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ORIGINAL INVESTIGATION

Caffeine intake and cognitive functions in children

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Abstract

Rationale There is a growing concern over excessive caffeine use and development of caffeine use disorder in children.

Objectives This study aimed to identify the association between caffeine intake and cognitive functioning in children.

Methods This study included 11,718 youths aged 9–10 years with cognitive and caffeine intake information that were extracted from the Adolescent Brain Cognitive Development (ABCD) study. The ABCD study is a longitudinal cohort study started in 2017 that aims to understand the relationships between substance use and neurocognition in youths living in the USA. Cognitive measures were obtained through the 7 core cognitive instruments from the NIH toolbox (vocabulary comprehension, reading decoding, inhibitory control, working memory, cognitive flexibility, processing speed, and episodic memory). Associations between caffeine intake and the seven cognitive functions were examined using multiple regression models.

Results Our study revealed that caffeine intake negatively correlated with all the seven cognitive measures. After adjustment for age, gender, sleep, and socioeconomic status (SES), caffeine intake was still found to be negatively associated with most of the cognitive functions, such as vocabulary comprehension, working memory, cognitive flexibility, processing speed, and episodic memory, except reading decoding, and inhibitory control.

Conclusions As beverages with caffeine are consumed frequently, controlling their intake may reduce a risk for nonoptimal cognitive development in children.

Keywords Caffeine · Cognition · Children · Executive function

Introduction

Caffeine is one of major components in the most commonly consumed beverages, such as tea, energy drinks, and soda, in the world (Higdon and Frei 2006). Globally, a large number of children consume caffeine on a day-to-day basis with a daily consumption level of 37.3 mg/day (U.S), 26.7 mg/day (Canada), 20 mg/day (New Zealand), 19.2 mg/day (Australia), and 23.25 mg/day (Branum et al. 2014). Soda is the primary source (38%) of caffeine for children (aged 2–13 years) (Verster and Koenig 2018). Although according to some health regulatory bodies, such as Health Canada, the consumption of caffeine by adults less than 400 mg daily does not present any health risks and may provide certain benefits such as improved concentration, alertness, or even athletic performance, higher doses may instead result in adverse impacts on the consumer's mood, sleep, physical, and cognitive performances (McLellan et al. 2016). This is particularly concerning in children as they may be more vulnerable to any adverse effects of caffeine that might exist (Higdon and Frei 2006). There is a growing concern over excessive caffeine use and development of caffeine use disorder in children (Cotter et al. 2013; Budney and Emond 2014). But it is little known about influences of caffeine on child cognitive development.

There is a general agreement in the scientific community regarding specific acute effects of caffeine on cognitive function, such as improved alertness, reaction time, and vigilance. However, inconsistencies are still present among studies regarding the effects on higher cognitive functions, such as working memory, long-term memory, executive functions, and other higher-order cognitive functions (McLellan et al.

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2016). Even though studies have been conducted in this area, targets were mostly adults or the elderly instead of younger populations (Temple 2009). In cases where research was conducted on younger populations, they were usually animal studies or those with a small sample size (O'Neill et al. 2016; Atik et al. 2017).

Caffeine (1,3,7-trimethylxanthine) is structurally similar to one neurotransmitter, adenosine, that regulates neurotransmitter release by interfering with calcium ions and serves to inhibit or reduce neuronal activity (Ribeiro and Sebastio 2010). Once ingested and absorbed into the bloodstream from the gastrointestinal tract, caffeine blocks adenosine receptors in the brain and acts as antagonists to adenosine. Neural firing then becomes less inhibited, causing physiological effects such as increased heart rate, blood pressure, and vasodilation. Additionally, it may also trigger specific effects on cognitive functions such as alertness, memory, attention, and learning (Smit and Rogers 2000). These effects peak around 30–60 min after ingestion when caffeine concentration in plasma reaches maximum (Lorist and Snel 2008). Eventually, caffeine gets eliminated from the body system with a half-life of approximately 5–7 h depending on individual (Tarrus et al. 1987).

Chronic arousal caused by alterations in adenosine signaling from habitual and excessive caffeine consumption has shown to affect not only sleep duration and quality but also neuronal plasticity and brain developmental processes, such as synaptic pruning and myelination (Olini et al. 2013). This is an important concern during the phase of childhood as sleep plays a crucial role in their brain development (Aepli et al. 2015). Moreover, during this phase of growth, the brain is plastic with considerable changes in neuronal circuitry and very prone to environmental influences. Hence, we hypothesize that caffeine intake may result in unexpected effects on cognitive functioning in children. In this study, we took an advantage on the public available data from the ongoing Adolescent Brain Cognitive Development (ABCD) study. We aimed to primarily investigate the relationship between caffeine intake (not psychoactive substances) and cognitive function in children aged 9–10 years. Our findings provide several future avenues for developing new intervention approaches of cognitive improvement.

