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The Role of Socioeconomic Status in Cognition and Brain Health Across the Lifespan

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Abstract

Disparities in cognition are inevitable throughout the lifespan due to socioeconomic gaps. Individuals of lower socioeconomic status (SES) may have fewer access to environmental resources, especially with regard to education, than individuals of higher socioeconomic status. Differences in available resources from a young age may affect brain development, leading to detriments in cognition and behavior, further impacting socioeconomic success in adulthood. In the present study, we modeled the development of the dorsolateral prefrontal cortex (DLPFC) and changes in cognitive function throughout the life trajectory in the Nathan Kline Institute for Psychiatric Research Rockland Sample. The DLPFC volume was predicted to be associated with SES and executive function, measured by Digit Span Backward, Color-Word Interference, Trail Making Test, and Verbal fluency tasks: lower SES would hinder DLPFC development, which would relate to progressively impaired executive functioning. Greater age would show increased detriments to executive functioning with lower SES due to accumulated effects from health and environmental disparities on the DLPFC. Results demonstrated that low SES impaired performance on all executive function tasks, with greater differences as age increases. The DLPFC failed to correlate with SES and executive function across the lifespan when we controlled for age, suggesting age is a critical factor in the impairment of executive function and reduction of DLPFC volume. The importance of age and SES in executive functioning and brain development patterns points to the urgency of support in young people to help mitigate the detrimental effects of SES throughout life.

Keywords: socioeconomic status, dorsolateral prefrontal cortex, executive function, lifespan

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The Role of Socioeconomic Status in Cognition and Brain Health Across the Lifespan

The United States is one of the most diverse countries in the world, composed of people of different racial/ethnic, social, and economic backgrounds. However, disparities exist due to the stratification of individuals' amount of social power. In particular, socioeconomic status (SES), measured by one's income, occupation, and education, is a factor that plays a role in nearly all aspects of individuals' lives (American Psychological Association, n.d.). Most relevant to the present work, individuals' physical and mental health may be impacted by their SES background. A low SES may affect and be affected by social and environmental factors on the individual, family, and neighborhood level. For instance, families with parents who have financial stressors, such as taking on multiple jobs, may not have enough time, money, and mental energy to focus on the quality of housing, take care of children, and maintain their own health (Chen & Miller, 2013). Limited resources and unexpected or conflicting demands may lead to instability and unpredictability of daily routines, which may ultimately influence individuals' psychological characteristics and behaviors, as well as health outcomes (Chen & Miller, 2013).

Specifically, childhood SES can predict executive function (EF), which includes the mental processes necessary for regulating behavior (Hackman et al., 2015). EF involves several processes required for concentrating (self-control), selecting what to attend to rather than relying on instincts (interference control), retaining information temporarily in the mind (working memory), creativity and adjusting perspectives (cognitive flexibility/shifting), problem solving, and planning (Diamond, 2013). Lower childhood SES is related to worse performance on tests of EF over time, and the correlation between SES and EF is stable over time through adolescence unless there are changes in family SES, which in turn contribute to developmental changes in EF

(Hackman et al., 2015). Family SES and children's EF are positively correlated, as stress experienced in the early years of life may have had genetic and environmental effects on EF, as are children's EF and academic achievement in math and literacy, both of which require cognitive control and self-regulation (Nesbitt et al., 2013). Additionally, EF mediates the association of SES and academic achievement measured by math ability and literacy in young children. All in all, children with lower family SES had lower executive functioning, which led to lower academic skills. These findings point to the importance of the environment for young individuals as their development of EF may be impacted in the long term.

EF develops rapidly in preschool years (3-6 years) and growth slows after puberty (Ashtari & Cyckowski, 2011). The development of EF follows an inverted U-shape as maximum cognitive function is reached at early adulthood and begins to decline (Blair & Berry, 2017). Thus, lower EF from a young age may lead to long-term effects on cognition and lower quality of life with achievement gaps through early adulthood due to initial difficulties in cognitive inhibition and flexibility. Demonstrated in a longitudinal study, declines in inhibition and shifting may begin as early as the 20s and continue reducing throughout the rest of life as the brain ages, becoming less efficient in processing and communicating information (Fjell et al., 2017). In particular, the quality of education, which was measured by reading achievement, significantly accounted for discrepancies in older adults' performance on a neuropsychological battery, which measured cognitive functions such as learning, memory, and abstract reasoning (Manly et al., 2002). Specifically, an estimated higher education quality predicted greater performances on cognitive tasks during late adulthood (Manly et al., 2002). Therefore, people who experience a weaker development of EF in childhood may manifest even greater detriments in cognitive aging as they become older.

Features of EF can be assessed by numerous cognitive tasks across the life trajectory. For example, the Digit Span Task, in which participants repeat strings of numbers forward and backward, measures working memory, as information is stored for short-term (Ruscheweyh et al., 2013). The Trail Making Test is typically used to measure cognitive flexibility, or set-shifting, because individuals must shift their strategies and cognitive searches to draw a line alternating between numbers and letters sequentially (Ruscheweyh et al., 2013). Inhibitory control, or inhibition, is the ability to prevent distractions from hindering one's thought or action and generally assessed with the Stroop Task (Stroop, 1935) because the task involves ignoring features of presented words to produce a correct answer (i.e., naming the stimulus color while ignoring word meaning; Diamond, 2013). The various methods to measure each aspect of EF demonstrate the diverse role of EF in cognition necessary for day-to-day functioning and the necessity to study deviations from average cognitive task performance.

Furthermore, SES influences on EF may be related to the structural brain region that is highly involved with EF: the dorsolateral prefrontal cortex (DLPFC). The DLPFC is only found in primates and is one of the latest brain structures to complete developing (Panikratova et al., 2020). The DLPFC also remains one of the most complex brain structures and directs all components of EF through of its connectivity to various brain regions, including the anterior cingulate (ACC) for inhibitory control and occipital region for verbal EF (Panikratova et al., 2020). Functional and structural imaging data demonstrate that the DLPFC is associated with performance in tasks measuring EF (Ruscheweyh et al., 2013). In other words, increased activation and large volume are both positively correlated with EF task performance. A longitudinal study of adolescent participants demonstrated that individuals of lower SES had worse behavioral inhibition (Spielberg et al., 2015). These individuals also had a decreased

ACC-DLPFC coupling, which is the psychophysiological connectivity between the two brain regions necessary for behavioral inhibition, over time. In other words, throughout development, those with lower SES had less efficient inhibition in the DLPFC. A decreased ability to inhibit one's thoughts and actions could lead to poor planning and decision making during adolescence and throughout adulthood, which may ultimately hinder one's potential to thrive at school and in a future career.

