Developmental changes in executive functions during adolescence

A study of inhibition, shifting, and working memory

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Title: Developmental changes in executive functions during adolescence: a study of inhibition, shifting and working memory.

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Abstract:

The development of executive functions (EFs) has primarily been studied among younger children, despite research suggesting that particular aspects of EFs continue to develop throughout adolescence and into adulthood. This study investigated whether EFs continue to develop during the later stages of adolescence: three related, yet separable EF components - inhibition, shifting and working memory - were examined in a cross-sectional sample of 347 adolescents (aged 14-18 years). After adjusting for covariates, age was found to be a significant predictor of pupils' performance on the inhibition but not the shifting or working memory tasks, suggesting different developmental trajectories for the three EF components. Controlling for non-executive processes implicated in performing the inhibition and working memory tasks had the most pronounced effect on the relationship between performance on those tasks and age. Finally, socioeconomic status was a significant predictor of performance on all tasks. Implications for research and practice are discussed.

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Statement of Contribution

What is already known on this subject?

- Brain regions associated with EFs continue to mature throughout adolescence, implying ongoing development of EFs.
- Behavioural studies demonstrate that certain EFs have not yet reached their adult levels in early adolescence.

What the present study adds:

- Changes in inhibition, but not shifting or working memory task performance are evident among older adolescents.
- Lower-order processes tapped by EF tasks act as confounds in the relationship between age and task performance.
- Socioeconomic status is a significant predictor of adolescents’ performance on EF tasks.

Background

During the last few decades, executive functions (EFs) have gained increasing attention in educational and developmental research. Despite there being no single, universal definition that fully captures the conceptual scope of EFs, it is predominantly agreed that the term covers a range of complex cognitive skills, which help people regulate their cognitive, emotional and motor activity and enable them to engage in purposeful, goal-directed behaviour, especially when faced with novel or difficult situations. EFs are associated with many different activities such as planning, problem solving, attentional control, self-regulation, and therefore, most researchers conceptualise EF as being multifaceted, comprising of a set of at least partially dissociable processes (Baddeley, 1996; Miyake et al., 2000; Robbins, 1998; Shallice & Burgess, 1998) rather than a single underlying unitary construct (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan, Johnson, Swales, & Freer, 1997).

In recent years, the distinction has frequently been made between three EF components: i) inhibition, which refers to the ability to override dominant impulses/responses, ii) shifting, which reflects the ability to shift attention between different information and mental states and iii) updating, the ability to update one's working memory by adding, deleting and monitoring pieces of information. This tripartite EF model, was first proposed by Miyake and his colleagues, who found that these three EF components were related, yet separable, in a sample of undergraduate students (Miyake et al., 2000). Many researchers have since explored the extent to which the components of inhibition, shifting and working memory/updating are evident and discernible in children and adolescents. Some studies have confirmed the existence of these three separate EF components in children as young as 8 years old (Latzman & Markon, 2010; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003), but the general pattern accruing from the majority of research is that EFs differentiate with age. In preschool-aged children, cognitive performance can be adequately explained by a unitary model, consisting of a single general EF factor (Fuhs & Day, 2011; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011; Willoughby, Blair, Wirth, & Greenberg, 2010), whereas among primary school–aged children, a two factor model of EF in which the working memory component is separated from inhibition and shifting is regularly found to provide the best fit (Brydges, Fox, Reid, & Anderson, 2014; van der Sluis, de Jong, & van der Leij, 2007; Van der Ven, Kroesbergen, Boom, & Leseman, 2013) and finally, during adolescence, a fully-separated three-factor structure is evident (Latzman & Markon, 2010; Lee, Bull, & Ho, 2013; Li et al., 2015). Despite some discrepancies regarding the ages at which the transitions in EF structure take place, these studies suggest that there is an increasing specialisation of EFs with age, with the tripartite model of EF emerging during early adolescence, around the age of 13-14 years.

