reflect a larger Stroop effect. The Stroop effect is thought to result from cognitive conflict induced by incongruent trials (Kane & Engle, 2003), which is exacerbated by a deficient ability to resist interfering stimuli (Andrews-Hanna et al., 2011; Marsh et al., 2006). Additionally, researchers assert that the Stroop effect results from a failure to maintain the task goal in active memory (Kane & Engle, 2003). In effect, individuals with stronger inhibitory control and greater working memory capacity typically evince smaller Stroop effects compared to individuals with weak inhibitory control and low working memory (cf., Engle & Kane, 2004). Thus, performance on the Stroop task captures information about both inhibitory function and working memory capacity.

Considering that executive functions such as response inhibition and working memory are not fully developed during the adolescent years, one might expect that, compared to adults, adolescents evince a larger Stroop effect. However, cross-sectional examinations of Stroop performance yield inconsistent results, with findings from some studies indicating that adolescents evince a larger Stroop effect with respect to response time (Huizinga et al., 2006) and accuracy (Marsh et al., 2006) compared to adults, other

studies suggesting that these age differences are only observed for the Stroop effect for response time, but not accuracy (Schroeter, Zysset, Wahl, & von Cramon, 2004), and still others finding no differences between adolescents and adults for either response time or accuracy (Andrews-Hanna et al., 2011). The inconsistency of these findings may be explained in part by certain methodological limitations. Importantly, very few cross-sectional studies of Stroop performance incorporate task manipulations that influence the difficulty of the task. This is particularly important for developmental research on executive functioning, given previous work demonstrating that task difficulty influences the extent to which differences in both inhibitory control (Albert & Steinberg, 2011) and working memory (DeLuca et al., 2003) are observed between adolescents and adults.

One task manipulation frequently employed in adult studies of Stroop performance is the relative frequency with which incongruent and baseline trials are presented within a given task block (i.e., *block type;* Egner & Hirsch, 2005; Engle, 2002; Hutchison, 2011). Manipulations of block type are shown to affect the relative difficulty of the Stroop task by placing differential demands on both working memory and inhibitory control (Davidson et al., 2006; Kane & Engle, 2003; Morey et al., 2012). Specifically, blocks with a greater frequency of incongruent trials compared to baseline trials are easier than those with a lower frequency of incongruent trials (and higher frequency of baseline trials) (see Kane & Engle, 2003). Incongruent trials remind participants of the task goal (to focus on the color of the word). Thus, in blocks with a higher frequency of incongruent trials relative to baseline trials, working memory demands are reduced because successful performance on the task does not require that participants actively engage in goal maintenance. On the other hand, working memory demands are greater on blocks in which baseline trials are more frequent because baseline trials, which have no conflicting stimuli, leave participants vulnerable to automatic responding (since there is no cognitive conflict) rather than using the active representation of the task goal (i.e., to respond only on the basis of the word's color) to guide behavior. While prepotent responding without goal maintenance may lead to faster and more optimal performance on baseline trials, performance on incongruent trials suffers because the lack of goal maintenance (or *goal neglect,* Morey et al., 2012) either diminishes accuracy, increases response latency, or both. Viewed in this way, response inhibition on the Stroop task is undermined by low working memory capacity.

Research comparing Stroop performance between adults with low and high working memory capacity reveals two important findings: (1) individuals with high working memory capacity are less susceptible to Stroop interference (e.g., Kane & Engle, 2003; Long & Prat, 2002), and (2) these working memory differences are exaggerated in blocks within which incongruent trials are rare (e.g., Hutchison, 2011; Morey et al., 2012). Whether these findings hold true across different ages is yet to be determined. Whereas high working memory may be associated with successful behavioral inhibition on the Stroop task across age, it may also be the case that the memory and inhibitory demands of the task are handled differently across different stages of development (e.g., Albert & Steinberg, 2011; Davidson et al., 2006). One compelling reason to explore the association between working memory and response inhibition across age groups is to determine whether individuals with high working memory demonstrate mature response inhibition at an earlier age than their low working memory counterparts.

In the present study, we explored the association between working memory capacity and response inhibition as a function of age. In order to improve our ability to detect age differences in Stroop performance that may have been overlooked in previous cross-sectional studies using this task, we explored Stroop performance across age and working memory in the context of task difficulty (measured by block type). We predicted that higher working memory capacity would be associated with greater response inhibition (i.e., a smaller Stroop effect), and that age differences in the Stroop effect would be comparatively smaller among individuals with high working memory. Findings from this study contribute to the literature on cognitive development, which is currently limited in its understanding of the interplay between working memory and inhibitory functioning across age.

2. Materials and methods

2.1. Participants

Data were analyzed using a multinational sample of 5099 individuals ages 10 through 30 ($M = 17.04$ years; $SD = 5.9$). The participants used for this study were initially recruited for an ongoing longitudinal study of parenting across cultures, *Parent Behavior and Child Adjustment Across Cultures* (Lansford & Bornstein, 2011), which was approved by the participating university's IRB (approval 2032), and has been described elsewhere (Steinberg et al., 2017). Participants were recruited from eleven countries: Guang-Zhou and Shanghai, China ($n = 484$); Medellin, Colombia ($n = 495$); Nicosia, Cyprus ($n = 344$); Delhi, India ($n = 416$); Naples and Rome, Italy ($n = 543$); Amman and Zarqa, Jordan ($n = 418$); Kisumu, Kenya ($n = 463$); Manila, the Philippines ($n = 501$); several cities in the west of Sweden ($n = 411$); Chang Mai, Thailand ($n = 495$); and Durham and Winston-Salem, the United States ($n = 529$). The gender distribution was nearly even within the full sample (49.3% ($n = 2514$) male) and within countries. Participants were primarily working and middle class, with similar standings in terms of within-country socioeconomic status (SES). Participants in all but the United States did not identify as being members of any ethnic minority groups. In the United States, approximately equal numbers of Black, Latino, and White participants were enrolled.

2.2. Procedures

Participants were recruited via flyers posted in neighborhoods and schools, ads placed in newspapers, and word of mouth. Because of the varied recruitment methods, we could not determine whether those who responded to recruitment ads differed from those who did not. Informed consent was obtained from all adults age 18 and older, and parental consent and adolescent assent were acquired for all individuals younger than 18. (In Sweden, informed consent was obtained from all participants age 15 and older, and

parental consent and adolescent assent were acquired for all individuals younger than 15, in accordance with Swedish law.) Local Institutional Review Boards approved all procedures.

Participants completed a 2-h test battery administered on laptop computers that included several behavioral tasks, self-report measures, a demographic questionnaire, computerized tests of executive functions, and an intellectual functioning assessment. These sessions were completed individually by the participant but in the presence of a research assistant in participants' homes, schools, or other locations designated by the participants.

To keep participants engaged, they were told that they would receive a base payment for participating, and that they could obtain a bonus based on their performance on the computer tasks. In actuality, all participants received the bonus. This strategy was used to increase motivation to perform well on tasks but ensure that no participants were penalized for their performance. In the United States, the base payment was US$30 and the bonus was US$15. In other countries, the principal investigators and site coordinators (with the approval of the local IRB) determined an appropriate amount of payment, accounting for the local standard of living and minimum wage, and ensuring that the amount was sufficient to encourage participation but not so large so as to be coercive. (The participating university in Sweden does not permit research subjects to be paid, so participants were given three movie tickets [two as the base payment and one as a bonus] as compensation.)