Early environmental factors due to SES may influence age-related brain changes. The brain has the potential for plasticity, which means that neural connections alter throughout development and aging and cause changes in behavior and cognition (Fjell & Walhovd, 2020). For instance, the neurons in the prefrontal cortex region decrease in resilience to stress during aging, leading to detriments in aspects of EF, such as working memory and self-regulatory behaviors (McEwen & Morrison, 2013). Although age-related brain differences in the DLPFC may be observed through functional studies, examining the structure of the brain is crucial to understanding the potential physical changes that may gradually lead to detrimental cognitive effects. The DLPFC may reach its absolute maximum size in the early 20s and then begins to decrease throughout adulthood, which means that early influences on the brain may have lasting effects (Giedd, 2004). Throughout healthy aging, the brain volume decreases as neurons shrink or are lost, the ventricular system expands, and synapses and synaptic spines reduce (Fjell & Walhovd, 2020). However, environmental and lifestyle factors may also impact gray matter volume, which may in turn affect risks for cognitive impairment. Older adults with lower aerobic fitness levels had smaller gray matter volume and worse performance on EF tasks, including the Stroop task (Weinstein et al., 2012). Over time, individuals who lack access, resources, or opportunities, including high quality education and exercise, may have volumetric changes in the

DLPFC. Thus, an accumulation of disadvantages throughout early parts of life may then lead to disproportionate effects on EF impairment as additional neurons and synapses are lost or reduced in older adulthood.

Overall, SES may be associated with changes in both the DLPFC volume and EF throughout life. Specifically, SES may influence DLPFC volume, which may be associated with impacts on cognitive ability. Consistent with this hypothesis, in a recent study, people from lower SES groups performed worse than those from higher SES groups on EF tasks, including Trails B, Digit Span Backwards, and Verbal Fluency (Shaked et al., 2018). In Shaked et al.'s work, there was a limited participant sample in terms of race and age with only White and African American participants with a mean age of 51.62 (range = 33-69 years). In addition, a binary classification defined their SES factor (above or below 124% of the 2004 federal poverty line). Although the DLPFC only mediated SES and EF in the Trails B task, this study utilized a novel model to represent the associations between socioeconomic demographics, brain volume, and executive function. The limited age range of adult participants in Shaked et al. (2018) may have led to insignificant findings in many of the EF task performances, as EF changes may not be as apparent while comparing only individuals in mid-adulthood.

The present study extended upon these findings. We investigated how SES is associated with EF and DLPFC volume throughout the life trajectory by utilizing the Nathan Kline Institute for Psychiatric Research's Rockland Sample, which includes participants aged 6-85 years, a much larger age range than that of Shaked et al. (2018). Our sample included more levels of SES to encompass and represent the local population. We analyzed Digit Span Backwards, as well as different cognitive tests of the Delis-Kaplan Executive Function System (D-KEFS) (Delis et al., 2001; Delis & Kramer, 2004), including Color-Word Interference, Trail Making, and Phonemic,

Semantic, and Category Switching Verbal Fluency tasks to examine working memory, inhibition, shifting, and information retrieval. Expanding on Shaked et al. (2018), we analyzed both phonemic and semantic verbal fluency. They found that the DLPFC volume did not significantly mediate the relationship between SES and verbal fluency performance, attributing to the fact that semantic-based verbal fluency may lead participants to search their semantic memory, which is more heavily dependent on temporal lobe regions. Conversely, letter-based or phonemic verbal fluency may lead participants to use phonemic cues for word retrieval, which causes greater activation in the prefrontal cortex region and may rely more on the DLPFC (Gourovitch et al., 2000). In addition, Shaked et al. (2018) did not correct for intracranial volume because they removed the DLPFC variances. However, correction is a key step to study the volume of the DLPFC in relation to the total brain volume and reduce individual differences, especially for our study with a wide age gap.

We focused on when and how we would see differences in DLPFC volume and executive function by including individuals from a young age to late adulthood. We expected in our cross-sectional study an inverted U-shape trajectory for DLPFC size across age, as DLPFC size would develop to the maximum size by age 20, after which DLPFC size progressively decreases (Giedd, 2004). In addition, we expected a linear relationship between SES and DLPFC: a lower SES would be associated with a smaller DLPFC volume, whereas higher SES individuals would have a larger DLPFC volume. Similarly for EF, we anticipated an inverted U-shape trajectory because EF would increase to the maximum capacity by early adulthood and decrease relative to age. SES and EF would also have a positive correlation: as SES increases EF performance would increase. Altogether, we predicted that DLPFC is influenced by and affects SES and EF, respectively, across the lifespan. We anticipated an inverted U-shape trajectory for both DLPFC

size and cognitive ability with more pronounced differences between lower and higher SES groups as age increases. In other words, both DLPFC and EF would increase to maximum capacity until early adulthood, after which DLPFC size decreases and leads to an increased impairment of executive function task performance. However, older adults from lower SES backgrounds would have a smaller DLPFC volume and more evident cognitive decline than older adults from higher SES backgrounds. Consequently, we predicted that individuals of low SES backgrounds would have lower accuracy, inhibitory control, shifting, and information retrieval in all cognitive tasks than individuals of higher SES backgrounds, with more pronounced differences as age advances. The richness of our cross-sectional data provided our study the ability to understand and identify potential interventions for detrimental effects on cognitive function and brain health over the lifespan.

Method

Participants

Two-thousand four-hundred forty-five participants aged 6-85 years old (1445 females; M_{age} = 37.77 years; SD_{age} = 22.27) were recruited in the Rockland Sample. Participant recruitment involved advertisement flyer mailings and postings in Rockland County, New York. The sample represented the racial distribution (74.3% White, 15.9% Black, 5.8% Asian, American Indian/Native Alaskan = 1%, Native Hawaiian/Other Pacific Islander = 0.3%, Other = 2.7%) and ethnic (Hispanic, Latino, Spanish = 13.4%) of the area. Following Shaked et al. (2018), our study exclusions were individuals (a) diagnosed with AIDS or HIV positive status; (b) diagnosed with a terminal illness (e.g., metastatic cancer); (c) suffering from history of dementia, stroke, or transient ischemic attack or other neurological disorder (e.g., epilepsy, multiple sclerosis, Parkinson’s disease); (d) affected by magnetic resonance imaging (MRI)

contraindications (e.g., claustrophobia, indwelling ferromagnetic material). After exclusions, 821 participants of the Rockland Sample aged 7-84 years old (500 females, M_{age} = 36.57 years; SD_{age} = 21.48) were included in the analysis. Our sample's racial (77.3% White, 13.5% Black, 4.6% Asian, American Indian/Native Alaskan = 1.1%, Native Hawaiian/Other Pacific Islander = 0.4%, Other = 2.9%) and ethnic (Hispanic, Latino, Spanish = 11.2%) distrubutions also aligned with those of the area. All participants completed demographic information and various physical and psychological assessments.