Further evidence in support of the specialisation of EFs derives from studies of brain maturation, which demonstrate that the prefrontal cortex - the brain region associated with EFs – continues to undergo substantial changes during adolescence. In the prefrontal cortex, the myelination of axons, a process known to boost the transmission speed of signals across neurons, continues well into adolescence (Yakovlev & Lecours, 1967). In MRI studies, this ongoing axonal myelination is manifested as a linear increase in prefrontal white matter volume during adolescence (Barnea-Goraly et al., 2005; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). In addition to the increase in white matter, MRI studies show that adolescence is characterised by a decrease in prefrontal grey matter volume (Gogtay et al., 2004; Sowell, Thompson, Tessner, & Toga, 2001). This has been attributed to the synaptic reorganisation that takes place in the prefrontal cortex after puberty (Huttenlocher, 1979), during which infrequently used synaptic connections are eliminated whilst frequently used ones are strengthened, resulting in a decline in synaptic density but rendering the remaining synaptic circuits more efficient (Blakemore & Choudhury, 2006).

In accordance with the factor analytic and neuropsychological studies that suggest ongoing development and increasing refinement of EFs with age, researchers have accentuated the importance of examining the full developmental trajectory of EFs. Nevertheless, the majority of research has focused on pre-schoolers and, secondarily, primary school-aged children, while fewer studies have investigated EFs' development during adolescence (Best, Miller, & Jones, 2009; Romine & Reynolds, 2005). The disproportionate focus on younger ages is well grounded, since the preschool and early school years are characterised by fundamental changes in cognition, as reflected in the reports of rapid improvements in behavioural tasks tapping into EF components (particularly inhibition) during these ages (Best & Miller, 2010). However, it has also been shown that performance on tasks of different complexity and/or evaluating different EF components improves at different rates (Best & Miller, 2010; Hughes, 2011) and adult levels of performance on some tasks has not yet been reached by the beginning of adolescence (Davidson, Amso, Anderson, & Diamond, 2006), thus, indicating that certain aspects of EFs may continue changing after puberty.

Behavioural studies investigating EF development beyond the ages of 11-12 years, provide some important evidence that EFs continue developing throughout adolescence and into adulthood (e.g. Boelema et al., 2014; Gur et al., 2012; Luna, Garver, Urban, Lazar, & Sweeney, 2004) and that the different EF components assessed follow somewhat discrete development pathways (e.g. Luna et al., 2004; Magar, Phillips, & Hosie, 2010). The most robust findings concern the protracted development of working memory, since multiple studies using a variety of measures (e.g., digit/letter span, n-back, search and oculomotor tasks) have found significant changes in performance transpiring from early to middle adolescence (Conklin, Luciana, Hooper, & Yarger, 2007; Huizinga, Dolan, & van der Molen, 2006; Lee et al., 2013; but see also some contradicting accounts by Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001 and Prencipe et al., 2011) and, in some cases, extending beyond the age of 18 (Boelema et al., 2014; Gur et al., 2012; Luna et al., 2004). The shifting component of EF also appears to continue developing after puberty, as is evident from the findings of studies investigating adolescents' performance on tasks that require switching between different rules or response sets. More specifically, studies investigating age-group differences have found that performance on shifting tasks levelled off around the ages of 14-15 years (Anderson et al., 2001; Huizinga et al., 2006), while other studies have demonstrated a linear relationship between age and shifting ability extending from early adolescence into young adulthood (Boelema et al., 2014; Magar et al., 2010). Findings are less consistent for the ongoing development of the inhibition component during adolescence, with some results even suggesting no further improvement of response inhibition beyond the age of 11 (Magar et al., 2010). However, most studies show that performance on inhibition tasks continues improving up to the age of 15 (Huizinga et al., 2006; Lee et al., 2013; Luna et al., 2004), with the exception of Stroop tasks (Stroop, 1935), in which functional gains in efficiency continue to emerge after 15 years of age and into early adulthood (Huizinga et al., 2006; Leon-Carrion, García-Orza, & Pérez-Santamaría, 2004).

It is important to note that individual studies vary considerably on many different aspects of their design and methodology. One of the most notable inconsistencies regards the age range across which EF development is examined, with differences evident in both the lower and upper age limits studied. In fact, in some studies, the upper age limit examined is 15 years of age (e.g., Lee et al., 2013; Prencipe et al., 2011; Spielberg et al., 2015); thus, only providing information about the earlier stages of adolescence, whereas less is known about the development of EF during late adolescence and early adulthood (Taylor, Barker, Heavey, & McHale, 2013). Furthermore, studies investigating the maturation of EFs beyond the age of 15, often rely on examining differences in EF performance between discrete groups with large divergences in age, for example 15 year olds compared to 19-21 year olds (Gur et al., 2012; Huizinga et al., 2006; Luna et al., 2004), therefore, potentially masking the specific changes that EF processes may undergo during late adolescence. Finally, there is a large amount of diversity among studies regarding the EF components under examination. Only three of the aforementioned studies (Huizinga et al., 2006; Lee et al., 2013;

Magar et al., 2010) examined the development of all three components of inhibition, shifting and working memory; the others research different combinations of EFs or even certain EF components in isolation (Conklin et al., 2007; Leon-Carrion et al., 2004). In conclusion, more research is needed to further elucidate and disentangle the developmental trajectories of the three EF components, particularly in late adolescence where the existing literature is scarce.