Following each assessment, the interviewer answered five questions that asked about the participant's perceived compliance and engagement in the assessment and the quality of the data. A small number of assessments (3.2%, $n = 172$) were rated as unusable (e.g., the participant did not appear to understand the questions or tasks, did not pay attention to instructions, or was obviously disengaged); these cases were dropped from the analyses.

2.3. Measures

Measures were administered in the predominant language at each site, following forward- and back-translation and meetings to resolve ambiguities in linguistic or semantic content (Erkut, 2010; Maxwell, 1996). Translators were fluent in English and the target language. In addition to translating the measures, translators flagged items that did not translate well, were inappropriate for the participants, were culturally insensitive, or elicited multiple meanings, and worked with site coordinators to make appropriate modifications. Measures were administered in Mandarin Chinese (China), Spanish (Colombia and the United States), Italian (Italy), Arabic (Jordan), Dholuo (Kenya), Filipino (the Philippines), Greek (Cyprus), Hindi (India), Swedish (Sweden), Thai (Thailand), and American English (India, Kenya, the Philippines, and the United States).

2.3.1. Stroop

A computerized version of the classic Stroop color-word task was administered to assess prepotent response inhibition (see Banich et al., 2007). On each trial, the participant was presented with either a color-word (e.g., "blue", "yellow") or a neutral, non-color word (e.g., "Math", "Add") against a black screen and instructed to identify the color in which the word was printed (while ignoring its semantic meaning) by pressing a corresponding key as quickly as possible. All color-word trials were incongruent such that the color of the word did *not* match the semantic meaning of the word (e.g., the word "blue" displayed in yellow). There were no congruent trials in this task.

Participants completed 16 practice trials followed by two 48-trial experimental blocks. Equal blocks included an equal mix of neutral and incongruent trials (50/50) and unequal blocks included a greater number of neutral than incongruent trials (75/25). Half of the participants were presented with an equal block first, and half of the participants were presented with an unequal block first. Block order was assigned randomly and used as a covariate in all analyses. The order in which incongruent and neutral trials were presented within these blocks was also random across participants.

The variable of interest was the *Stroop effect*, which was calculated as the difference in performance between incongruent and neutral trials (i.e., *Incongruent – Neutral*) for both accuracy (percentage of correct responses) and response time (time recorded in milliseconds) (Friedman & Miyake, 2004; Kane & Engle, 2003; Long & Prat, 2002; MacLeod, 1991; Schroeter et al., 2004; Veroude et al., 2013). Only response times for accurate trials were used, consistent with previous research (e.g., Kane & Engle, 2003). (Response times for inaccurate trials often yield excessive amounts of statistical noise that produce inaccurate and un-interpretable representations of participant response patterns.) A larger Stroop effect is typically characterized by lower accuracy and longer response times on incongruent relative to neutral trials. Thus, greater response inhibition was characterized by a smaller Stroop effect for both accuracy and response time (e.g, MacLeod, 1991; Kane & Engle, 2003; Long & Prat, 2002).

2.3.2. Working memory composite

Working memory was measured using a standardized composite of three common working memory tasks: an item-recognition task, spatial working memory, and backwards digit span. Correlations among these items ranged from 0.30–0.35 (all $ps < 0.001$). In the *item-recognition task* (Thompson-Schill et al., 2002), participants saw a target set of four letters on the computer screen, followed by a screen displaying a '+', followed by a screen displaying a probe letter. Participants were asked whether the probe was a member of the current target set (to which they answered either 'yes' or 'no' using the keyboard). Half of the trials contained probe items that were members of the current target set (positive trials) and half of the trials contained probe items that were not members of the current target set (negative trials). For both positive and negative trials, half of the trials contained probe items that were members of the previous target set (hard/recent trials), and half of the trials contained probe items that were not members of either of the previous two target sets (easy/non-recent trials). For all trials, two of the four letters in the target set were repeated from the previous trial (so that repetition of items in the target set was not confounded with trial type). After 8 practice trials, subjects were presented

with a total of 64 trials (32 easy and 32 hard) that were presented in pseudo-random order, split into blocks of 8 trials each. Working memory was measured as the number of correct responses on negative-recent trials (i.e., participants correctly indicated that the current probe was not among the previous target set).

The *spatial working memory* task (Chein & Morrison, 2010) examined the ability to both maintain and retrieve information in spatial working memory. Using a computer, subjects were shown a series of red squares on a white grid, presented one at a time (with each square disappearing before the presentation of the subsequent square). After a short delay, participants were then asked to recall the order in which the squares had appeared on the grid (by clicking with the computer mouse). This task was adaptive; when subjects responded correctly, the task offered an additional square to remember (starting at a baseline of 3 squares for all participants). The number of test items increased until participants failed to correctly recall two successive trials at a given list length. Spatial working memory was defined as the maximum list length for which all items were recalled in the correct serial order.

Finally, in the *backwards digit span* task (Wechsler, 1974), participants heard 12 sequences of digits (beginning with 2 digits and increasing to 7) that they were asked to recall in the reverse order from which they had been presented. Backwards digit span was defined as the highest number of digits correctly recalled backwards.

Items from all three tasks were standardized within the sample as a whole, and then averaged to create a working memory composite score. Previous studies examining Stroop performance as a function of working memory capacity typically compare individuals at the bottom and top tertiles of the distribution (i.e., "low" and "high" working memory; Kane & Engle, 2003; Long & Prat, 2002). In the interest of preserving the continuous nature of the variable and using data from all participants rather than eliminating a subset of the sample, working memory was used as a continuous variable in these analyses.

2.3.3. Intellectual functioning

A computerized version of the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI) was used to estimate nonverbal intellectual ability, and used as a covariate in the analyses. This test provides a brief and reliable measure of general intelligence that is normed across the lifespan (Psychological Corporation, 1999). The verbal subscale was not used given the variability in language across the research sites. Intelligence scores are based on age-normed WASI T-scores ($M = 48.63$, $SD = 10.98$).

2.3.4. Socioeconomic status

Participants reported the highest level of education achieved by their parents. Responses included *no education, grade school, some college, college degree,* and *education beyond college.* These responses were given numeric values that represented *years* of education completed. A value of 0 indicated no education, values 1 through 12 corresponded to grade level (e.g., value of 10 indicates completion of 10th grade), a value of 13 indicated some college, 14 indicated a college degree, and 15 represented education beyond college. The average of the participant's parents' (or primary caregivers') education levels was computed to index socioeconomic status (SES), which was also used as a covariate in the analyses. Most participants came from homes in which the average of their parents' education was *some college.*

2.4. Data analysis

The purpose of the present study was to examine the relation between response inhibition and working memory across age. Response inhibition (the Stroop effect) was computed as the difference in accuracy and response time between incongruent and neutral trials (incongruent − neutral), across equal and unequal blocks. Two separate nonlinear mixed regression models were conducted in Mplus Version 7.0—one for accuracy and one for response time. Block type (equal and unequal) was entered as a dichotomous within-subjects variable. Age and working memory were continuous between-subjects variables. Age was centered on 10 years (the youngest age). A mixed modeling approach was used to account for the non-independence of the data within block type. Both the linear and quadratic terms for age were tested to examine age patterns in response inhibition (the quadratic term was included in light of previous work suggesting a curvilinear pattern of change in executive functioning across development).