Measures

The study measures consisted of participants' SES values, EF task performance scores, and structural magnetic resonance imaging (MRI) volumes of the brain. We analyzed performance on cognitive tasks that involve different aspects of EF, including working memory (Ivnik et al., 1992; Kaufman, 1975), inhibition (Benton, 1968; Delis & Kramer, 2004; Stroop, 1935), shifting (Reitan, 1955), and information retrieval (Benton, 1968). In addition, the SES variable and EF tasks in our study extend upon Shaked et al. (2018).

SES. Participants' composite SES score involved a calculation of their highest level of education, occupation, and spouse's/significant other's education and occupation based on the Hollingshead Four-Factor Index of Socioeconomic Status (Hollingshead, 1975). Education was rated on a 7-point scale, and occupation was rated on a 9-point scale (Table 1). If participants indicated a spouse/significant other in their household, their education level and occupation were also coded. SES for child participants were also coded with the Hollingshead Four-Factor Index of Socioeconomic Status using parental information. Raw scores of the Hollingshead range from 1 to 66, in which higher values indicate higher SES (Juhn et al., 2011).

Table 1

Hollingshead Four-Factor Index of Socioeconomic Status

	Score
Education	
Not applicable	0
Less than 7th grade	1
Junior high school, including 9th grade	2
Partial high school, 10th or 11th grade	3
High school graduate	4
Partial college (at least one year) or specialized training	5
Standard college or university graduation	6
Graduate/professional training	7
Occupation	
Not applicable or unknown	0
Farm laborers, menial service workers, students, housewives(dependent on welfare, no regular occupation)	1
Unskilled workers	2
Machine operators and semi-skilled workers	3
Smaller business owners (<$25,000), skilled manual laborers, craftsmen, tenant farmers	4
Clerical and sales workers, small farm and business owners (business valued at $25,000-50,000)	5
Technicians, semi-professionals, small business owners (business valued at $50,000-70,000)	6
Smaller business owners, farm owners, managers, minor professionals	7
Administrators, lesser professionals, proprietor of medium-sized business	8
Higher executive, proprietor of large businesses, major professional	9

Note. Codes for education and occupation are based on Hollingshead (1975).

Executive Function. We specifically focused on cognitive measures of executive function: the Digit Span Task and the Delis-Kaplan Executive Functioning System (D-KEFS) (Delis & Kramer, 2004), which includes Trail Making, Verbal Fluency, and Color-Word Interference.

The Digit Span Task is a cognitive measure for working memory (Ivnik et al., 1992; Kaufman, 1975). Participants repeat aloud a string of numbers that becomes increasingly longer after each correct trial. During the Digit Span Backward (DSB) trials, participants must recall and repeat the string of numbers in reverse order. The session ended after two consecutive incorrect trials of the same length or completion of all trials. To measure working memory, we analyzed the total score, which is the total number of correct trials for a maximum score of 14, of the DSB trials.

The Trail Making test measures cognitive shifting, as participants must alternate between two types of stimuli (Reitan, 1955). Participants draw a continuous line shifting between number and letter in sequential order. We obtained the total time to complete the task to analyze participants' cognitive flexibility.

Verbal Fluency (VF) measures individuals' ability to retrieve information from long-term knowledge stores, as well as inhibition (Benton, 1968). There are two types of VF tests, phonemic and semantic, so we utilized both to compare performances in the phonemic VF test, which may tap more into the DLPFC, and the semantic VF test, which may rely more on temporal lobe areas (Gourovitch et al., 2000). Participants are provided with 60 seconds each to

name as many words starting with the letter ‘F’, ‘A’, and ‘S’ in the phonemic test, whereas participants must name as many animals and boy’s names in the semantic test. We also analyzed the semantic category switching VF condition, in which participants must switch between naming fruits and furniture for 60 seconds, to further study participants’ semantic knowledge retrieval, inhibition, and switching. Inhibition is measured in all three versions, as participants must avoid morphological variants and repetitions. We analyzed the total set loss errors, total repetition errors, total errors, and total correct responses in the phonemic, semantic, and category switching VF tasks.

Expanding on Shaked et al. (2018), we included Color-Word Interference into our analyses in order to study the different aspects of executive functioning. Color-Word Interference, which is based on the Stroop task, involves ignoring and responding to different stimuli in four conditions (Delis et al., 2001; Stroop, 1935). In the first condition, participants must name the colors shown. In the second condition, participants read color words in black ink. In the third condition, participants must respond to the font color of the word, rather than the actual color word. Trials in the third condition included words that are incongruent, in which the font color and color word are not identical (e.g., the word “red” in blue color font). In the fourth condition, participants must switch between naming the color of the word and stating the color word only when the word appears inside a black ink box. We studied the total time to complete the trials in the third condition (referred to as Inhibition trials) to measure participants’ inhibition when the color of the word and the color name mismatch, as well as the total time to complete trials for the fourth condition (referred to as Inhibition/Switching trials) to measure both inhibition and switching.

DLPFC Measures.

Similar to Shaked et al. (2018), we conducted a manual calculation to obtain the volumetric measurement of the DLPFC from MRI data. Although Shaked et al. (2018) summed the superior frontal gyrus and middle frontal gyrus to construct the DLPFC, we combined the volumes of the middle frontal gyrus and other regions of the frontal gyrus to analyze the regions specifically activated during executive function tasks. Furthermore, previous studies show variations in frontal lobe parcellation techniques to depict the DLPFC and the uncertainty in the regions of the superior medial frontal cortex involved in task-switching behaviors, such as in executive function tasks (Cox et al., 2014). After excluding subjects who did not have available volumetric data or had MRI images that could not be run successfully through the MindBoggle software, we obtained structural MRI images from 738 participants.

Results

Descriptives

The sample analyzed in this study included 821 participants of a broad age range and SES based on the Hollingshead Four-Factor Index of SES. The characteristics of our study sample are further detailed in Table 2.

Table 2

Study Characteristics

	Mean	*SD*	Percent	Range
Age (years)	36.57	21.48		7-84
% Male			39.1	
% White			77.3	
SES score	47.49	11.30		11.50-66
DLPFC proportion of TCV	.13	.01		.10-.16
Test scores				
DSB (total score)	6.32	2.25		2-13
CWI (inhibition time in sec)	60.88	22.17		25-180
CWI (inhibition/switching time in sec)	66.00	20.61		32-180
Trails (sec)	85.42	43.84		25-240
Phonemic VF (total responses)	38.51	14.24		4-84
Semantic VF (total responses)	40.50	9.82		8-75
CS VF (total responses)	14.22	3.19		5-24

Note. SES = socioeconomic status, DLPFC = dorsolateral prefrontal cortex; TCV = total cortival volume; DSB = Digit Span Backward; CWI = Color-Word Interference; VF = Verbal Fluency; CS = Category Switching. *N* = 821. *N* = 704 for DLPFC data.