Methods

Participants

We used data from the ongoing Adolescent Brain Cognitive Development (ABCD) study (data release 2.0; https://abcdstudy.org/). Youths (n = 11,875) aged 9–10 years consisting of a similar proportion of males and females living in the USA were recruited (Volkow et al. 2018). The sample selection criteria were targeted to reflect the sociodemographic proportion of the US population as described in the ABCD study design (Garavan et al. 2018). All participants were administered assessments to obtain data on the respective youth's brain morphology, cognitive function, substance use, demographics, and environment (Barch et al. 2018). All parents provided written informed consent, and all children provided assent to a research protocol approved by the institutional review board at each data collection site (https://abcdstudy.org/study-sites/).

Of the 11,875 participants, 6 did not report caffeine intake information, 144 did not complete any task of the cognitive battery (i.e., NIH Toolbox), and 7 did not have both of these two data. Therefore, our study included 11,718 children who reported the caffeine intake information and underwent the cognitive battery (Lisdahl et al. 2018; Luciana et al. 2018).

Caffeine intake

The ABCD Substance Use module was administered to the youth by a trainer using an iPad. Youth reported caffeine use via modified Supplemental Beverage Questions, which were widely used and have been validated in terms of high correlation with caffeine concentration biomarkers in urine (Fred Hutchinson Cancer Research Center 2004; Schliep et al. 2013; Vanderlee et al. 2018). Total 5 types of caffeinated drinks, such as coffee, espresso, tea, soda, and energy drinks, were included. The typical serving size of each type of drinks was defined as follows: 1 cup (8 oz) for coffee, 1 shot for espresso, 1 cup (8 oz) for tea, 1 can (12 oz) for soda, and 1 cup (2 oz. for the drink 5-h energy; 8 oz. for other energy drinks such as Red Bull) for energy drinks. Each type was asked in the same fashion described below. For example, "typically, how many drinks of the following beverages did you have per week in the past 6 months? coffee (instant, brewed), with caffeine, including flavored types." According to the youth's response, the interviewer determined how many typical cups of caffeine drinks per week in the past 6 months. If the youth drinks less than weekly, then the drink amount was coded as the fraction representing weekly use. For example, if someone had 1 cup of coffee per month, it would be 1/4 = 0.25 cup per week because there are 4 weeks in 1 month. Estimated caffeine content for each type of drink was obtained by averaging the caffeine content of all items under each beverage category in the database according to D.C Mitchell et al. (Mitchell et al. 2014). Similar to the study on caffeine use in soldiers by McLellan et al., caffeine intake per week was calculated by multiplying the number of cups of each type of drink reported with their estimated caffeine content (McLellan et al. 2018). Caffeine intake per week was then converted to caffeine intake per day (mg/day).

Cognition

This study selected 7 cognitive instruments from the NIH toolbox (http://www.nihtoolbox.org). According to the

structure of this toolbox, we obtained two domains of cognitive functions (Akshoomoff et al. 2014), crystallized and fluid cognitive domains. Crystallized cognitive battery includes picture vocabulary (vocabulary comprehension) and oral reading recognition tasks (reading decoding). Fluid cognitive battery includes flanker (inhibitory control), dimensional change card sort (cognitive flexibility), list sorting working memory (working memory), picture sequence memory (episodic memory), and pattern comparison processing speed tasks (processing speed) (Luciana et al. 2018). These measures were selected as they were proven to be psychometrically sound and provided reliable evaluations of cognitive functioning for the current age group of interest (Luciana et al. 2018). The scoring method for the NIH toolbox cognitive instruments can be found in the overview of the NIH cognition battery and NIH Scoring and Interpretation guide (Weintraub et al. 2013; Luciana et al. 2018).

On the day of cognitive assessment, the Participant Last Use Survey (PLUS) was administered to children to report whether they had taken any caffeine within the last 24 h. We used this measure to examine chronic effects of caffeine on cognition.

Socioeconomic status and sleep

SES factors, such as income, education, parental care, and presence of a sufficiently cognitive stimulating environment, were previously studied and suggested to exert influences on cognitive abilities, such as executive function, working memory, and language (Noble et al. 2015; Farah 2017). A composite SES score was generated by dividing the sum of scores of selected ordinal variables from the maximum possible score. Family income, parental education, family environment, neighborhood safety, and parental behavior were chosen to be included in the composite SES score based on suggestions from previous studies (Christensen et al. 2014).