This study aimed to investigate the development of each of the components comprising the tripartite EF model during the latter part of adolescence. Three aspects of EF – inhibition, shifting and working memory - were examined in relation to age in a large sample of 14-18 year olds. Based on the findings of the existing studies discussed above, it was expected that each of these EFs should show some change during the period of 14-18 years of age, but the exact pattern and magnitude of these changes is equivocal due to inconsistencies in the literature. An important objective of this study was to examine the independent effect of age on EFs, whilst controlling for any other factors that may affect individuals' EF abilities, such as individuals' socioeconomic status and the presence of developmental conditions or learning difficulties. Most importantly, because the behavioural tasks used to assess EFs do not constitute pure measures of EFs but also tap other lower-order processes (Burgess, 1997; Miyake et al., 2000), this study aimed to control for the non-executive processes implicated in performing the EF tasks. Many studies examining age-related changes in EFs do not address the task impurity problem, making it difficult to determine whether their findings of improved EF performance over time reflect actual changes in the EF components or arise from changes in lower-order processes (e.g., processing speed). In this study, we accounted for this by including control conditions of the tasks used to assess the EF components wherever possible. The control conditions resemble the EF tasks in every way, but do not place any significant demand on EFs, thus, allowing us to measure relevant lower-order processes and control for them in subsequent analyses (Denckla, 1996; van der Sluis et al., 2007).

Method

Participants

The sample for this study comprised of 347 adolescents (171 females, 176 males) recruited from three different secondary schools in and around the city of Edinburgh, Scotland UK. The participants were drawn from the third (N=134), fourth (N=113) and fifth (N=100) years (M_{age}=15.74 years, SD=1.07, range=13.83-17.83) and the majority were British (88%) and right handed (87%). The three secondary schools served children from different socioeconomic backgrounds. The schools' free meal entitlement rates at the time testing took place were 5%, 13% and 48%, while the corresponding national rates were 15% (2015) and 14% (2016).

The study received ethical approval from the School of Philosophy, Psychology and Language Sciences Ethics Committee within the university and permission to contact the schools was obtained from the City of Edinburgh and West Lothian councils in Scotland, UK. Information forms were sent out to the pupils' parents/carers providing them with the opportunity to opt their child out from participating in the study. Assent was also obtained, from each pupil individually, prior to them being tested.

Materials

The tasks used to measure the three EF components of interest derived from two cognitive assessment batteries: the Delis Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) and the British Ability Scales Second Edition (BAS II; Elliott, Smith, & McCullouch, 1997).

Inhibition

The Colour-Word Interference (CWI) test from the D-KEFS was used to measure inhibition. For the inhibition condition, participants were presented with 50 colour names (i.e., "green", "red" and “blue”) printed on a page in a colour that is incompatible with each word’s meaning (e.g., the word green printed in red ink). The participants had to inhibit their prepotent response to read out the words and instead name the ink colour in which the words were printed; the time it took participants to do this for the total of 50 items was recorded as their inhibition score. The colour naming condition of the CWI was used as a control condition, since it measures the speed with which participants name colours i.e., the non-EF process that influences performance on the inhibition condition. Participants were shown a page depicting 50 colour patches and were asked to name the colour of these patches as fast as possible; the time it took participants to do this was recorded as their (control condition) score.

Shifting

The Sorting test from the D-KEFS battery - more specifically the Free sorting condition of the test--was administered as a measure of shifting, since scores on this condition have previously been found to load on factors associated with conceptual flexibility (Latzman & Markon, 2010; Li et al., 2015). Participants were presented with a set of six cards that each displayed a printed word and discernible perceptual stimuli. The participants’ task was to sort the cards into two groups of three cards each according to as many different categorisation rules as they could identify (e.g., according to the shape of the cards - angular or curvy - or the words displayed on them - animals or means of transportation). The six cards could be grouped into a maximum of eight sorts, and the procedure was carried out with two different sets of cards, yielding a maximum of 16 sorting rules to be identified. For each sort generated, participants were expected to provide a verbal description of the rule/concept they used to sort the cards and only sorts accompanied by an at least partially accurate description of the sorting rule were awarded points. Descriptions were also awarded up to four points each, according to their quality. The total number of correct sorts participants generated across the two sets of cards (maximum = 16) and the overall score for their corresponding descriptions (maximum = 64) were recorded as sorting scores.