Executive Function Measures

To predict the trend for EF task performance throughout age, we transformed the age variable by subtracting the mean age from each participants' age. These calculated centered age scores tested for a linear trend of the EF performance. We then found the squares of the centered ages to use these values to predict a quadratic trend of the EF performance. We also multiplied the centered age values by participants' SES scores to use this calculated value as a predictor for EF performance, testing for the age and SES interaction effect. For all regression analyses of the EF measures, we created 3 groups of low, medium, and high SES levels based on below one standard deviation of the sample SES mean, the sample SES mean, and above one standard deviation of the sample SES mean, respectively, to plot the curves of EF performance for different SES levels across age.

Correlation analyses revealed the number of correct trials in DSB, time to complete in CWI (inhibition trials and inhibition/switching trials), time to complete in the Trail Making Test, and total responses on VF tasks all significantly correlated with one another. In the analysis of the phonemic, semantic, and category switching VF tasks, fewer than approximately 25% of the participants made one or more errors in the trials, so we focused on participants' total responses for all three VF versions. Time to complete for CWI and Trails positively correlated with each other, whereas they negatively correlated with DSB and total responses for all VF tasks, which positively correlated with each other. These results indicate that participants who took longer to complete tasks whose scores are time-dependent (CWI, Trails) also produced lower numbers of responses in the DSB and VF tasks. Table 3 displays the correlations between each of the executive function tasks, as well as with age and SES.

Table 3

Correlations for Age, SES, and Executive Function Tasks

Variable	1	2	3	4	5	6	7	8	9
1. Age	-								
2. SES	.24**	-							
3. DSB	.18**	.08*	-						
4. CWI In	-.20**	.08*	-.42**	-					
5. CWI In/Sw	-.24**	.02	-.44**	.79**	-				
6. Trails	-.13**	.01	-.44**	.65**	.66**	-			
7. Phonemic VF	.49**	.09**	.39**	-.46**	-.48**	-.40**	-		
8. Semantic VF	.31**	.05	.31**	-.49**	-.51**	-.47**	.68**	-	
9. CatSw VF	.31**	.07*	.27**	-.48**	-.46**	-.40**	.56**	.65**	-

Note. This table displays the correlations between age, socioeconomic status (SES), and all of the executive function task measures: Digit Span Backward (DSB) time to complete, Color-Word Interference (CWI) time to complete for Inhibition condition (In) and Inhibition/Switching condition (In/Sw), Trail Making Test (Trails) time to complete, as well as total responses for each of the Phonemic, Semantic, and Category Switching (CatSw) Verbal Fluency (VF) tasks.

** Correlation is significant at the .01 level (2-tailed).

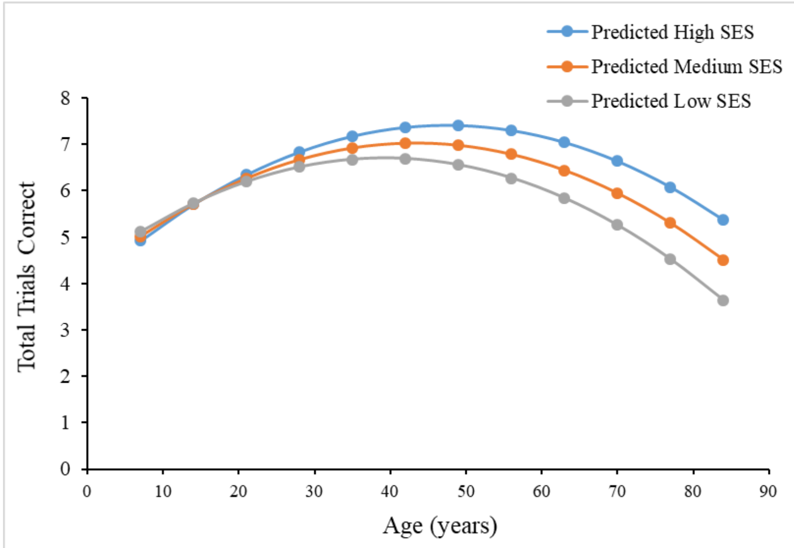
* Correlation is significant at the .05 level (2-tailed).

Regression analyses for DSB demonstrated that age significantly predicted the total trials correct in a positive linear manner ($\beta = .24$, $t(818) = 6.95$, $p < .001$), which indicates that the total

trials correct increases with age. Also, age significantly predicted the total trials correct in an inverted U-shape, in which the total number of correct trials increases across age until approximately 40 years and then decreases (β = -.23, $t(818) = -6.71$, $p < .001$). There was a significant main effect of age predicting total trials correct for low, medium, and high SES in a negative linear (β = -0.31, $t(816) = -1.66$, $p = .098$) and inverted U-shape trajectory (β = -.26, $t(816) = -7.33$, $p < .001$). There was a significant main effect of SES predicting total trials correct in a positive linear manner (β = .12, $t(816) = 3.25$, $p = .001$), in which higher SES predicts higher DSB total trials correct. There was a significant interaction between age and SES (β = .54, $t(816) = 2.94$, $p = .003$), in which lower SES predicts greater decreases in DSB total trials correct across age. Figure 1 exhibits the estimated curve of the association between age and SES for DSB. In sum, these findings demonstrate the potential for negative effects of SES to accumulate over time and manifest as progressively impaired EF performance in late adulthood. The subsequent results for the other EF measures follow this pattern of continuous detriments to EF with lower SES as age increases throughout older adulthood.

Figure 1

Interaction of Age and SES for Digit Span Backward (DSB)

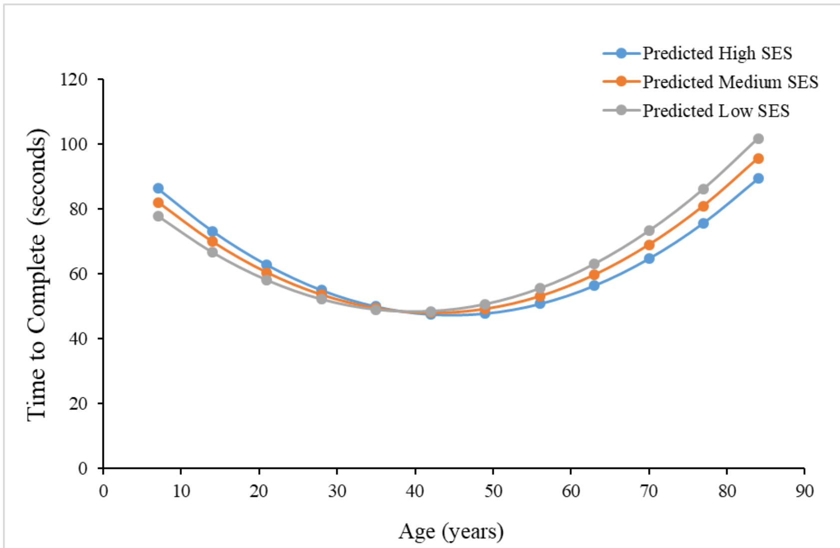


Note. An inverted U-shape trajectory of total trials correct in Digit Span Backward (DSB) was predicted across age for low, medium, and high SES. Lower SES predicted greater deficits in DSB performance throughout life.