The Sleep Disturbance Scale for Children (SDSC) was used to measure children's sleep function. The SDSC is a 26-item Likert-type rating scale administrated to a parent (Bruni et al. 1996). A higher score reflects a greater degree of disturbed sleep. In this study, SES and sleep were used as confounding variables in statistical analysis described below.

Statistical analysis

Several potential confounders, such as age, gender, sleep, and SES, were included in statistical analysis as they were not only found to be correlated with caffeine intake and cognitive abilities in our study but also identified as covariates in previous association studies related to the effects of caffeine use on cognition (Skinner et al. 2000; Kyle et al. 2010; Lo et al. 2016).

Spearman's rank-order correlations were used to assess relationships between caffeine, cognition, and potential confounding variables (de Winter et al. 2016). Multiple linear regression models were also used to examine the association of caffeine intake with each cognitive function after controlling of potential confounders, such as age, gender, sleep, and SES. Before entering into multiple linear regression, all variables were first normalized through a rank-based inverse Gaussian transformation to avoid potential influences of outlier values and improve the robustness of our findings (Miller et al. 2016). Moreover, we computed the variance inflation factor (VIF) of all confounding variables. The VIF varied from 1.01 to 1.06, suggesting no collinearity problem among the confounding variables (Belsley et al. 1980). All data analysis was conducted using MATLAB (Statistics and Machine Learning Toolbox, Release 2017b). Two-tailed tests with a significance level of $p < 0.05$ were set for this study.

Results

Demographics

This study included 11,718 participants (age: 9.9 ± 0.6 years), consisting of 52.1% male and 47.9% females (Table 1).

Table 1 Demographic characteristics ($n = 11,718$)

Variable	**Mean (Rijlaarsdam et al.)**
Age	9.9 (0.6)
Sleep	36.5 (8.2)
Variable	**Participants no. (%)***
Gender	
Male	6104 (52.1)
Female	5611 (47.9)
Race/ethnicity	
White	6104 (52.1)
Black	1743 (14.8)
Hispanic	2377 (20.3)
Asian	252 (2.2)
Others	1227 (10.5)
Annual family income	
< $50,000	3166 (27.0)
$50,000–$199,999	6317 (53.9)
> $200,000	1232 (10.5)
Parent's highest educational level	
Never completed high school	581 (5.0)
High school graduate or GED	1112 (9.5)
Some college or Bachelor's degree	6021 (51.4)
Master's degree or above	3991 (34.1)

*Due to missing values, the sum of percentages may not equal to 100%

Table 1 lists the demographic information of the study sample. The parental highest level of education and annual income were reported during the interview. About 51.4% of children had at least one parent who graduated from college or university and 34.1% had at least one parent who completed a Master's degree or above. Additionally, 53.9% of the participated families received an annual household income of $50,000–$200,000. The range of sleep disturbance scores was 26–126 (mean ± SD = 36.5 ± 8.2; median = 34, IQR = 9).

Caffeine intake and cognition

The youth substance use interview reported that 66.9% of the sample consumed at least one type of caffeinated beverages in the past 6 months. Of all subjects who consumed caffeinated drinks, soda was the greatest contributor to their total caffeine intake followed by tea, coffee, espresso, and energy drinks (Table 2). Average caffeine intake is 13.00 ± 43.73 mg/day (Table 3), which is equivalent to 1/8 of a can of AMP energy drink (12 fl oz) or two packages of M & M's Milk Chocolate Candies according to USDA National Nutrient Database (https://www.nal.usda.gov/sites/www.nal.usda.gov/files/caffeine.pdf). The distribution of caffeine intake amount was skewed with a range from 0 to 1195 mg/day and median of 1.76 mg/day.