Working memory

The Recall of Digits Backward scale of the BAS II was administered as a measure of verbal working memory. For this task, participants were read sequences of digits at a rate of two digits per second and were asked to repeat the digits in the reverse order. In total, there were 30 sequences arranged in blocks of increasing length (from two to seven digits). The number of sequences (maximum = 30) which the participant recalled correctly (with all digits recalled in the correct reverse order) was recorded as their working memory score. The Recall of Digits Forward scale was also administered as a control condition that measures verbal short-term memory. In this version, the participants have to repeat sequences of digits that are read to them in the same order. The sequences are presented at a rate of two digits per second and increase in length from two to nine digits. The number of sequences (maximum = 36) correctly recalled was used as participants' (control condition) score.

Procedure

Pupils were individually tested in a quiet room within their school premises. Each participant completed the cognitive tasks during a single session lasting approximately 40 minutes. The order of the tasks was counterbalanced across the majority of the sample (56%)[1] and for the tasks comprising of more than one condition, the control-conditions measuring non-EF processes were always administered before the corresponding EF conditions.

Covariates

Certain demographic variables were considered potential confounders in the relationship between EFs and age, and were thus included as covariates in the analyses. Socioeconomic status was indicated by the Scottish Index of Multiple Deprivation (SIMD; Scottish Government, 2016), which is used to rank small areas within Scotland from most to least deprived (ranked 1 to 6,976

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[1] The results of the corresponding MANOVA showed that there were no significant differences in performance on any of the tasks among these pupils (Pillai's Trace= .19, F (25,880)=1.42, p>.05).

respectively). In this study's sample, the SIMD values ranged from 116 to 6807 (M_{SIMD}=4506, SD=2050.12, SIMD not available for 3 pupils). Because the participants for this study were recruited as part of a project aiming to investigate the relationship among EFs and the educational attainment of pupils within a typical secondary school classroom, our sample included individuals with developmental conditions, learning and/or physical difficulties that could affect performance on the cognitive tasks. In order to control for individual differences in performance resulting from this, a binary variable, denoting whether or not participants had a condition, was included in the analyses. A list containing a variety of conditions that influence performance on the cognitive tasks of the D-KEFS and BAS II batteries (e.g., learning difficulties, hearing, speech or visual impairment, head injury requiring hospitalisation/traumatic brain injury, autism spectrum disorder etc.) was provided to the schools and a relevant member of staff checked the participating pupils against this list. Pupils were categorised into two groups (Condition, No condition) with no further distinctions made, since distinguishing among pupils with different kinds or number of conditions was beyond the scope of this study. A total of 58 pupils were recorded as having a condition that may affect their EF performance.

Data preparation

Raw scores on each of the cognitive measures were examined for univariate outliers resulting in four scores on the CWI colour naming condition and one score on the CWI inhibition condition being recoded as missing, as they constituted major outliers[2]. Together with missing data accruing from procedural and/or administration errors, approximately 3% of the data were missing.

Statistical analyses

Statistical analyses were performed in R, version 3.4.4 (R Development Core Team, 2018). Firstly, the relationship among pupils' performance on each of the measures and their age was examined

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[2] Major outliers were determined based on the Interquartile Range (IQR) rule. Any value more than 3xIQR beyond the Upper or Lower Quartile was considered a major outlier.

by calculating the zero-order correlations between these variables. Next, multiple linear regression models were developed in which performance on each of the EF measures was regressed on pupils' age, gender, level of deprivation (SIMD), condition status (binary variable indicating whether or not they had a condition) and their performance on the respective non-EF condition of each task.

The Full Information Maximum Likelihood (FIML) method was utilised for handling missing data across all analyses. The FIML estimator uses all the available information from all cases and incorporates it into the estimation process. Therefore, it is considered superior to other missing data techniques (i.e., listwise/pairwise deletion or mean imputation) and has been found to produce regression coefficients and R^2 estimates with little or no bias in simulation studies (Enders, 2001). FIML estimation was implemented through the lavaan package in R Studio (version 1.1.453) and the analyses were consequently carried out using Structural Equation Modelling (SEM).