In the first step of the analysis, the Stroop effect for accuracy was regressed on block type, age, and working memory. In the second step, the quadratic term for age (age^2) was added to the model. In the third step, the interaction between age and working memory was examined (Age x WM), as well as the interaction between block type and age (Block x Age) and between block type and working memory (Block x WM). In the fourth step, the two-way interaction between age^2 and working memory was examined (Age^2 x WM), as well as the two-way interaction between age^2 and block type (Age^2 x Block), and the three-way interaction among block type, age, and working memory (Block x Age x WM). Finally, the three-way interaction among block type, age^2, and working memory was examined (Block x Age^2 x WM). This same analysis was repeated for the Stroop effect for response time.

Although culture was not a central component to the study, we chose to take advantage of our uniquely diverse sample and explore age patterns in Stroop performance for accuracy and response time within individual countries. Based on previous research suggesting noteworthy cross-cultural similarities in the development of self-regulation (Steinberg et al., 2017), we expected that age would be associated with Stroop performance across cultures, with most countries evincing a linear increase in Stroop performance across the adolescent years, followed by an apex in late adolescence or early adulthood. Using multiple group analysis, we entered age in the first step of the analysis and age^2 in the second step. The linear and quadratic effects of age were free to vary within countries, but the covariates (described below) were constrained to be equal across countries. Constraining the covariates to be equal across countries was necessary to avoid producing a saturated model, and is a method that has been used in previous cross-national research (e.g., Duell et al., 2017; Steinberg et al., 2017).

To control for practice effects, block *order* (i.e, whether participants started the task with unequal or equal blocks) was included as a covariate in all analyses, as well as intellectual functioning, which has been consistently linked to executive functioning e.g., Unsworth, Fukuda, Awh, & Vogel, 2014). SES was also included as a covariate given findings demonstrating that across cultures, socioeconomic factors such as parental education influence cognitive development (cf., Bradley & Corwyn, 2002). Country was also included as a covariate in the primary analyses. Each country was entered as a dichotomous variable, with the United States excluded as the comparison group. Correlations among the primary study variables and covariates are presented in Table 1. Gender was not included as a covariate in the analysis given non-significant associations between gender and the main study variables. Results for accuracy and response time are presented separately below.

3. Results

Adjusted means and standard errors for the Stroop effect across age, working memory group, and block type are presented in Table 2 for accuracy and Table 3 for response time. Corresponding figures for the adjusted means are presented in Figs. 1 and 2 for accuracy and response time, respectively. Adjusted means and standard errors for the individual countries included in our analyses are tabled and graphed as a function of age in the supplementary material (for accuracy: Table and Fig. S1; for response time: Table and Fig. S2).

3.1. Accuracy

Analysis of the Stroop effect for accuracy yielded a significant main effect of block type, such that individuals evinced a larger Stroop effect for unequal than equal blocks. Furthermore, results yielded a significant effect of working memory, such that higher working memory was associated with a lower Stroop effect for accuracy. Finally, there were significant linear and quadratic effects of age (see Table 4 for regression coefficients). Fig. 3 illustrates the estimated regression coefficients for the linear and quadratic effects of age on the Stroop effect for accuracy. Examination of the figure suggested that the Stroop effect for accuracy decreased linearly across age groups before stabilizing in early adulthood and increasing again somewhat around the age of 30. There were no significant interactions, indicating that block type, working memory, and age had independent effects on Stroop accuracy.

Table S3 in the supplementary material presents the within-country results for the linear and quadratic effects of age on the Stroop effect for accuracy. Results indicate that most countries evinced a linear or quadratic function of age such that the Stroop effect for accuracy decreased between the young adolescent and the adult age groups (age was not associated with Stroop performance in India and Thailand). Age accounted for a small but comparable amount of variance (using R^2) in the Stroop effect for accuracy across countries. Examination of the graphed means in Fig. S1 suggests that in most countries, performance either plateaued in early adulthood or continued improving into adulthood.

3.2. Response time

Results from the analysis examining the Stroop effect for response time revealed a main effect of block type, such that the Stroop effect was larger in unequal than equal blocks. Results also pointed to a main effect of working memory, such that individuals with higher working memory evinced a larger Stroop effect for response time (i.e., greater slowing on incongruent compared to neutral trials). Furthermore, there were significant linear and quadratic effects of age groups, such that the Stroop effect increased linearly through adolescence and stabilized in early adulthood. Finally, there was a three-way interaction among block type, working memory, and the linear term for age. Given the presence of a significant quadratic effect of age, the three-way interaction suggested that the instantaneous rate of change in the Stroop effect for response time (at age 10) varied as a function of working memory and

Table 1
Bivariate correlations among main study variables and covariates.

	1	2	3	4	5	6	7	8	9
1. RT Unequal	–	0.12***	−0.11***	−0.04**	0.13***	0.09**	0.17***	0.11***	0.07***
2. RT Equal		–	−0.09***	−0.06***	0.12***	0.06***	0.02	0.05***	−0.03*
3. Acc. Unequal			–	0.22***	0.13***	0.12***	−0.21***	0.09***	−0.03*
4. Acc. Equal				–	0.17***	0.13***	0.14***	0.13***	−0.01
5. WM					–	0.26***	0.02	0.46***	0.12***
6. Age						–	0.01	0.14***	−0.07***
7. Block Order							–	0.01	0.003
8. Intellectual Functioning								–	0.21***
9. SES									–

Note. RT = Response time; Acc = Accuracy. Values for RT and Accuracy reflect the Stroop effect (Incongruent – Neutral) within a given block (unequal/equal). For RT, higher scores are associated with a larger Stroop effect; for accuracy, higher scores are associated with a *lower* Stroop effect. WM Comp = Working memory. Block order is a dichotomous variable indicating whether participants played from equal (0) or unequal (1) blocks first.

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 2

Adjusted means (M) and standard errors (SE) for Stroop effect for accuracy for unequal and equal blocks within each age and working memory group.

Block Type	WM Group	10–11		12–13		14–15		16–17		18–21		22–25		26–30		Total	
		M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Unequal	Low	−7.14	0.42	−6.49	0.65	−5.05	0.75	−6.19	0.85	−2.82	0.84	−5.30	0.86	−5.06	0.83	−5.44	0.31
	Medium	−8.04	0.54	−6.55	0.65	−3.33	0.71	−4.49	0.71	−4.59	0.72	−4.06	0.72	−4.70	0.71	−5.11	0.26
	High	−7.37	0.84	−5.39	0.83	−4.67	0.67	−2.53	0.66	−3.78	0.57	−3.10	0.61	−3.71	0.64	−4.37	0.28
	Total	*−7.52*	*0.36*	*−6.15*	*0.41*	*−4.35*	*0.41*	*−4.41*	*0.43*	*−3.73*	*0.41*	*−4.15*	*0.42*	*−4.49*	*0.42*	*−4.97*	*0.15*
Equal	Low	−6.08	0.34	−4.79	0.52	−5.14	0.61	−2.44	0.69	−3.92	0.68	−4.37	0.69	−2.97	0.67	−4.24	0.25
	Medium	−5.49	0.44	−4.28	0.53	−3.40	0.58	−3.57	0.57	−3.59	0.58	−3.10	0.58	−3.75	0.57	−3.88	0.21
	High	−6.55	0.68	−4.56	0.67	−3.25	0.54	−3.14	0.53	−2.10	0.46	−2.72	0.49	−3.03	0.52	−3.62	0.23
	Total	*−6.04*	*0.29*	*−4.55*	*0.33*	*−3.93*	*0.33*	*−3.05*	*0.34*	*−3.20*	*0.33*	*−3.40*	*0.34*	*−3.25*	*0.34*	*−3.92*	*0.12*