The descriptive statistics for each administered cognitive test can be found in Table 3. Figure 1 illustrates the correlation heat map between caffeine intake and all seven cognitive measures, suggesting significant negative correlations with all crystallized cognitive functions (vocabulary comprehension: $\rho = -0.12$, $p < 0.01$; reading decoding: $\rho = -0.07$, $p < 0.01$) and all fluid cognitive functions (inhibitory control: $\rho = -0.02$, $p = 0.02$; working memory: $\rho = -0.08$, $p < 0.01$; cognitive flexibility: $\rho = -0.07$, $p < 0.01$; processing speed: $\rho = -0.06$, $p < 0.01$; episodic memory: $\rho = -0.08$, $p < 0.01$). This indicates that increased caffeine intake was associated with decreased crystallized and fluid cognitive abilities. All cognitive functions were positively correlated to each other (min $\rho > 0.16$, $p < 0.01$). Lower SES was associated with greater caffeine intake ($\rho = -0.19$, $p < 0.01$) and worse cognitive performance (min $\rho > 0.12$, $p < 0.01$). Older age children consumed more caffeine ($\rho = 0.09$, $p < 0.01$) and had better cognitive functions (min $\rho > 0.12$, $p < 0.01$) except the episodic memory ($\rho = 0.01$, $p = 0.12$). More sleep disturbances were associated with greater caffeine intake ($\rho = 0.06$, $p < 0.01$) and worse performance in most of the seven cognitive functions (max $\rho < -0.02$, $p < 0.01$) except the crystallized cognitive functions and inhibitory control. Compared to females, males had higher caffeine consumption ($\rho = -0.07$, $p < 0.01$), performed better in vocabulary comprehension, inhibitory control, and working memory (max $\rho < -0.03$, $p < 0.01$), but performed worse in the other three fluid cognitive functions (min $\rho > 0.05$, $p < 0.01$). Interestingly, better SES was associated with fewer sleep disturbances ($\rho = -0.12$, $p < 0.01$), and males showed more sleep disturbances than females ($\rho = -0.03$, $p < 0.01$).

After controlling for age, gender, sleep, and SES, caffeine intake was no longer significantly associated with reading decoding ($\beta = -0.02$, $p = 0.07$) and inhibition control ($\beta = -0.01$, $p = 0.80$). Increased caffeine intake was significantly associated with decreased vocabulary comprehension ($\beta = -0.07$, $p < 0.01$), suggesting with every increase of one standard

Table 2 Distribution of caffeinated drink consumption and the corresponding demographics ($n = 11{,}718$)

Beverages	Participants no. (%)	Age (mean ± SD)	Gender* (male/female)	Race/ethnicity* (White/Black/Hispanic/Asian/Others)
No consumption	3877 (33.1)	9.8 ± 0.6	1867/2008	2180/452/756/108/377
Consume one type				
Coffee	178 (1.5)	9.9 ± 0.6	90/88	81/2151/7/18
Espresso	76 (0.7)	10.0 ± 0.7	30/46	34/9/21/5/7
Tea	642 (5.5)	9.9 ± 0.6	283/359	316/117/103/26/79
Soda	3190 (27.2)	9.9 ± 0.6	1823/1367	1822/364/661/51/286
Energy drinks	15 (0.1)	9.9 ± 0.7	10/5	9/1/3/0/2
Consume two types				
Coffee and tea	113 (1.0)	9.9 ± 0.6	52/60	53/15/29/5/11
Coffee and soda	532 (4.5)	10.0 ± 0.6	218/253	218/66/187/5/56
Espresso and soda	231 (2.0)	10.0 ± 0.6	100/131	94/18/88 5/25
Tea and soda	1609 (13.7)	9.9 ± 0.6	891/718	715/432/229/22/209
Others	144 (1.2)	20.0 ± 0.6	8163	63/28/24/1/28
Consume three or more types	1111 (9.5)	20.0 ± 0.6	589/513	519/220/225/17/129

*Due to missing values, the sum of percentages may not equal to 100%

Table 3 Caffeine intake and cognitive scores derived from the ABCD youth substance use interview and the NIH toolbox

	Mean (Rijlaarsdam et al.)	Median (IQR)	Range
Caffeine intake/mg per day	13.00 (43.73)	1.76 (9.49)	0–1195
Crystallized cognitive skills			
Vocabulary comprehension	106.79 (16.99)	106.00 (22.00)	0–208
Reading decoding	102.52 (19.12)	100.00 (20.00)	64–206
Fluid cognitive skills			
Inhibitory control	95.43 (13.67)	97.00 (22.00)	62–171
Working memory	100.55 (14.78)	103.00 (21.00)	39–194
Cognitive flexibility	96.72 (15.16)	94.00 (17.00)	65–191
Processing speed	93.79 (22.10)	95.00 (26.00)	20–185
Episodic memory	100.96 (16.11)	99.00 (21.00)	64–172

Abbreviations: *SD* standard deviation, *IQR* interquartile range

deviation in caffeine intake, the vocabulary comprehension score decreases by 0.02 standard deviation. Similarly, increased caffeine intake was also significantly associated with decreased working memory ($\beta = -0.04$, $p < 0.01$), cognitive flexibility ($\beta = -0.04$, $p < 0.01$), processing speed ($\beta = -0.05$, $p < 0.01$), and episodic memory ($\beta = -0.04$, $p < 0.01$). Because the sample was from 21 research sites, our study further added the site ID as a random effect in statistical analysis. The abovementioned findings remained the same.