The regression analysis for CWI showed age significantly predicts the total time to complete interference inhibition trials in a negative linear manner (β = -.33, $t(818) = -10.37$, $p < .001$). Age also significantly predicted the total time to complete inhibition trials in a U-shape curve (β = .47, $t(818) = 14.92$, $p < .001$), in which the total time to complete interference trials decreases across age until approximately 40 years and then increases. There was a significant main effect of age predicting total time to complete inhibition trials for low, medium, and high SES in a U-shape trajectory (β = .47, $t(816) = 14.74$, $p < .001$). There was no significant main effect of SES predicting total time to complete inhibition trials. There was a significant interaction between age and SES (β = -.59, $t(816) = -3.57$, $p < .001$), in which lower SES predicts greater increases in total time to complete inhibition trials with increases in age after about 40 years (Figure 2).

Figure 2

Interaction of Age and SES for CWI Inhibition Trials



Note. A U-shape trajectory of total time to complete inhibition trials in Color-Word Interference was predicted across age for low, medium, and high SES across age. Lower SES predicted greater deficits in inhibition trial performance throughout the age trajectory as age increased after 40 years.

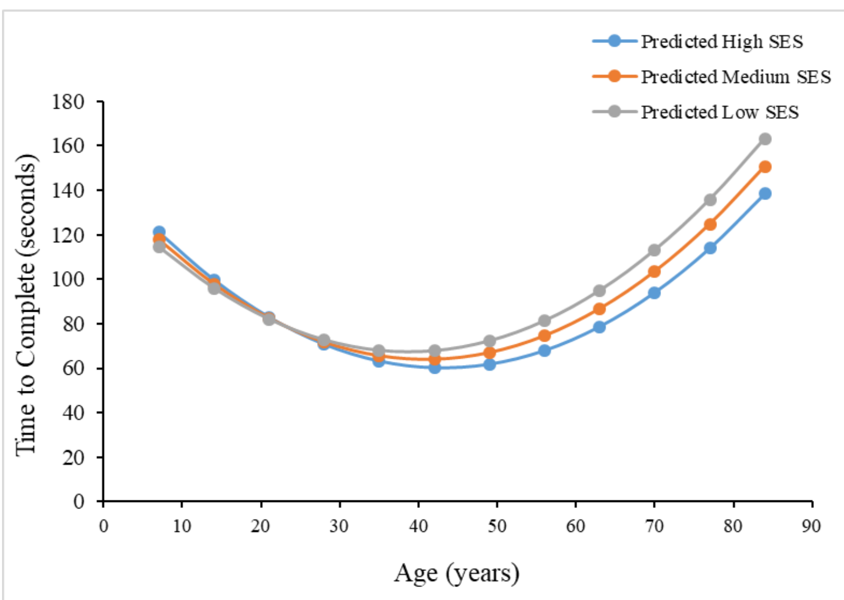
Similarly, age significantly predicted the total time to complete interference trials in the inhibition/switching condition of the CWI in a negative linear manner ($\beta = -.36$, $t(818) = -11.49$, $p < .001$). Age also significantly predicted the total time to complete in a U-shape curve, in which the total time to complete interference trials decreases across age until approximately 40 years and then increases ($\beta = .45$, $t(818) = 14.23$, $p < .001$). As did for the CWI inhibition condition trials, there was a significant main effect of age predicting total time to complete inhibition/switching trials for low, medium, and high SES in a U-shape trajectory ($\beta = .46$, $t(816) = 14.32$, $p < .001$). There was also a significant interaction between age and SES ($\beta = -.59$, $t(816)$

= -3.59, $p < .001$), in which lower SES predicts greater increases in total time to complete inhibition/switching trials across ages after about 40 years.

For the Trail Making Test, age significantly predicted the total time to complete in a negative linear manner (β = -.23, $t(818) = -6.92$, $p < .001$), and in a U-shape curve (β = .39, $t(818) = 11.82$, $p < .001$), in which the total time to complete decreases across age until approximately 40 years and then increases. There was a significant main effect of age predicting total time to complete Trails for low, medium, and high SES in a U-shape trajectory (β = .41, $t(816) = 12.01$, $p < .001$). There was a significant interaction between age and SES (β = -.45, $t(816) = -2.56$, $p = .011$), in which lower SES predicts greater increases in total time to complete Trails with age increases after about 40 years (Figure 3).

Figure 3

Interaction of Age and SES for Trail Making Test

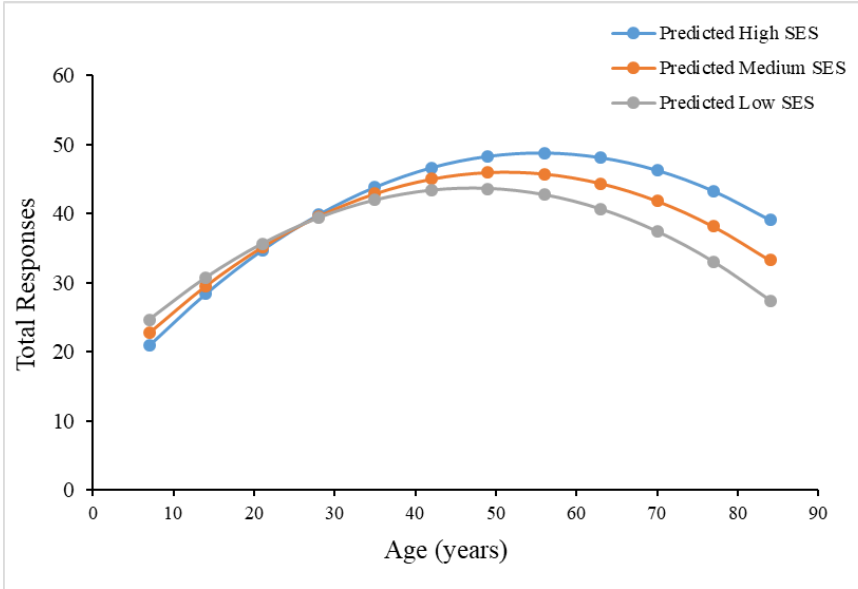


Note. A U-shape trajectory of total time to complete the Trail Making Test was predicted across age for low, medium, and high SES across age. Lower SES predicted greater and greater deficits in Trails performance throughout life as age increased after approximately 40 years.

For Phonemic VF, age significantly predicted the total responses in a positive linear manner ($\beta = .57$, $t(818) = 19.03$, $p < .001$), and in an inverted U-shape curve ($\beta = -.30$, $t(818) = -10.05$, $p < .001$), in which total responses increase across age until approximately 40 years and then decrease. There was a significant main effect of age predicting total responses in phonemic verbal fluency for low, medium, and high SES in an inverted U-shape trajectory ($\beta = -.32$, $t(816) = -10.53$, $p < .001$). Results suggest that total responses increase across age until approximately 40 years and then decrease. There was a significant main effect of SES predicting total responses ($\beta = .08$, $t(816) = 2.44$, $p = .015$), in which higher SES predicts greater number of responses. There was a significant interaction between age and SES ($\beta = .68$, $t(816) = 4.33$, $p < .001$), in which lower SES predicts a smaller increase and greater decrease in total responses across age, whereas higher SES predicts a greater increase and smaller decrease in total responses (Figure 4).