Results

Descriptive statistics for the raw scores on all cognitive measures after the removal of extreme values are shown in Table 1 (for the whole sample) and Table 2 (for each age-group separately). Higher scores indicate better performance for all measures apart from the scores on the inhibition task (CWI), which correspond to completion times.

The correlations among performance on the cognitive measures and age are shown in Table 3. For these analyses, the time scores from the two conditions of the CWI task were inverted so that, similarly to all other measures, higher scores indicated better performance. Pupils' age was found to be significantly correlated to their inhibition ($r=.20$, $p<.001$) and working memory scores ($r=.12$, $p<.05$), as well as their scores on the control conditions measuring colour naming speed and short-term memory ($r=.20$, and $r=.18$ respectively, both $p_s<.001$), which were in turn strongly correlated to the corresponding EF scores, i.e., inhibition and working memory (r=.68 and r=.61 respectively, all p_s<.001). Neither of the two measures obtained from the sorting task were found to correlate with age (number of correct sorts, r= -.02, p=.74 or description score, r= -.01, p=.81) but they were very highly related to each other (r=.94, p<.001) and presented the same pattern of correlations with the other EF scores. On this account, only the number of correct sorts generated was chosen to be included in the regression models as a measure of shifting.

In the next step, three regression models were developed, in order to examine the independent effect of age on each of the three EF components whilst controlling for the other variables of interest. Pupils' inhibition (performance on the CWI Inhibition condition), shifting (number of correct sorts generated in the Sorting task) and working memory (performance on Recall of Digits Backward task) were set as the outcomes in each model respectively. In addition to pupils' age, their gender, SIMD and condition status were included as predictors in each model. Furthermore, the non-EF processes of colour naming speed and short-term memory were considered in the respective EFs' models.

The full models are presented in Table 4. In the inhibition model, pupils' SIMD, condition, age and colour naming speed were all significant predictors of pupils' inhibition scores and accounted for approximately 50% of the variance; gender was the only insignificant predictor. In the shifting model, and in line with the correlational analyses, age was not found to be a significant predictor. The model only accounted for 6% of the variance in shifting scores and pupils' SIMD was the only significant predictor. Finally, in the working memory model, 39% of the variance in performance was explained, with pupils' condition, SIMD and short-term memory as significant predictors. Pupils' age and gender were not significant predictors of their working memory scores.

Discussion

The main objective of this study was to investigate the development of three different aspects of EF, namely inhibition, shifting and working memory, during the late stages of adolescence. The results showed that within a large cross-sectional sample of 14 to 18 year olds, there was no evidence of age-related changes in performance on the tasks used to measure shifting or working memory, but notable changes in performance on the inhibition task.

Initially, the correlational analyses showed that scores on the inhibition and working memory tasks were significantly and positively correlated with pupils' age but scores on the shifting task were not. It is important to note that even in the case of inhibition and working memory, the correlations with age albeit significant, were small, suggesting only tenuous changes in performance across these ages. The next step was to examine whether the effect of age remained after controlling for gender, socioeconomic status, and the presence of any learning/developmental condition. Importantly, adolescents' performance on the control conditions used to measure non-EF processes implicated in performing the EF tasks was also included in the relative regression models. After controlling for all these variables, age only remained a significant predictor of performance on the inhibition task.

The finding that developmental changes were only evident in the case of inhibition is rather counterintuitive, as many previous studies found no further improvements in inhibition after early adolescence (Lee et al., 2013; Luna et al., 2004; Magar et al., 2010). Since the Stroop-like task used to measure inhibition in this study was scored in terms of speed, as opposed to the shifting and working memory tasks, it is possible that our results reflect a selective age effect on speed rather than inhibition. However, this explanation seems less plausible when considering the findings of Huizinga et al. (2006), who assessed each EF component using multiple tasks scored either in terms of accuracy or speed, and found that the Stroop task was the only task on which performance continued improving beyond the age of 15. Furthermore, the findings of Leon-Carrion et al., (2004) who found age-related differences in 6-17 year olds' speed and accuracy scores on a Stroop-like task, provide further support for the idea that performance on Stroop-like tasks, regardless of whether it is measured in terms of speed or accuracy, undergoes ongoing changes during late adolescence. In their review, Best and Miller (2010) make a case for different inhibition tasks showing different ages of mastery as a result of their different cognitive demands. Perhaps then, Stroop-like tasks tap into more complex inhibitory processes, which continue developing beyond the age of 15.