To avoid potential acute effects of caffeine on cognition, we re-run the analysis and excluded the children who reported caffeine intake in last 24 h prior to cognitive assessment. This analysis only included 3798 children among 4518 who reported the PLUS measure and revealed the results similar to those in Table 4. In details, increased caffeine intake was significantly associated with decreased vocabulary comprehension ($\beta = -0.07$, $p < 0.01$), working memory ($\beta = -0.04$, $p = 0.04$), cognitive flexibility ($\beta = -0.04$, $p = 0.03$), processing speed ($\beta = -0.06$, $p < 0.01$), and episodic memory ($\beta = -0.06$, $p < 0.01$). No significant findings were found in the associations of caffeine intake with reading decoding ($\beta = -0.01$, $p = 0.46$) and inhibitory control abilities ($\beta = 0.01$, $p = 0.65$).

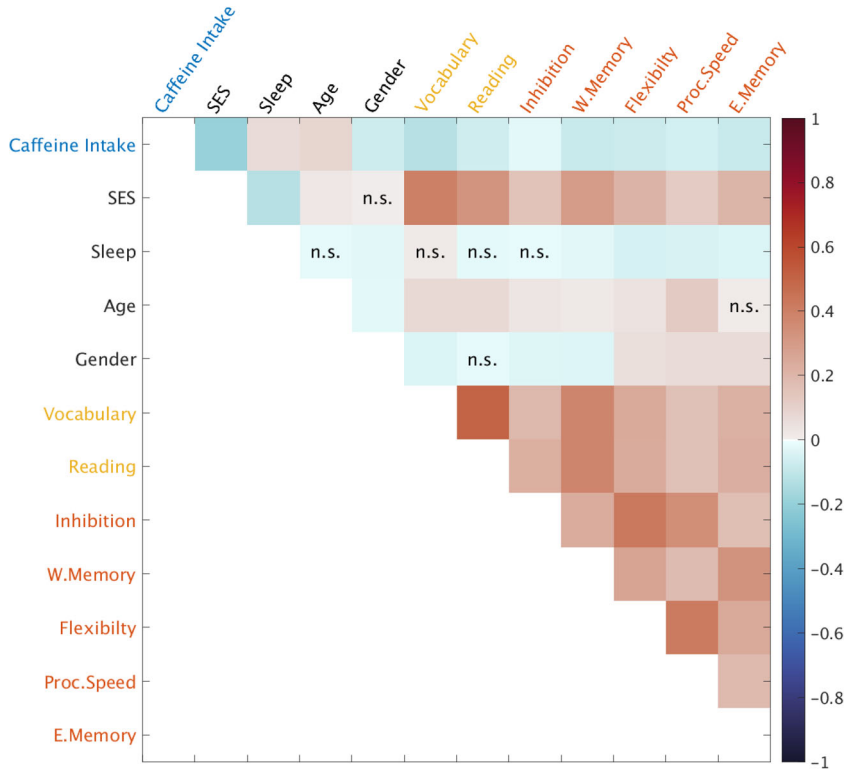

Fig. 1 Spearman's correlation heat map. Abbreviations: n.s., no significance; vocabulary, vocabulary comprehension; reading, reading decoding; inhibition, inhibitory control; W.Memory, working memory; flexibility, cognitive flexibility; Proc.Speed, processing speed; E.Memory, episodic memory

Table 4 Regression coefficients, standardized β, and p values indicate the relationship between caffeine intake and cognitive functions after controlling for age, gender, sleep, and socioeconomic status

	Standardized β value (95% CI)	p value	df
Crystallized cognitive skills			
Vocabulary comprehension	− 0.07 (− 0.09, − 0.05)	< 0.01	10,587
Reading decoding	− 0.02 (− 0.04, 0.01)	0.07	10,576
Fluid cognitive skills			
Inhibitory control	− 0.01 (− 0.02, 0.02)	0.80	10,582
Working memory	− 0.04 (− 0.06, − 0.02)	< 0.01	10,548
Cognitive flexibility	− 0.04 (− 0.06, − 0.02)	< 0.01	10,583
Processing speed	− 0.05 (− 0.07, − 0.03)	< 0.01	10,567
Episodic memory	− 0.04 (− 0.06, − 0.02)	< 0.01	10,577

Abbreviations: *CI* confidence interval, *df* degrees of freedom

Discussion

The results obtained from this study indicated that increasing caffeine intake was associated with lower scores in several cognitive functions, such as vocabulary comprehension, working memory, cognitive flexibility, processing speed, and episodic memory in children.