Note. Means and SEs adjusted for block order, intellectual functioning, SES, and country. Stroop effect for accuracy computed as: (% Incongruent Accuracy − % Neutral Accuracy). Higher values indicate a *lower* Stroop effect. For purposes of presentation, working memory (WM) and age were categorized into groups. WM groups were created based on WM scores at the lower ($M = −0.83$), middle ($M = 0.06$), and top ($M = 0.8$) tertiles of the distribution. In unequal blocks, the ratio of neutral to incongruent trials was 3:1, respectively. In equal blocks, the ratio of neural to incongruent trials was 1:1. Italicized values represent grand means within each age group (horizontal values) and within each working memory group (vertical values).

Table 3

Adjusted means (M) and standard errors (SE) for the Stroop effect for response time for unequal and equal blocks within each age and working memory group.

| Block Type	WM Group	10–11		12–13		14–15		16–17		18–21		22–25		26–30		Total	
		M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Unequal	Low	37.83	3.06	39.64	4.70	42.84	5.47	43.59	6.17	57.97	6.09	48.34	6.25	59.65	6.02	47.12	2.28
	Medium	46.98	3.92	42.90	4.73	43.54	5.19	60.59	5.17	71.54	5.21	59.57	5.22	62.67	5.15	55.40	1.88
	High	47.16	6.11	34.27	6.04	49.49	4.89	52.84	4.76	64.14	4.12	56.87	4.42	59.47	4.68	52.03	2.05
	Total	*43.99*	*2.62*	*38.94*	*2.97*	*45.29*	*2.98*	*52.34*	*3.09*	*64.55*	*2.98*	*54.92*	*3.06*	*60.60*	*3.05*	*51.52*	*1.12*
Equal	Low	14.66	2.56	25.94	3.93	19.98	4.57	19.54	5.15	31.13	5.09	31.38	5.22	29.62	5.03	24.61	1.90
	Medium	18.73	3.27	27.53	3.95	21.56	4.34	30.47	4.32	33.15	4.36	32.56	4.36	30.93	4.30	27.85	1.57
	High	26.55	5.10	24.35	5.04	27.87	4.08	30.95	3.98	35.42	3.44	29.18	3.69	24.24	3.91	28.37	1.72
	Total	*19.98*	*2.19*	*25.94*	*2.48*	*23.14*	*2.49*	*26.99*	*2.58*	*33.23*	*2.49*	*31.04*	*2.56*	*28.26*	*2.55*	*26.94*	*0.93*

Note. Means and SEs adjusted for block order, intellectual functioning, SES, and country. Stroop effect for response time computed as: (% Incongruent *ms* − % Neutral *ms*). Higher values indicate a larger Stroop effect. For purposes of presentation, working memory (WM) and age were categorized into groups. WM groups were created based on WM scores at the lower ($M = −0.83$), middle ($M = 0.06$), and top ($M = 0.8$) tertiles of the distribution. In unequal blocks, the ratio of neutral to incongruent trials was 3:1, respectively. In equal blocks, the ratio of neural to incongruent trials was 1:1. Italicized values represent grand means within each age group (horizontal values) and within each working memory group (vertical values).
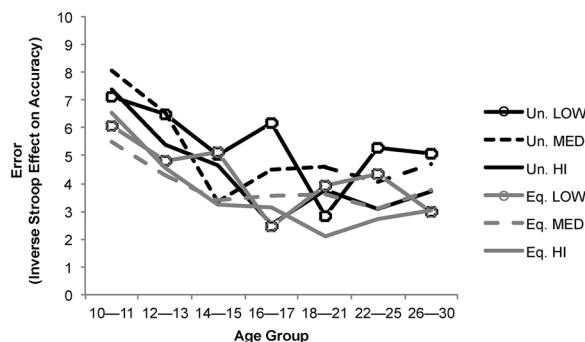
Fig. 1. Adjusted means of the Stroop effect for accuracy across age for individuals with low, medium (MED), and high (HI) working memory within unequal (Un.) and equal (Eq.) blocks. The Stroop effect was calculated as the difference in% accuracy between incongruent and neutral trials. The inverse of this value was graphed so that higher values indicate a larger Stroop effect. Values represent means adjusted for block order, intellectual functioning, SES, and country. Working memory (WM) and age were categorized into groups for purposes of presentation only. WM groups were created based on WM scores at the lower ($M = −0.83$), middle ($M = 0.06$), and top ($M = 0.8$) tertiles of the distribution. In unequal blocks, the ratio of neutral to incongruent trials was 3:1, respectively. In equal blocks, the ratio of neural to incongruent trials was 1:1. See Table 2 for corresponding mean values and standard errors.

block type, but that the overall shape of age patterns in the Stroop effect did not vary as a function of working memory and block type (see Table 5 for the regression coefficients).

To probe the three-way interaction, we examined the two-way interaction between age and working memory in equal and unequal blocks separately. As indicated in Table 6, there was no two-way interaction between age and working memory in unequal
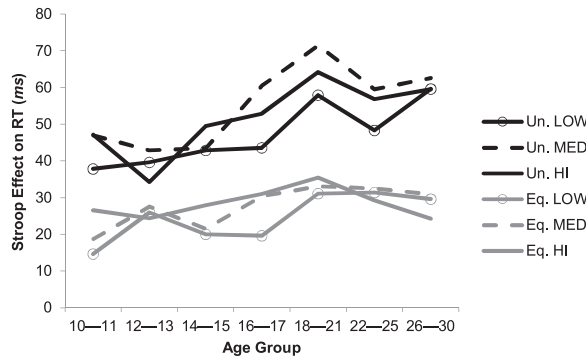
Fig. 2. Adjusted means of the Stroop effect for response time (RT) in milliseconds (*ms*) across age for individuals with low, medium (MED), and high (HI) working memory within unequal (Un.) and equal (Eq.) blocks. The Stroop effect was calculated as the difference in response time between incongruent and neutral trials. Values represent means adjusted for block order, intellectual functioning, SES, and country. Working memory (WM) and age were categorized into groups for purposes of presentation only. WM groups were created based on WM scores at the lower (*M* = −0.83), middle (*M* = 0.06), and top (*M* = 0.8) tertiles of the distribution. In unequal blocks, the ratio of neutral to incongruent trials was 3:1, respectively. In equal blocks, the ratio of neural to incongruent trials was 1:1. See Table 3 for corresponding mean values and standard errors.

Table 4
Results from nonlinear multilevel model regression analysis for the Stroop effect for accuracy.