Figure 4

Interaction of Age and SES for Phonemic Verbal Fluency

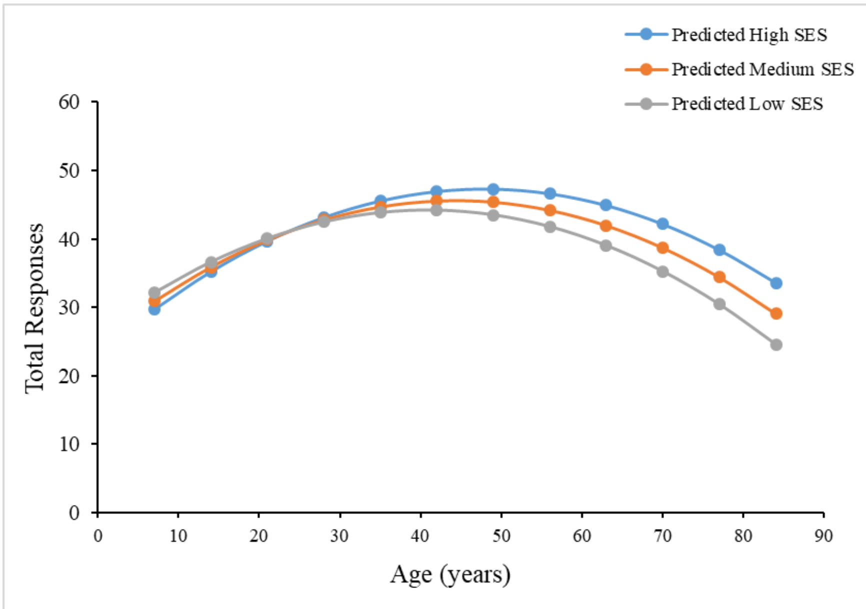


Note. A U-shape trajectory of total responses in phonemic Verbal Fluency was predicted across age for low, medium, and high SES. Lower SES predicted a lower number of responses in phonemic Verbal Fluency throughout life.

Following the trend of Phonemic VF, the regression analysis for Semantic VF also showed that age was a significant predictor of total responses in a positive linear manner (β = .41, $t(818) = 12.90$, $p < .001$) and inverted U-shape curve (β = -.39, $t(818) = -12.19$, $p < .001$), in which total responses increase across age until approximately 40 years and then decrease. In addition, there was a significant main effect of age predicting total responses for low, medium, and high SES in an inverted U-shape trajectory (β = -.41, $t(816) = -12.76$, $p < .001$). There was a significant main effect of SES predicting total responses (β = .10, $t(816) = 2.93$, $p = .003$), in which higher SES predicts greater number of responses. There was a significant interaction between age and SES (β = .73, $t(816) = 4.39$, $p < .001$), in which lower SES predicts a larger decrease in total responses across age, whereas higher SES predicts a smaller decrease in total responses across age (Figure 5).

Figure 5

Interaction of Age and SES for Semantic Verbal Fluency



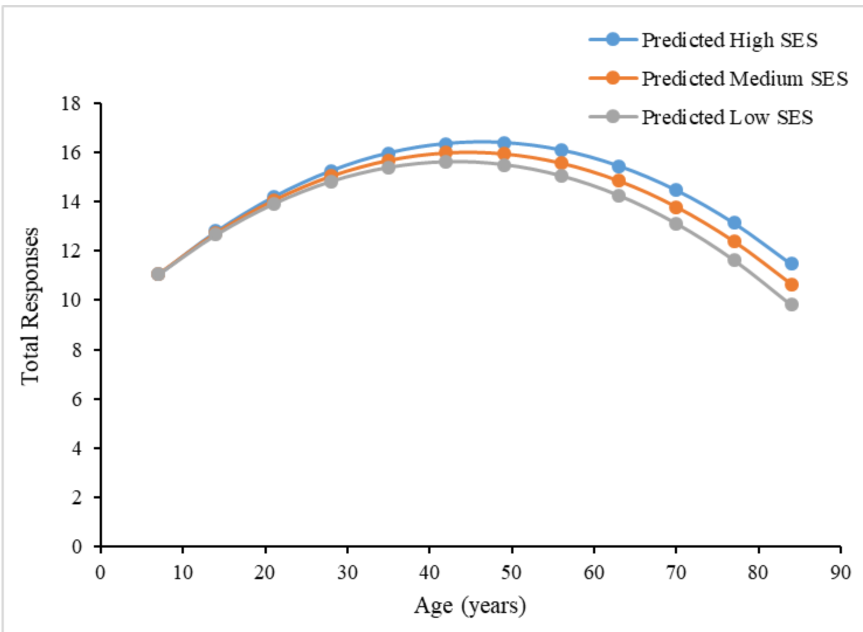
Note. A U-shape trajectory of total responses in semantic Verbal Fluency was predicted across age for low, medium, and high SES across age. Lower SES predicted lower total responses in semantic Verbal Fluency throughout life.

Likewise for Category Switching VF, age significantly predicted the total responses in a positive linear manner (β = .41, $t(818) = 13.04$, $p < .001$) and an inverted U-shape curve (β = -.40, $t(818) = -12.47$, $p < .001$), in which total responses increase across age until approximately 40 years and then decrease. There was a significant main effect of age predicting total responses for low, medium, and high SES in an inverted U-shape trajectory (β = -.42, $t(816) = -12.88$, $p < .001$). In addition, there was a significant main effect of SES predicting total responses (β = .10, $t(816) = 2.89$, $p = .004$), in which higher SES predicts greater number responses. The interaction between age and SES (β = .33, $t(816) = 1.96$, $p = .050$) suggested lower SES predicts smaller

increases in total responses across age, whereas higher SES predicts greater increases in total responses across age (Figure 6).

Figure 6

Interaction of Age and SES for Category Switching Verbal Fluency



Note. An inverted U-shape trajectory of total responses in category switching Verbal Fluency was predicted across age for low, medium, and high SES. Lower SES predicted a lower number of responses than when SES was higher across the lifespan.