Previous literature suggested that caffeine at a certain level may benefit cognitive function, such as executive function and processing speed (Heatherley et al. 2006; Hunt et al. 2011; Soar et al. 2016), which is inconsistent with our findings. Notably, most of existing studies were based on a randomized double-blind, placebo-controlled design and found the acute effect of caffeine on cognition (Castellanos and Rapoport 2002). In contrast, our study was a population-based study. We revealed adverse influence of caffeine intake on youth's cognitive function. When excluding children with caffeine intake in last 24 h prior to cognitive assessment, we still observed the adverse influence of caffeine intake on cognition. Even we controlled for psychopathology in our analysis, such as ADHD that was often observed in children, the negative association between caffeine intake and cognition remained the same (see the Supplementary Material). Similar to the current study, one of recent studies asked adolescents to report their consumption of caffeine drinks during a week of time and found the negative correlation between executive functions and caffeine intake (Van Batenburg-Eddes et al. 2014).

Our study focused specifically on children aged 9–10 years, during which the brain maturation that has a large impact on a variety of cognitive functions (Casey et al. 2000). Our findings suggest that children who consume more caffeine on a regular basis perform worse in cognition. Although the effects of caffeine intake on youth's brain development have not yet been examined, caffeine may alter normal brain development during critical developmental periods. This stems from the evidence that the animal model of perinatal caffeine exposure had long-lasting effects on brain function (Temple 2009). Moreover, the tendency of more caffeine intake in childhood may increase the risk of habitual and even excessive caffeine consumption later in life. This could cause chronic arousal and sleep problems and affect neuronal plasticity and brain developmental processes, such as synaptic pruning and myelination (Olini et al. 2013).

Despite some studies reported that of the habitual caffeine use improves motor speed (Van Boxtel et al. 2003), further study should be conducted on the effects of caffeine intake on cognitive processes during tasks that require less motor-weighted components, particular in children (Nehlig 2010). Moreover, past studies have never shown any relationship between caffeine intake and crystallized abilities such as language. Thus, more investigation should be carried out to confirm our results where oral reading and vocabulary comprehension scores decreased significantly with increasing caffeine intake, suggesting that improper amount of caffeine intake may negatively affect crystallized cognitive functions.

The strengths of this study include the large sample size of young subjects and administration of reliable cognitive performance measures. However, there are some limitations of the present analysis that have to be considered. Firstly, most measures were either self or parent-reported, which may result in discrepancies for caffeine intake measure. Secondly, the study would have benefited from the inclusion of more high-caffeine consumers to generate a more balanced distribution of caffeine. Last but not least, it has been shown that sugar consumption during childhood may adversely impact child cognition (Cohen et al. 2018). Hence, there could be confounding effects on cognitive functions due to sugar content of caffeinated beverages. Unfortunately, the sugar intake was not a major focus of the ABCD study and hence was not assessed. Future investigation is needed to parse out which sugar and caffeine intakes contribute most to cognitive development in children.

Although further study is required on the complex pharmacologic and neural mechanisms of caffeine intake to understand its effects on each specific cognitive function, the results from this study suggest a negative impact by caffeine on cognitive development in children. This is especially important today where a large number of children consume beverages

with caffeine regularly. Thus, from a public health perspective, we advise parents to control their children's intake of beverages with caffeine to reduce the risk of interference with normal cognitive development.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Aepli A, Kurth S, Tesler N et al (2015) Caffeine consuming children and adolescents show altered sleep behavior and deep sleep. Brain Sci 5: 441–455. https://doi.org/10.3390/brainsci5040441

Akshoomoff N, Newman E, Thompson WK et al (2014) The NIH toolbox cognition battery: results from a large normative developmental sample (PING). Neuropsychology 28:1–10. https://doi.org/10.1037/neu0000001

Atik A, Harding R, De Matteo R et al (2017) Caffeine for apnea of prematurity: effects on the developing brain. Neurotoxicology 58: 94–102. https://doi.org/10.1016/j.neuro.2016.11.012

Barch DM, Albaugh MD, Avenevoli S et al (2018) Demographic, physical and mental health assessments in the adolescent brain and cognitive development study: rationale and description. Dev Cogn Neurosci 32:55–66. https://doi.org/10.1016/j.dcn.2017.10.010

Belsley DA, Kuh E, Welsch RE (1980) Regression diagnostics: identifying influential observations and sources of collinearity. John Wiley Sons

Branum AM, Rossen LM, Schoendorf KC (2014) Trends in caffeine intake among US children and adolescents. Pediatrics 133:386–393. https://doi.org/10.1542/peds.2013-2877