Analysis	Model	Variable	B	SE (B)	β	R^2
Step 1	Within	Block Type	−1.11***	0.17	−0.06	0.004**
	Between	WM	1.08***	0.19	0.18	0.22***
		Age	0.14***	0.02	0.18	
Step 2	Between	Age^2	−0.02***	0.003	−0.51	0.24***
Step 3	Random Mixed	Block x WM	−0.16	0.25		
		Block x Age	0.03	0.03		
		Age x WM	0.04	0.03		
Step 4	Random Mixed	Block x Age^2	−0.01	0.01		
		Block x Age x WM	0.02	0.04		
		Age^2 x WM	−0.01	0.01		
Step 5	Random Mixed	Block x Age^2 x WM	−0.001	0.01		

Note. Predictors were entered into the model in various steps (displayed under the *Analysis* heading). Random-mixed models indicate interactions between within- and between-subjects variables. Mplus does not provide standardized estimates for models with random slopes. In the present analysis, the random slope of accuracy scores regressed on block type was included as a moderating variable for the between-subjects variables of age and working memory (WM). For accuracy, higher scores are indicative of a *lower* Stroop effect.

** $p < 0.01$.
*** $p < 0.001$.
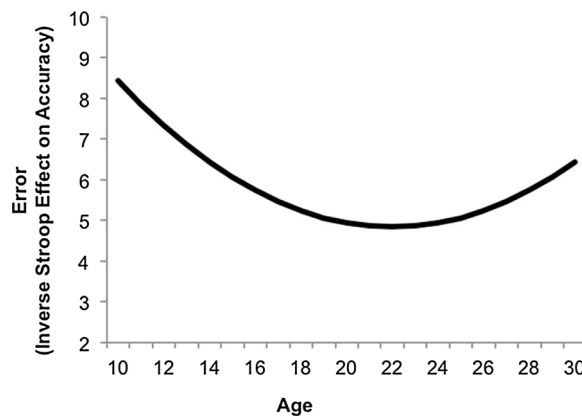
Fig. 3. Age patterns in the Stroop effect for accuracy. The Stroop effect was calculated as the difference in % accuracy between incongruent and neutral trials. The inverse of this value was graphed so that higher values indicate a larger Stroop effect. Values represent estimated regression coefficients.

blocks, but a significant two-way interaction in equal blocks. Further, age and working memory appeared to account for substantially more variance in response time on equal blocks compared to unequal blocks. To further explore this effect, age patterns in the Stroop effect for response time were graphed as a function of working memory by creating estimated slopes for individuals with low,

Table 5
Results from nonlinear multilevel model regression analysis for the Stroop effect for response time.

Analysis	Model	Variable	B	SE (B)	β	R^2
Step 1	Within	Block Type	24.85***	1.36	0.18	0.03***
	Between	WM	3.84**	1.23	0.11	
		Age	0.83***	0.13	0.19	0.52***
Step 2	Between	Age^2	−0.1***	0.03	−0.42	0.53***
Step 3	Random Mixed	Block x WM	2.13	1.88		
		Block x Age	0.4	0.24		
		Age x WM	−0.36*	0.18		
Step 4	Random Mixed	Block x Age^2	0.03	0.05		
		Block x Age x WM	0.65*	0.32		
		Age^2 x WM	−0.01	0.03		
Step 5	Random Mixed	Block x Age^2 x WM	−0.05	0.06		

Note. Predictors were entered into the model in various steps (displayed under the *Analysis* heading). Random-mixed models indicate interactions between within- and between-subjects variables. Mplus does not provide standardized estimates for models with random slopes. In the present analysis, the random slope of accuracy scores regressed on block type was included as a moderating variable for the between-subjects variables of age and working memory (WM). For response time, higher scores are indicative of a higher Stroop effect.

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 6
Results from regression analyses examining the effect of age and working memory on the Stroop effect for response time in equal and unequal blocks separately.

Model	Variable	B	SE (B)	β	R^2
Equal	WM	8.58***	2.04	0.09	0.18***
	Age	0.5**	0.16	0.04	
	Age x WM	−0.64**	0.21	−0.06	
Unequal	WM	4.59	2.44	0.04	0.08***
	Age	1.16***	0.19	0.09	
	Age x WM	−0.2	0.25	−0.02	

Note. There was a significant 3-way interaction among block type, the linear term for age, and working memory. The present table displays results from two separate regression analyses probing this interaction by examining the effect of age and working memory (WM) on the Stroop effefor response time in equal and unequal blocks separately.

** $p < 0.01$.
*** $p < 0.001$.
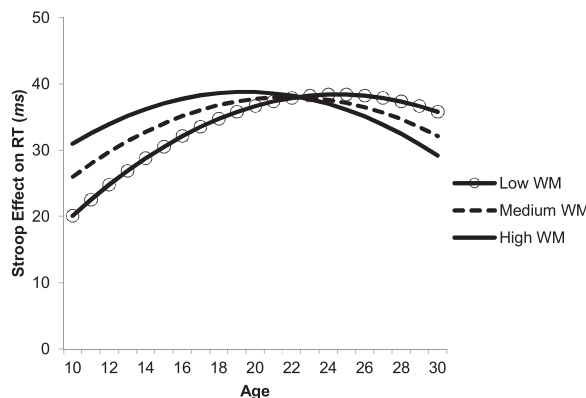
Fig. 4. Age patterns in the Stroop efect for response time (RT) in milliseconds (*ms*) among individuals with low, medium, and high working memory (WM) in *equal* blocks. The Stroop effect was calculated as the difference in RT between incongruent and neutral trials. WM groups were created for purposes of presentation only, based on WM scores at the lower (*M* = −0.83), middle (*M* = 0.06), and top (*M* = 0.8) tertiles of the distribution. In equal blocks, the ratio of neutral to incongruent trials was 1:1. Values represent estimated regression coefficients with a constant of 100 added, for ease of interpretation. Although there was no interaction with Age^2, this term was included in the model to more accurately depict the significant curvilinear trajectory of changes in RT across age.

medium, and high working memory (based on scores at the lower, middle, and top tertiles of the distribution; see Fig. 4). The figure revealed a steep increase in the Stroop effect for response time between early adolescence and early adulthood among individuals with low working memory. In contrast, among individuals with high working memory, there appeared to be little-to-no change in the

Stroop effect for response time between early adolescence and early adulthood, followed by a subtle decrease in the 20s.

Table S4 in the supplementary material presents results for the country-specific effects of age on the Stroop effect for response time. As the table indicates, most countries in the sample evinced a linear or quadratic function of age (age was not associated with Stroop performance in China and the US), suggesting that the Stroop effect for response time increased between the younger and older age groups, such that late adolescents and adults slowed down responding in the presence of incongruent stimuli to a greater extent than did younger adolescents. Consistent with the results for accuracy, age accounted for a minimal, but comparable amount of variance (using R^2) in Stroop performance across countries. Examination of the graphed means in Fig. S2 suggests that in most countries, the Stroop effect either continued increasing into adulthood, or evinced a modest dip among the oldest adults.

4. Discussion

Evidence suggests that working memory facilitates response inhibition by supporting processes related to sustained attention and goal maintenance (Engle, 2002), but few studies have explored this relation in a developmental context. In the present study, we examined the association between working memory and response inhibition on the Stroop task across adolescence and early adulthood. Traditionally, lower accuracy scores and slower response times on incongruent relative to neutral trials reflect a larger Stroop effect and therefore weaker inhibitory control. The Stroop effect is thought to result from cognitive conflict induced by incongruent trials, which is exacerbated by a deficient ability to resist interfering stimuli and a failure to maintain the task goal in active memory. When measuring response inhibition in terms of accuracy, our results indicated that working memory was associated with greater inhibitory control across development. On the other hand, when measuring response inhibition using response time, the effect of age varied as a function of working memory, particularly in task conditions that minimized demands on working memory (equal blocks). Thus, the effect of working memory on age differences in inhibitory control was most evident with respect to response-time interference.