Another unusual finding was that shifting appeared not to change within the age period under study. Previous studies have demonstrated ongoing improvements in shifting up to the age of 15 (Anderson et al., 2001; Huizinga et al., 2006) or linear improvements up to young adulthood (Boelema et al., 2014; Magar et al., 2010); however, these findings are not directly comparable to ours, due to dissimilarity in the tasks used to assess shifting. These studies often measured shifting using computerised tasks in which participants have to switch between different kinds of responses based on the stimuli presented to them. In addition to shifting, these tasks rely on individuals' ability to hold different rules in mind and inhibit one response in favour of another, which renders them more complex than the Sorting task used in this study and may explain why performance on these tasks is shown to improve at a slower pace.

The third EF component - working memory- was found to correlate with age, but this effect was grossly attenuated after controlling for demographic variables and short-term memory. Findings from other studies utilising the backwards digit recall task are mixed, with performance showing no further improvement beyond early adolescence in some studies (Anderson et al., 2001; Prencipe et al., 2011), while in others, 16-17 year olds were found to perform better than younger adolescents (Conklin et al., 2007). It is noteworthy, however, that Conklin et al. (2007) did not control for differences between older and younger adolescents' short-term memory capacity when examining age-related changes in working memory, which might explain their contrasting results. All things considered, changes in performance on backwards digit recall tasks observed during late adolescence may not result from changes in working memory efficiency as such, but rather reflect the expansion of short-term memory capacity. This interpretation of the results also fits well with the current study's surprising finding that our measure of short-term memory was correlated more strongly to age compared to that of working memory, which, in accordance to the findings of other studies using Digit span tasks (Anderson et al., 2001; Conklin et al., 2007), indicates that short-term memory may still be significantly changing during adolescence.

Similar to short-term memory, the other non-EF process measured in this study (colour naming speed) was correlated to age as strongly as its corresponding EF component (inhibition), suggesting that it also changes significantly within the age range examined and should be controlled for when examining age-related changes in inhibition. Indeed, both non-executive processes were strong, significant predictors of their EF counterparts in the corresponding regression models. In the case of working memory, in fact, controlling for short-term memory and other variables rendered the individual effect of age insignificant. These results highlight the importance of controlling for lower order, non-executive processes when studying EFs. Failing to do so is likely to lead to biased conclusions.

Among the other covariates examined in this study, socioeconomic status (indicated by SIMD) was found to consistently explain unique variance in performance on all three EF tasks. Thus, individual differences in adolescents' inhibition, shifting and working memory appear to be influenced by their home background, with lower socioeconomic status being associated with poorer EF performance. This is in agreement with several other behavioural studies that detected socioeconomic disparities in EF performance in younger samples of infants (Lipina, Martelli, Vuelta, & Colombo, 2005), preschoolers and school-aged children (Arán-Filippetti & Richaud De Minzi, 2012; Noble, McCandliss, & Farah, 2007; Sarsour et al., 2011 and see Lawson, Hook, &

Farah, 2018 for a meta-analysis of mutliple studies), but fewer studies have focused on socioeconomic disparities in EF performance among adolescents. Two studies that examined the development of adolescents' EFs in relation to socioeconomic status longitudinally, found that it is significantly related to changes in certain aspects of EF over time (Boelema et al., 2014; Spielberg et al., 2015). In the case of inhibition, Boelema et al. (2014) found that the socioeconomic gap in performance was not only maintained but magnified during adolescence, with inhibition maturing at a faster rate among the adolescents with higher socioeconomic status compared to their less affluent counterparts. Although our study was not longitudinal and thus, no inferences could be made about the role of socioeconomic status in the maturation of EF, the fact that it was found to uniquely contribute to adolescents' EF performance, even after controlling for age, confirms that it is an important predictor of EF across the ages of 14-18.

The fact that our study was cross-sectional constitutes one of its main limitations. Studies with a longitudinal design that allow within-person comparisons of performance on EF tasks constitute a better way to control for effects of external variables and reliably detect developmental changes. Another limitation was that only one task was used to assess each EF component. Administering multiple tasks would allow us to use latent variable modelling to extract shared variance across these tasks and yield a purer measure of each EF (Cassidy, 2016; Lehto et al., 2003; van der Sluis et al., 2007).