We conducted additional analyses with the Vocabulary subscale of the Wechsler Abbreviated Scale of Intelligence Second Edition (WASI-II) (Wechsler, 1999) to explore the difference in performance of higher and lower SES young participants in the CWI and VF tasks. The Vocabulary test performance reflects individuals' verbal knowledge and storage of information (Wechsler, 1999). We utilized the Vocabulary T score, which is the converted raw

score using the WASI-II conversion tables in order to standardize the scores across age. The CWI Inhibition condition time to complete negatively correlated with the Wechsler Abbreviated Scale of Intelligence (WASI-II) Vocabulary T Score, $r(702) = -.12$, $p < .001$. The CWI Inhibition/Switching condition time to complete also negatively correlated with the Vocabulary T score, $r(702) = -.15$, $p < .001$. These results suggest that higher scores of vocabulary are associated with shorter times to complete the CWI trials. The WASI-II Vocabulary T score positively correlated with all three types of the verbal fluency tests: phonemic ($r(702) = .21$, $p < .001$), semantic ($r(702) = .19$, $p < .001$), category switching ($r(702) = .13$, $p < .001$). In other words, higher vocabulary scores are associated with greater total responses on all the verbal fluency tests. Further regression analysis revealed that SES only significantly predicts time to complete in both CWI conditions (inhibition: $\beta = .23$, $t(437) = 4.77$, $p < .001$; inhibition/switching: $\beta = .19$, $t(437) = 3.99$, $p < .001$) and total responses in all verbal fluency tests (phonemic: $\beta = -.19$, $t(437) = -3.94$, $p < .001$; semantic: $\beta = -.17$, $t(437) = -3.64$, $p < .001$; category switching: $\beta = -.11$, $t(437) = -2.20$, $p = .029$) for persons younger than 40 years old with the WASI-II Vocabulary T score as a second predictor. In other words, higher SES and higher vocabulary score for participants younger than 40 years predicted longer time to complete for the CWI tests and more total responses for the VF tests. SES was not a significant predictor of CWI or VF tests for individuals ages 40 and older when the WASI-II Vocabulary T score was a second predictor.

DLPFC Volume

We analyzed data from 704 participants after excluding individuals with MRI image euler values greater than 2 standard deviations above the mean to ensure analysis of high quality MRI images.

Because MindBoggle is based on gyrus segmentation, we utilized NeuroQuery to determine the region of the DLPFC probabilistically activated in executive function tests, such as working memory and verbal fluency tasks. From the MindBoggle parcellation, we identified the gyri that overlapped with the NeuroQuery region of interest (ROI). NeuroQuery identified the following regions in the left and right hemisphere volumes that are activated during working memory and verbal fluency tasks: the rostral middle frontal gyrus (MFG), caudal MFG, gyrus pars opercularis (po), and pars triangularis (pt). We summed all of these volumes to model the DLPFC volume. To standardize the DLPFC volume, we calculated the DLFPC's proportion by dividing by the total cortical volume (TCV).

Age negatively correlated with the rostral MFG, caudal MFG, PO, PT, and TCV of both hemispheres, whereas all of the brain regions correlated positively with each other (Table 4). After summing the rostral MFG, caudal MFG, PO, and PT, the DLPFC volume mean was calculated to be 63571.34 cubic millimeter (mm^3) (*SD* = 12803.12). Age negatively correlated with the DLPFC proportion of the TCV, $r(702) = -.58$, $p < .001$. Regression analyses demonstrated that age significantly predicts the proportional size of the DLPFC, in which the proportional DLPFC size decreases linearly throughout age, $\beta = -.62$, $t(701) = -18.97$, $p < .001$.

Table 4

Descriptive Statistics and Correlations for Age and each region of the Dorsolateral Prefrontal Cortex

Variable	*n*	*M*	*SD*	1	2	3	4	5	6	7	8	9	10	11
1. Age	704	38.50	20.80	-										
2. LH RMFG	704	1660.64	3688.91	-.72**	-									
3. RH RMFG	704	17099.46	3904.03	-.70**	.90**	-								
4. LH CMFG	704	6591.68	1479.12	-.59**	.71**	.73**	-							
5. RH CMFG	704	6186.46	1492.55	-.59**	.75**	.70**	.77**	-						
6. LH PO	704	4769.24	1064.37	-.63**	.70**	.68**	.61**	.66**	-					
7. RH PO	704	4044.89	890.82	-.65**	.71**	.70**	.66**	.66**	.77**	-				
8. LH PT	704	3808.45	893.26	-.64**	.75**	.70**	.55**	.61**	.76**	.68**	-			
9. RH PT	704	4470.51	1067.45	-.65**	.72**	.72**	.61**	.54**	.66**	.77**	.76**	-		

10. LH TCV	704	247075.86	38334.13	-.70**	.90**	.89**	.77**	.78**	.77**	.79**	.77**	.76**	-	
11. RH TCV	704	242204.93	38020.73	-.70**	.91**	.89**	.77**	.77**	.78**	.79**	.77**	.76**	1.00**	-

Note. This table displays the descriptives and correlations between age and all of the left (LH) and right (RH) rostral middle frontal gyrus (RMFG), caudal middle frontal gyrus (CMFG), pars opercularis (PO), pars triangularis (PT), and total cortical volume (TCV). Volumes are all measured in cubic millimeter (mm^3).

** Correlation is significant at the .01 level (2-tailed).

SES also negatively correlated with the total DLPFC volume ($r(702) = -.14$, $p < .001$), TCV ($r(702) = -.10$, $p = .008$), and DLPFC proportion ($r(702) = -.17$, $p < .001$). However, when we controlled for age in a partial correlation, SES no longer correlated with DLPFC proportion, TCV, or DLPFC proportion. Although there were slight correlations between the DLPFC proportion and each of the executive function tasks, they were also no longer significant once we controlled for age. These findings indicate that age contributed to most of the variance in DLPFC proportion, suggesting the importance of observing trends in DLPFC volume in separate age groups to identify the overall trajectory of the DLPFC throughout the lifespan.

Discussion

The current study examined the influence of SES in EF and DLPFC volume across the life trajectory—from children to older adults. Specifically, we analyzed participants' performances in four EF tasks (DSB, CWI, Trails, and VF) and structural MRI data to investigate differences in EF performance and DLPFC volume with relation to age and SES. The findings support that EF performance follows curvilinear trends across the lifespan, in which EF performance increases maximally until approximately mid-life and then begins to decrease. In addition, SES changed the trajectories of EF performance on all tasks across age, in which a lower SES predicted greater detriments to EF as age increases. Although there was no significant correlation between the DLPFC proportional volume of the TCV and SES or EF measures, the results showed that age accounted for much of the variances. Altogether, the findings demonstrate the significance of age, as well as the interaction of age and SES, in EF performance volume as age increases and the key factor of age in brain volumetric changes.

The positive correlations between age and each of the EF measures indicate that as age increases, EF task performance increases. However, regression analyses in which quadratic age

is a predictor of EF task performance revealed that the increases in EF task performance occur until about 40 years old, after which EF performance declines across age. The positive correlation likely accounts for the trend of the U-shape curve until approximately 40 years old, as the mean and standard deviation of the sample age suggest a greater distribution of participants in that estimated age range. Thus, our modeled U-shaped curves support our hypothesis that EF performance improves until about early adulthood, after which EF impairments begin to occur.