The Stroop effect for accuracy was generally lower among older individuals and individuals with high working memory. These findings are in line with previous studies of differences in Stroop accuracy during adolescence and adulthood (Marsh et al., 2006) and among individuals with low versus high working memory (Kane & Engle, 2003). Likewise, and consistent with work demonstrating that response inhibition continues improving into early adulthood (Davidson et al., 2006; Luna et al., 2001), we found that inhibitory control (measured using accuracy scores) followed a curvilinear trajectory across development, improving into the early 20s. Unlike previous work demonstrating that age patterns in executive functioning vary as a function of task difficulty (Albert & Steinberg, 2011; DeLuca et al., 2003; Huizinga et al., 2006; Luciana et al., 2005), we did not find that the age patterns observed in our study differed between block types. Further, although we had hypothesized that individuals with high working memory would demonstrate mature response inhibition at an earlier age than those with low working memory, we found no evidence that individual differences in working memory moderated age differences in response inhibition—at least with respect to accuracy.

With respect to response time, age patterns in response inhibition varied as a function of both individual differences in working memory and task difficulty. In unequal blocks, which placed higher demands on working memory by encouraging goal neglect, being older was associated with a larger Stroop effect (i.e., more time spent on incongruent relative to neutral trials), independent of individual differences in working memory. On the other hand, in equal blocks, which placed relatively fewer demands on working memory, being older was associated with a larger Stroop effect only among individuals with relatively poorer working memory. Among individuals with relatively higher working memory, age differences in the Stroop effect were comparatively subtler. This moderating effect may have been driven by the 10 year olds in the low working memory group, who demonstrated a notably weaker Stroop effect than older individuals in the low working memory group, and than all individuals in the high working memory group. Alternatively, the finding that age was associated with a larger Stroop effect for response time among individuals with low working memory may be reflective of these individuals slowing down their responding in order to preserve accuracy (Davidson et al., 2006; Morey et al., 2012). This notion is in line with our finding that, regardless of individual differences in working memory, adults demonstrated greater inhibitory control than young adolescents, evincing a lower Stroop effect for accuracy. Put differently, adults with low working memory demonstrated greater response time interference compared to adults with higher working memory, despite comparable accuracy scores.

Stroop interference is thought to be a function of two mechanisms: interference resolution on incongruent trials (i.e., resolving the cognitive interference induced by color words being displayed in an incongruent font color) and goal maintenance (i.e., actively maintaining in memory the need to indicate the color of the word rather than its meaning), which is especially difficult in unequal blocks with infrequent incongruent trials. In studies of adults, the process of interference resolution is reflected primarily in response times, and prevails in task contexts that minimize the need for goal maintenance, such as in equal blocks (Kane & Engle, 2003). Our results have added to this finding by suggesting that the effect of working memory on age patterns in the Stroop effect for response time are also limited to task contexts that minimize the need for goal maintenance. We do not have an obvious explanation as to why age patterns in response inhibition varied as a function of working memory in equal but not unequal blocks. It may be that the effect of working memory on response inhibition is primarily involved in interference resolution (which is a time-consuming process), whereas other executive functions, such as attention (e.g., Unsworth, Redick, Lakey, & Young, 2010), are more prominently involved in successful goal maintenance. Thus, individuals at a given age who vary in their working memory may be equally capable of inhibiting prepotent responses, but those with low working memory take longer (compared to the time it takes to respond to neutral trials) to resolve cognitive interference.

Differences between the correlates of inhibitory control indexed via accuracy versus response time are frequently reported in both the developmental (see Andrews-Hanna et al., 2011; Huizinga et al., 2006; Marsh et al., 2006; Schroeter et al., 2004) and adult (Kane

& Engle, 2003; Long & Prat, 2002) literatures. For example, in a series of experiments comparing Stroop performance between young adults with low and high working memory, Kane and Engle (2003) found that in task contexts with a high frequency of incongruent trials (and therefore lower demands on working memory), working memory was related only to response time, but not accuracy. In other words, individuals with low working memory took longer to respond to incongruent trials, but were still able to preserve their accuracy. This is consistent with the present findings, which demonstrated that on equal blocks (with lower working memory demands), individuals with low working memory took longer to respond to incongruent trials (compared to neutral trials) than did individuals with high working memory. Differences in findings for response time and accuracy may be due to the extent to which age-related differences in inhibitory functioning overlap with individual differences in working memory. Thus, age-related cognitive development may determine the *time* it takes an individual to resolve cognitive conflict, regardless of accuracy, whereas individual differences in working memory may affect the extent to which an individual is able to successfully inhibit prepotent responding (as observed in the accuracy scores).

Results from the multiple group analyses examining age patterns in Stroop performance across countries yielded noteworthy similarities, even when adjusting for in intellectual functioning and SES. In almost all countries, the Stroop effect for accuracy decreased as a function of age, suggesting that across the world, inhibitory functioning (at least as measured by accuracy) improves across adolescence and into adulthood, consistent with findings from previous cross-cultural research (Steinberg et al., 2017). Results for response time indicated that in almost all countries, the Stroop effect increased as a function of age, consistent with the results of the full-sample analysis, and suggesting that older individuals may slow down responding in the presence of incongruent stimuli in an effort to preserve accuracy. We do not have an obvious explanation as to why we did not observe an association between age and Stroop performance among a small number of countries (India and Thailand for accuracy; China and the US for response time), although observation of the means suggests that floor effects (in India, Thailand, and the US) and ceiling effects (in China) may have precluded improvement with age.

The extent of the observed cross-national similarities in inhibitory control may be a function of patterns in neurological development in prefrontal brain regions subserving executive functions, a developmental process that is thought to be nearly universal (e.g., Spear, 2013). Granted, age only accounted for a small portion of the variance in inhibitory control within countries; thus, there are surely various other, potentially country-specific, factors influencing age patterns in inhibitory control. For example, countries around the world vary in the expectations for and socialization practices of self-regulation (Larson, Wilson, & Rickman, 2009). Many non-Western countries such as China, for example, place a strong emphasis on self-control and discipline (Chaudhary & Sharma, 2012; Chen, Cen, Li, & He, 2005). For this reason, individuals from non-Western countries may evince adult-like inhibitory control at an earlier age, or they may evince greater inhibitory control overall compared to people from countries that do not place such a strong emphasis on self-control (e.g., Rubin et al., 2006). Ultimately, more nuanced examinations of factors contributing to country-level differences in cognitive development will be important for future research. At the most basic level, it seems that age patterns in inhibitory control are largely consistent across cultures, but that the level of inhibitory functioning and the age at which this functioning reaches adult levels is likely influenced by various cultural factors.