Bruni O, Ottaviano S, Guidetti V et al (1996) The sleep disturbance scale for children (SDSC) construct ion and validation of an instrument to evaluate sleep disturbances in childhood and adolescence. J Sleep Res 5:251–261. https://doi.org/10.1111/j.1365-2869.1996.00251.x

Budney AJ, Emond JA (2014) Caffeine addiction? Caffeine for youth? Time to act! Addiction 109:1771–1772. https://doi.org/10.1111/add.12594

Casey BJ, Giedd JN, Thomas KM (2000) Structural and functional brain development and its relation to cognitive development. Biol Psychol 54:241–257. https://doi.org/10.1016/S0301-0511(00)00058-2

Castellanos FX, Rapoport JL (2002) Effects of caffeine on development and behavior in infancy and childhood: a review of the published literature. Food Chem Toxicol

Christensen DL, Schieve LA, Devine O, Drews-Botsch C (2014) Socioeconomic status, child enrichment factors, and cognitive performance among preschool-age children: results from the follow-up of growth and development experiences study. Res Dev Disabil 35: 1789–1801. https://doi.org/10.1016/j.ridd.2014.02.003

Cohen JFW, Rifas-Shiman SL, Young J, Oken E (2018) Associations of prenatal and child sugar intake with child cognition. Am J Prev Med. https://doi.org/10.1016/j.amepre.2018.02.020

Cotter BV, Jackson DAE, Merchant RC et al (2013) Energy drink and other substance use among adolescent and young adult emergency department patients. Pediatr Emerg Care. https://doi.org/10.1097/PEC.0b013e3182a6403d

de Winter JCF, Gosling SD, Potter J (2016) Comparing the Pearson and spearman correlation coefficients across distributions and sample sizes: a tutorial using simulations and empirical data. Psychol Methods 21:273–290. https://doi.org/10.1037/met0000079

Farah MJ (2017) The neuroscience of socioeconomic status: correlates, causes, and consequences. Neuron 96:56–71. https://doi.org/10.1016/j.neuron.2017.08.034

Fred Hutchinson Cancer Research Center (2004) Caffeine questionnaire. In: Seattle, WA Fred Hutchinson Cancer Res. Cent. https://sharedresources.fredhutch.org/documents/caffeine-questionnaire

Garavan H, Bartsch H, Conway K et al (2018) Recruiting the ABCD sample: design considerations and procedures. Dev Cogn Neurosci 32:16–22. https://doi.org/10.1016/j.dcn.2018.04.004

Heatherley SV, Hancock KMF, Rogers PJ (2006) Psychostimulant and other effects of caffeine in 9- to 11-year-old children. J Child Psychol Psychiatry Allied Discip. https://doi.org/10.1111/j.1469-7610.2005.01457.x

Higdon JV, Frei B (2006) Coffee and health: a review of recent human research. Crit Rev Food Sci Nutr 46:101–123. https://doi.org/10.1080/10408390500400009

Hunt MG, Momjian AJ, Wong KK (2011) Effects of diurnal variation and caffeine consumption on Test of Variables of Attention (TOVA) performance in healthy young adults. Psychol Assess 23:226–233. https://doi.org/10.1037/a0021401

Kyle J, Fox HC, Whalley LJ (2010) Caffeine, cognition, and socioeconomic status. J Alzheimers Dis 20:151–159. https://doi.org/10.3233/JAD-2010-1409

Lisdahl KM, Sher KJ, Conway KP et al (2018) Adolescent Brain Cognitive Development (ABCD) study: overview of substance use assessment methods. Dev Cogn Neurosci 32:80–96. https://doi.org/10.1016/j.dcn.2018.02.007

Lo JC, Ong JL, Leong RLF et al (2016) Cognitive performance, sleepiness, and mood in partially sleep deprived adolescents: the need for sleep study. Sleep 39:687–698. https://doi.org/10.5665/sleep.5552

Lorist MM, Snel J (2008) Caffeine, sleep, and quality of life. In: Sleep and quality of life in clinical medicine. Humana Press, Totowa, pp 325–332

Luciana M, Bjork JM, Nagel BJ et al (2018) Adolescent neurocognitive development and impacts of substance use: overview of the Adolescent Brain Cognitive Development (ABCD) baseline neurocognition battery. Dev Cogn Neurosci 32:67–79. https://doi.org/10.1016/j.dcn.2018.02.006

McLellan TM, Caldwell JA, Lieberman HR (2016) A review of caffeine's effects on cognitive, physical and occupational performance.