Despite these limitations, this study attempted to minimise the noise in the results by controlling for pupils' demographic characteristics and non-executive abilities –variables that are often overlooked –thus, allowing us to obtain a clearer picture of the independent effect of age on EF performance. Our results indeed confirmed the importance of controlling for these confounding variables when examining age-related changes in EFs within cross-sectional samples. Most importantly, since we found a selective age effect on inhibition but not the other EF components, this study contributes further evidence in support of the ongoing development of EFs during late adolescence and the different developmental trajectories of inhibition, shifting and working memory.

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Table 1. Descriptive statistics (sample size, mean and standard deviation) for all cognitive variables, after removing extreme values.

	N	M	SD
Inhibition, CWI INH time (s)	340	48.95	11.86
Colour naming speed, CWI CN time (s)	337	29.17	5.66
Shifting, ST correct sorts (max.16)	345	8.94	2.14
Shifting, ST description score (max. 64)	345	30.61	7.80
Working memory, RDB score (max. 36)	320	17.95	4.66
Short-term memory, RDF score (max. 30)	338	26.27	4.36

Note.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

Table 2: Descriptive statistics (sample size, mean and standard deviation) for all cognitive variables, after removing extreme values presented separately for each age group.

	Age 13			Age 14			Age 15			Age 16			Age 17		
	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD
Inhibition, CWI INH time (s)	3	57.67	16.5	106	51.33	11.60	81	49.04	10.75	89	49.38	13.03	61	43.66	10.22
Colour naming speed, CWI CN time (s)	3	31.00	4.36	105	30.42	5.47	80	29.75	5.65	88	28.32	5.78	61	27.38	5.39
Shifting, ST correct sorts (max.16)	3	8.33	2.31	108	8.88	2.19	83	9.08	2.21	90	9.07	2.07	61	8.69	2.07
Shifting, ST description score (max. 64)	3	28.00	9.64	108	30.22	7.98	83	31.30	7.76	90	31.06	7.92	61	29.80	7.36
Working memory, RDB score (max. 36)	2	17.50	4.95	93	16.85	4.39	78	17.94	4.48	88	18.86	4.98	59	18.34	4.63
Short-term memory, RDF score (max. 30)	3	25.67	2.52	99	24.96	3.89	83	26.07	3.88	92	27.15	4.88	61	27.34	4.46

Notes.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test,

RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

The total number of pupils within each age group was N=3 for Age 13; N=108 for Age 14; N=83 for Age 15; N=92 for Age 16 and N=61 for Age 17

Table 3. Correlations among cognitive variables and age.

	1.	2.	3.	4.	5.	6.
1. Inhibition, CWI INH	-					
2. Colour naming speed, CWI CN	.68***	-				
3. Shifting, ST correct sorts	.26***	.19**	-			
4. Shifting, ST description score	.26***	.19**	.94***	-		
5. Working memory, RDB	.46***	.42***	.24***	.24***	-	
6. Short-term memory, RDF	.38***	.32***	.25***	.24***	.61***	-
7. Age	.20***	.20***	-.02	-.01	.12*	.18***

Notes.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

*p<.05, **p<.01, ***p<.001

Table 4. Regression models: Information on the individual predictors and overall variance explained in the models predicting a) inhibition, b) shifting and c) working memory.

			B	SE(B)	β	p
a)	**Inhibition**	Gender	-1.403	0.909	-0.059	.123
		Condition	-3.940	1.501	-0.124	.009
		SIMD	0.057	0.028	0.098	.044
		Age	0.851	0.414	0.077	.040
		Colour naming speed	1.331	0.087	0.648	.000
b)	**Shifting**	Gender	-0.035	0.220	-0.008	.875
		Condition	-0.399	0.308	-0.070	.195
		SIMD	0.024	0.005	0.231	.000
		Age	-0.000	0.105	-0.000	.998
c)	**Working memory**	Gender	-0.375	0.412	-0.040	.364
		Condition	-1.442	0.568	-0.116	.011
		SIMD	0.020	0.010	0.088	.045
		Age	0.092	0.201	0.021	.649
		Short-term memory	0.600	0.048	0.561	.000

Note

SIMD: Scottish Index of Multiple Deprivation