Although these are novel findings, there are a few limitations of this study that warrant caution when interpreting the results. While other studies examining working memory differences in Stroop performance have tended to use complex working memory span tasks having both a storage and a processing component (e.g., operation or reading span task) to index working memory capacity (e.g., Hutchison, 2011; Kane & Engle, 2003; Long & Prat, 2002), ours utilized a composite of storage-only working memory measures (item recognition, spatial span, and backwards digit span). Complex span tasks may tax domain-general aspects of working memory to a greater extent than the tasks included in our battery. Although previous work has considered item recognition, spatial span, and backwards digit span tasks as valid measures of working memory (e.g., Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000; Thompson-Schill et al., 2002), it is possible that these tasks are best suited to capture variance with respect to storage in "short-term memory" rather than the executive processes most often described as working memory (Conway et al., 2005). We note, however, that because of the use of a composite index, we can be more confident that the observed differences in Stroop performance were not dependent upon idiosyncratic features of a specific task. Future developmental studies of response inhibition and working memory could benefit from an extension of these findings using different measures of working memory capacity and perhaps a construct-level assessment of response inhibition.

An additional limitation of our study is that the Stroop task did not include congruent trials (i.e., trials in which the color of the word matches its meaning), which may have affected our findings on age and working memory differences in response inhibition (e.g., Andrews-Hanna et al., 2011; Hutchison, 2011; Kane & Engle, 2003). In addition to presenting non-conflicting stimuli, congruent trials encourage word-reading, which ultimately becomes an adaptive (time-saving) strategy in blocks with a high proportion of congruent trials. From this vantage point, congruent trials increase the potential for interference on incongruent trials, when word reading is no longer an adaptive strategy. Thus, it is possible that including blocks that intermix congruent and incongruent trials (rather than neutral and incongruent as was done in our study), may increase the overall difficulty of the task, potentially yielding different results with respect to working memory differences in Stroop performance across age. Relatedly, the block manipulations (i.e., equal and unequal) in our Stroop task did not appear to have a strong effect on participant performance, thus limiting our ability to draw conclusions about the extent to which task difficulty interferes with inhibitory control across age and in relation to individual differences in working memory. Future studies may benefit from more extreme variations of block manipulation, such as blocks with 0% and 75% congruent trials (rather than 50% and 75% as was used in our study) (see Kane & Engle, 2003).

One final consideration is our use of cross-sectional rather than longitudinal data. Although the cross-sectional design employed in the present study did not allow for any conclusions to be made regarding the development of inhibitory functioning, it was well-suited for the aims of the study, which focused on determining whether the associations between working memory and inhibitory

functioning observed in previous studies of young adults were also present across different stages of development. Using a cross-sectional design affords an examination of age *differences* (e.g., adolescence versus adulthood) in the association between working memory and inhibitory control. Future research interested in examining predictors and moderators of the developmental trajectory of inhibitory control as a function of working memory would benefit from a longitudinal design. Notwithstanding the importance of longitudinal investigations of cognitive development, the research aims of the present study were ultimately more adequately addressed using a cross-sectional design.

5. Conclusions

The present study is one of the first to explore the association between working memory and response inhibition in a cross-sectional sample. The findings from this study contribute to the developmental literature on Stroop performance, which currently lacks an integrative account of how the interaction between development and individual differences influence executive functioning. By accounting for these factors in our study, in addition to including a large sample that covers a wide span of development, we were able to demonstrate that (a) working memory is associated with behavioral manifestations of inhibitory control, largely independent of age; (b) older age and higher working memory capacity are associated with greater inhibitory control when measured using accuracy; and (c) age differences in inhibitory control (as indexed by response time) are most pronounced among individuals with low working memory. Such findings may be relevant to research on working memory training, which has already offered preliminary evidence of transfer onto other executive functions such as response inhibition (see Chein & Morrison, 2010; Flook et al., 2010; Karback & Kray, 2009; Klingberg, Forssberg, & Westerberg, 2002; Olesen, Westerberg, & Klingberg, 2004). Further, considering the importance of inhibitory functioning during the adolescent years, specifically with respect to academic achievement, occupational success, law-abiding behaviors, and psychological well-being (Moffitt et al., 2013), understanding the ways in which inhibitory control may be improved during this developmental period has important implications for adolescent development and well-being. A compelling next step for future research might be to explore how individual differences in executive functioning influence a variety of outcomes in adolescence, such as academic achievement and risk taking.

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cogdev.2018.02.003.

References

Adleman, N. E., Menon, V., Blasey, C. M., White, C. D., Warsofsky, I. S., Glover, G. H., et al. (2002). A developmental fMRI study of the Stroop color-word task. *NeuroImage, 16*, 61–75. http://dx.doi.org/10.1006/nimg.2001.1046.

Albert, D., & Steinberg, L. (2011). Age differences in strategic planning as indexed by the tower of London. *Child Development, 82*, 1501–1517. http://dx.doi.org/10.1111/j.1467-8624.2011.01613.x.

Andrews-Hanna, J. R., Mackiewicz Seghete, K. L., Claus, E. D., Burgess, G. C., Ruzic, L., & Banich, M. T. (2011). Cognitive control in adolescence: Neural underpinnings and relation to self-report behaviors. *PLoS ONE, 6*, e21598. http://dx.doi.org/10.1371/journal.pone.0021598.

Banich, M., Crowley, T., Thompson, L., Jacobson, B., Liu, X., Raymond, K., et al. (2007). Brain activation during the Stroop task in adolescents with severe substance and conduct problems: A pilot study. *Drug and Alcohol Dependence, 90*, 175–182. http://dx.doi.org/10.1016/j.drugalcdep.2007.03.009.

Bradley, R. H., & Corwyn, R. F. (2002). Socioeconomic status and child development. *Annual Review of Psychology, 53*, 371–399. http://dx.doi.org/10.1146/annurev.psych.53.100901.135233.

Braver, T. S. (2012). The variable nature of cognitive control: A dual-mechanisms framework. *Trends in Cognitive Science, 16*, 106–113. http://dx.doi.org/10.1016/j.tics.2011.12.010.

Chaudhary, N., & Sharma, N. (2012). India. In J. Arnett (Ed.). *Adolescent psychology around the world* (pp. 103–120). New York: Psychology Press.

Chein, J., & Morrison, A. (2010). Expanding the mind's workspace: Training and transfer effects with a complex working memory span task. *Psychonomic Bulletin & Review, 17*, 193–199. http://dx.doi.org/10.3758/PBR.17.2.193.

Chen, X., Cen, G., Li, D., & He, Y. (2005). Social functioning and adjustment in Chinese children: The imprint of historical time. *Child Development, 76*, 182–195.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*, 769–786. http://dx.doi.org/10.3758/BF03196772.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51*, 42–100. http://dx.doi.org/10.1016/j.cogpsych.2004.12.001.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44*, 2037–2078. http://dx.doi.org/10.1016/j.neuropsychologia.2006.02.006.

DeLuca, C. R., Wood, S. J., Anderson, V., Buchanan, J., Proffitt, T. M., Mahony, K., et al. (2003). Normative data from the Cantab I: Development of executive function over the lifespan. *Journal of Clinical and Experimental Neuropsychology, 25*, 242–254. http://dx.doi.org/10.1076/jcen.25.2.242.13639.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. http://dx.doi.org/10.1146/annurev-psych-113011-143750.

Duell, N., Steinberg, L., Icenogle, G., Chein, J., Chaudhary, N., Di Giunta, et al. Age patterns in risk taking across the world. *Journal of Youth and Adolescence*, https://doi.org/10.1007/s10964-017-0752-y (in press).