Furthermore, our findings for quadratic patterns along the age scale are consistent with previous studies. Myerson et al. (2003) also found significant curvilinear trends for DSB score from their sample of over 1000 participants with the age range 16-89 years, indicating an increase in early adulthood and progressive decline in working memory as age increases. For phonemic and semantic VF, the total responses of both VF tasks types of 322 participants ranging from 18 to 84 years old in Rodríguez-Lorenzana et al. (2020) also fit an inverted U-shaped trajectory to model information retrieval and inhibition across age. Additionally, inhibition, as measured by the CWI inhibition trials time to complete, followed a nonlinear U-curve throughout age in our study, which matched the findings of Van der Elst et al. (2006) who also found a quadratic age effect on a color-word interference task performance where scores peak in early adulthood and then decreases through life. Thus, our U-shaped pattern for CWI inhibition trial performances across age supports our hypothesis, as lower scores indicate faster task completion and inhibition, whereas higher scores indicate slower task completion and inhibition. Likewise, we found that cognitive flexibility followed a curvilinear pattern in the EF tasks measuring shifting (i.e., Category Switching VF total responses, CWI inhibition/switching trials time to complete, Trails time to complete), exhibiting increasingly higher performance until mid-age and then subsequent increasingly poorer performance throughout the rest of life. This

pattern of change in cognitive flexibility across the lifespan is also consistent with previous studies that utilized functional MRI data and D-KEFS and modeled quadratic effects of age on shifting task performance (Kupis et al., 2021). However, none of the prior studies included as wide an age range, particularly including children, as our study to model the EF changes throughout life. Furthermore, representing the trend of EF development and impairment with a broad age range allows people to understand the vulnerable times for EF changes and take action to reduce detrimental effects during young and old ages.

The positive associations between SES and EF task performance in our study aligns with that of Shaked et al. (2018) on the DSB, Trails, and semantic VF tasks, in which a lower SES predicted lower performance. Our analyses of additional cognitive tasks, including the phonemic and category switching VF tasks, also indicate significant positive correlations with SES. The interaction between age and SES also predicted EF task performance, suggesting that the harmful effect of low SES compounds in early life, when differences in EF may not be as evident, and manifests continuously greater detrimental effects only after about mid-adulthood and through the rest of life.

Whereas the direct effect of SES did not predict EF performance in Trails and CWI, the interaction of age and SES predicted performance in both, in which we analyzed completion time. Because the Trail Making Test involves motor skills to draw a continuous line connecting the stimuli on paper, it is possible that the combination of age-related decline in motor skill and low SES may lead to further impairment and predict a lower task performance and cognitive flexibility. Türkeş et al. (2015) found that individuals older than the age of 50 years had strikingly slower Trails completion time than individuals younger than 50 years, which further suggests the likely contribution of the natural aging process in motor speed. Regarding CWI,

SES and Vocabulary score predicted CWI task performance only for individuals younger than 40 years old. In other words, higher SES and greater vocabulary knowledge predicted slower task completion time, indicating lower inhibition. This finding points to the potential cause of early literacy achievement in young individuals of higher SES, which may lead to a greater reading automaticity that interferes with the CWI task that involves inhibiting this automatic reaction. Higher reading level has been associated with a higher quality of education, as well as a better performance on neuropsychological tests (Manly et al., 2002). Therefore, although early attainment of reading automaticity may contribute to greater knowledge of words in high SES young individuals, as evidenced by their greater number of total responses in VF tasks and higher Vocabulary scores than lower SES young individuals, there may be disadvantages to CWI performance, and thus inhibition, until approximately age 40. When peak performance in CWI is attained, detriments in performance predicted by low SES may begin to take greater effect as age increases.

Although Shaked et al. (2018) found significant associations between SES, DLPFC, and EF performance (though notably in only the Trails Making Test), the DLPFC proportion in our sample was associated with neither SES nor EF measures. However, we did find that the DLPFC proportion, as well as the TCV, decreases linearly throughout the lifespan. Our finding is consistent with previous literature that found linear decreases in total gray matter volume and frontal gray matter volume likely due to synaptic pruning from as early as 5 years old (Brain Development Cooperative Group, 2012). Even though our study strengths included correcting for TCV, in contrast to Shaked et al. (2018), future studies should aim to create bins for age to more fully understand age-related structural changes within each age group.

The importance of age groups in data analysis also applies to lifespan EF performance research. Despite the fact that prior studies have found peak EF performance in early adulthood, usually defined by ages 20-30 years, our findings indicate peak functioning on all tasks across all SES levels at approximately 40 years old. One of the greatest strengths of our study was the large sample size and the broad age range, consisting of individuals from young, middle, and older groups. There are a limited number of studies that have taken this lifespan approach to study age-related changes in EF throughout life. Furthermore, many studies have focused on only either adolescents and young adults (12-28 years) or older adults (over 60 years old) or utilized the term "early adulthood" without defining the specific age range at which maximum EF occurs, likely because of conflicting findings in the literature (Hering et al., 2016). Although older studies from the early 2000s have suggested a maximal EF as early as the 20s (Salthouse, 2004; Taylor et al., 2013), recent studies have also found curvilinear patterns in EF task performance in which decline begins after 40 years (Rodríguez-Lorenzana et al., 2020) and even 50 years (Türkeş et al., 2015). An increased population of the United States across all races completes a minimum of high school level education, resulting in a more educated population since 1997 (Schmidt, 2018). Consequently, the potential shift in EF peak performance may be influenced by this increase in education in the United States over the years.

School environments may provide opportunities to enhance EF skills, particularly in low-income children who were found to have faster improvements in EF skills within the first 2 years of school intervention (Finch, 2019). In addition, resources in the environment, such as government support, may be beneficial in aiding young individuals from low SES families to ensure their development is not impacted by their challenging circumstances. For instance, the state of New York implemented the Head Start program, supporting children and families from

low-income backgrounds with housing, employment, and education. Some of our data for young individuals, including CWI, phonemic VF, and semantic VF performances in which lower SES children appear to perform slightly better than high SES children, suggest a compensatory effect already occurring possibly due to schooling and additional resources in the present day. We suggest continued research with wide age ranges to understand when EF performance maximally occurs across SES levels, especially because generational changes involving different resources may be in place, influencing EF performance in various age cohorts.

Our study findings demonstrate the importance of SES in EF across the lifespan and age in understanding DLPFC structural changes. Prior studies support the result of a linear decrease of DLPFC volume throughout life. Additionally, findings of EF performance for each cognitive task following a curvilinear pattern across age are consistent with previous literature. Our findings add to the literature, as we identify SES' impact in predicting greater detriments to EF performance as age increases. Understanding the role of SES provides support for the necessity of equitable access to opportunities for education and additional resources to bridge the gaps in cognition, health disparities, and overall quality of life.

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