Neurosci Biobehav Rev 71:294–312. https://doi.org/10.1016/j.neubiorev.2016.09.001

McLellan TM, Riviere LA, Williams KW, et al (2018) Caffeine and energy drink use by combat arms soldiers in Afghanistan as a countermeasure for sleep loss and high operational demands. Nutr Neurosci 0:1–10. https://doi.org/10.1080/1028415X.2018.1443996

Miller KL, Alfaro-Almagro F, Bangerter NK et al (2016) Multimodal population brain imaging in the UK Biobank prospective epidemiological study. Nat Neurosci 19:1523–1536. https://doi.org/10.1038/nn.4393

Mitchell DC, Knight CA, Hockenberry J et al (2014) Beverage caffeine intakes in the U.S. Food Chem Toxicol 63:136–142. https://doi.org/10.1016/j.fct.2013.10.042

Nehlig A (2010) Is caffeine a cognitive enhancer? J Alzheimers Dis 20. https://doi.org/10.3233/JAD-2010-091315

Noble KG, Houston SM, Brito NH et al (2015) Family income, parental education and brain structure in children and adolescents. Nat Neurosci 18:773–778. https://doi.org/10.1038/nn.3983

O'Neill CE, Newsom RJ, Stafford J et al (2016) Adolescent caffeine consumption increases adulthood anxiety-related behavior and modifies neuroendocrine signaling. Psychoneuroendocrinology 67:40–50. https://doi.org/10.1016/j.psyneuen.2016.01.030

Olini N, Kurth S, Huber R (2013) The effects of caffeine on sleep and maturational markers in the rat. PLoS One 8:1–8. https://doi.org/10.1371/journal.pone.0072539

Ribeiro JA, Sebastio AM (2010) Caffeine and adenosine. J Alzheimers Dis 20. https://doi.org/10.3233/JAD-2010-1379

Schliep KC, Schisterman EF, Mumford SL et al (2013) Validation of different instruments for caffeine measurement among premenopausal women in the BioCycle study. Am J Epidemiol 177:690–699. https://doi.org/10.1093/aje/kws283

Skinner JD, Carruth BR, Houck KS et al (2000) Caffeine intake in young children differs by family socioeconomic status. J Am Diet Assoc 100:229–231. https://doi.org/10.1016/S0002-8223(00)00069-9

Smit HJ, Rogers PJ (2000) Effects of low doses of caffeine on cognitive performance, mood and thirst in low and higher caffeine consumers. Psychopharmacology 152:167–173. https://doi.org/10.1007/s002130000506

Soar K, Chapman E, Lavan N et al (2016) Investigating the effects of caffeine on executive functions using traditional Stroop and a new ecologically-valid virtual reality task, the Jansari assessment of Executive Functions (JEF ©). Appetite 105:156–163. https://doi.org/10.1016/j.appet.2016.05.021

Tarrus E, Cami J, Roberts D et al (1987) Accumulation of caffeine in healthy volunteers treated with furafylline. Br J Clin Pharmacol 23:9–18. https://doi.org/10.1111/j.1365-2125.1987.tb03003.x

Temple JL (2009) Caffeine use in children: what we know, what we have left to learn, and why we should worry. Neurosci Biobehav Rev 33:793–806. https://doi.org/10.1016/j.neubiorev.2009.01.001

Van Batenburg-Eddes T, Lee NC, Weeda WD et al (2014) The potential adverse effect of energy drinks on executive functions in early adolescence. Front Psychol. https://doi.org/10.3389/fpsyg.2014.00457

Van Boxtel MPJ, Schmitt JAJ, Bosma H, Jolles J (2003) The effects of habitual caffeine use on cognitive change: a longitudinal perspective. Pharmacol Biochem Behav 75:921–927. https://doi.org/10.1016/S0091-3057(03)00171-0

Vanderlee L, Reid JL, White CM et al (2018) Evaluation of a 24-hour caffeine intake assessment compared with urinary biomarkers of caffeine intake among young adults in Canada. J Acad Nutr Diet 118:2245–2253.e1. https://doi.org/10.1016/j.jand.2018.07.016

Verster JC, Koenig J (2018) Caffeine intake and its sources: a review of national representative studies. Crit Rev Food Sci Nutr 58:1250–1259. https://doi.org/10.1080/10408398.2016.1247252

Volkow ND, Koob GF, Croyle RT et al (2018) The conception of the ABCD study: from substance use to a broad NIH collaboration. Dev Cogn Neurosci 32:4–7. https://doi.org/10.1016/j.dcn.2017.10.002

Weintraub S, Dikmen SS, Heaton RK et al (2013) Cognition assessment using the NIH toolbox. Neurology 80:S54–S64. https://doi.org/10.1212/WNL.0b013e3182872ded