Egner, T., & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience, 8*, 1784–1790. http://dx.doi.org/10.1038/nn1594.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *The Psychology of Learning and Motivation, 44*, 145–199. http://dx.doi.org/10.1016/S0079-7421(03)44005-X.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19–23. http://dx.doi.org/10.1111/1467-8721.

00160.

Erkut, S. (2010). Developing multiple language versions of instruments for intercultural research. *Child Development Perspectives, 4*, 19–24.

Flook, L., Smalley, S. L., Kitil, M. J., Galla, B. M., Kaiser-Greenland, S., Locke, J., et al. (2010). Effects of mindful awareness practices on executive functions in elementary school children. *Journal of Applied School Psychology, 26*, 70–95. http://dx.doi.org/10.1080/15377900903379125.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133*, 101–135. http://dx.doi.org/10.1037/0096-3445.133.1.101.

Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia, 44*, 2017–2036. http://dx.doi.org/10.1016/j.neuropsychologia.2006.01.010.

Hutchison, K. A. (2011). The interactive effects of listwide control, item-based control, and working memory capacity on Stroop performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 851–860. http://dx.doi.org/10.1037/a0023437.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132*, 47–70. http://dx.doi.org/10.1037/0096-3445.132.1.47.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*, 169–183. http://dx.doi.org/10.1037/0096-3445.130.2.169.

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical & Experimental Neuropsychology, 24*, 781–791. http://dx.doi.org/10.1076/jcen.24.6.781.8395.

Kuo, B. C., Stokes, M. G., & Nobre, A. C. (2012). Attention modulates maintenance of representations in visual short-term memory. *Journal of Cognitive Neuroscience, 24*, 51–60. http://dx.doi.org/10.1162/jocn_a_00087.

Lansford, J. E., & Bornstein, M. H. (2011). Parenting attributions and attitudes in diverse cultural contexts: Introduction ot the special issue. *Parenting: Science and Practice, 11*, 87–101. http://dx.doi.org/10.1080/15295192.2011.585552.

Larson, R. W., Wilson, S., & Rickman, A. (2009). Globalization, society change, and adolescence across the world. In R. M. Lerner, & L. Steinberg (Eds.). *Handbook of adolescent psychology* (pp. 590–692). New York: Wiley.

Long, D. L., & Prat, C. S. (2002). Working memory and Stroop interference: An individual differences investigation. *Memory & Cognition, 30*, 294–301. http://dx.doi.org/10.3758/bf03195290.

Luciana, M., Conklin, H. M., Hooper, C. J., & Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Development, 76*, 697–712. http://dx.doi.org/10.1111/j.1467-8624.2005.00872.x.

Luna, B., Thulborn, K. R., Munoz, D. P., Merriam, E. P., Garver, K. E., Minshew, N. J., et al. (2001). Maturation of widely distributed brain function subserves cognitive development. *NeuroImage, 13*, 786–793. http://dx.doi.org/10.1006/nimg.2000.0743.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*, 163–203. http://dx.doi.org/10.1037/0033-2909.109.2.163.

Marsh, R., Zhu, H., Schultz, R. T., Quackenbush, G., Royal, J., Skudlarski, P., et al. (2006). A developmental fMRI study of self-regulatory control. *Human Brain Mapping, 27*, 848–863. http://dx.doi.org/10.1002/hbm.20225.

Maxwell, J. A. (1996). *Qualitative research design: An interactive approach.* New York: Sage.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex functioning. *Annual Review of Neuroscience, 24*, 167–202. http://dx.doi.org/10.1146/annurev.neuro.24.1.167.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.

Moffitt, T. E., Poulton, R., & Caspi, A. (2013). Lifelong impact of early self-control: Childhood self-discipline predicts adult quality of life. *American Scientist, 101*, 352–359.

Morey, C. C., Elliott, E. M., Wiggers, J., Eaves, S. D., Shelton, J. T., & Mall, J. T. (2012). Goal-neglect links Stroop interference with working memory capacity. *Acta Psychologica, 141*, 250–260. http://dx.doi.org/10.1016/j.actpsy.2012.05.013.

Nee, D. E., Wager, T. D., & Jonides, J. (2007). Interference resolution: Insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective, & Behavioral Neuroscience, 7*, 1–17. http://dx.doi.org/10.3758/CABN.7.1.1.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin, 126*, 220–246. http://dx.doi.org/10.1037/0033-2909.126.2.220.

Oberauer, K., Süß, H.-M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity: Facets of a cognitive ability construct. *Personality & Individual Differences, 29*, 1017–1045. http://dx.doi.org/10.1016/S0191-8869(99)00251-2.

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7*, 75–79. http://dx.doi.org/10.1038/nn1165.

Psychological Corporation (1999). *Wechsler abbreviated scale of intelligence.* San Antonio: Pearson.

Rubin, K. H., Hemphill, S. A., Chen, X., Hastings, P., Sanson, A., Lo Coco, A., et al. (2006). A cross-cultural study of behavioral inhibition in toddlers: East-West-North-South. *International Journal of Behavioral Development, 30*, 219–226.

Schroeter, M. L., Zysset, S., Wahl, M., & von Cramon, D. Y. (2004). Prefrontal activation due to Stroop interference increases during development—an event-related fNIRS study. *Neuroimage, 23*, 1317–1325. http://dx.doi.org/10.1016/j.neuroimage.2004.08.001.

Spear, L. P. (2013). Adolescent neurodevelopment. *Journal of Adolescent Health, 52*, S7–S13. http://dx.doi.org/10.1016/j.jadohealth.2012.05.006.

Steinberg, L., Icenogle, G., Shulman, E. P., Breiner, K., Chein, J., Bacchini, D., et al. (2017). Around the world, adolescence is a time of heightened sensation seeking and immature self-regulation. *Developmental Science*, e12532. http://dx.doi.org/10.1111/desc.12532.

Thompson-Schill, S., Jonides, J., Marshuetz, C., Smith, E. E., D'Esposito, M., Kan, I. P., et al. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive, Affective, & Behavioral Neuroscience, 2*, 109–120. http://dx.doi.org/10.3758/CABN.2.2.109.

Unsworth, N., Redick, T. S., Lakey, C. E., & Young, D. L. (2010). Lapses in sustained attention and their relation to executive control and fluid abilities: An individual differences investigation. *Intelligence, 38*, 111–122. http://dx.doi.org/10.1016/j.intell.2009.08.002.

Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology, 71*, 1–26. http://dx.doi.org/10.1016/j.cogpsych.2014.01.003.

Velanova, K., Wheeler, M. E., & Luna, B. (2009). The maturation of task set-related activation supports late developmental improvements in inhibitory control. *The Journal of Neuroscience, 29*, 12558–12567. http://dx.doi.org/10.1523/jneurosci.1579-09.2009.

Veroude, K., Jolles, J., Croiset, G., & Krabbendam, L. (2013). Changes in neural mechanisms of cognitive control during the transition from late adolescence to young adulthood. *Developmental Cognitive Neuroscience, 5*, 63–70. http://dx.doi.org/10.1016/j.dcn.2012.12.002.

Wechsler, D. (1974). *Wechsler intelligence scale for children—revised.* New York: Psychological Corporation.

Weldon, R. B., Mushlin, H., Kim, B., & Sohn, M. (2013). The effect of working memory capacity on conflict monitoring. *Acta Psychologica, 142*, 6–14. http://dx.doi.org/10.1016/j.actpsy.2012.10.002.