Increasing Screen Exposure Time Harms Inhibitory-Control Network in Developing Children: A Two Years Follow-up of the ABCD Study

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ABSTRACT

As virtual experiences are rapidly substituting a significant proportion of in-person interactions during the COVID pandemic, it is critical to monitor the effect of screen exposure time on developing children's behavior and nervous system. Screen use boosts information accessibility and, therefore, may delay the development of the inhibitory control networks in children, who are vulnerable to immediate reward-orientated tendencies and not yet capable of controlling their impulsivity. Therefore, it was hypothesized that as children become more exposed to screens, the development of the inhibitory control network would be delayed and their reward sensitivity will be augmented. Using the ABCD Study Data Repository, 8,334 children's behavioral and neural data (aged 9-11) were included. Robust mediation analysis and correlation analysis were used to investigate how Screen Time interacts with children's reward-orientated tendency (e.g. Behavioral approach system, BAS) and the brain's inhibitory network. Intrinsic Frontoparietal Network-Striatum (FPN-Striatum) connectivity strength was used as neural indices of the inhibitory control quality in children. Results showed that Screen Time significantly mediated the relationship between BAS and both waves of the intrinsic inhibitory process. A higher BAS was linked to a longer Screen Time and weaker inhibitory network connectivity. This complete/full mediation model indicates that Screen Time negatively influenced the strength of FPN-Striatum connectivity. In conclusion, the study revealed specific behavioral and neural correlates of screen exposure using a large database, and suggested that increasing screen exposure time may impair the inhibitory capability and increase impulsivity in children.

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GENERAL AUDIENCE ABSTRACT

The current study explored the effect of daily screen exposure in pre-adolescent children to provide an important springboard for future work in protecting developing children against the negative impacts of screen use, which has increased significantly during the COVID-19 pandemic. Over 8,000 children's data from the Adolescent Brain Cognitive Development (ABCD) project was included and found that an increased daily screen exposure time is linked to an inefficient inhibitory control system in the brain. As children's inhibitory control systems are still developing, this negative effect further hinder the maturation of inhibitory-control systems two years later. Given that the virtual movement is irreversible, the results provide scientific evidence that a balance between screen time and non-screen activities is required for developing children.

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Data used in the preparation of this project were obtained from the Adolescent Brain Cognitive Development[SM] (ABCD) Study (https://abcdstudy.org), held in the NIMH Data Archive (NDA). This is a multisite, longitudinal study designed to recruit more than 10,000 children aged 9-10 and follow them over 10 years into early adulthood. The ABCD Study® is supported by the National Institutes of Health and additional federal partners under award numbers U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA041089, U24DA041123, U24DA041147. A full list of supporters is available at https://abcdstudy.org/federal-partners.html. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/consortium_members/. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in the analysis or writing of this report. This manuscript reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators. The ABCD data repository grows and changes over time. The ABCD data used in this report came from https://dx.doi.org/10.15154/1503209.

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Introduction

The negative impact of screen exposure on children's inhibitory control have been well documented (Domingues-Montanari, 2017; Twenge & Campbell, 2018; and for a comprehensive review see Carson et al., 2016). However, although governmental guidelines limit screen exposure to two hours per day in school-aged children for enhancing well-being (Communications et al., 2016; Okely et al., 2019), children's average entertainment screen time is 3-4 hours a day (Tsiros et al., 2017; Twenge & Campbell, 2018). Moreover, the screen exposure time has escalated at least 50% with *"stay-at-home"* orders during the COVID-19 pandemic. (SuperAwesome, 2020). As virtual experiences rapidly substitute for a significant proportion of in-person interactions, it is critical to monitor the influences of daily excessive screen exposure on the behavioral and neural impact of inhibitory control in children (Mills, 2016; Sigman, 2017). This introduction will overview the background knowledge of inhibitory control in both behavioral and neural level, and the role of personality charateristics in screen exposure and inhibitory control.

Literature Review

Inhibitory Control

Inhibitory control (IC) refers to one's ability to resist impulses and suppress response tendencies (Carlson et al., 2002; Duckworth & Kern, 2011). Childhood is a critical period for the development and establishment of inhibitory control, which continues to develop into adulthood (Williams et al., 1999). An over 30-year longitudinal study showed that the gradient of inhibitory ability in childhood steadily predicts physical health and personal finance outcomes as well as the rate of criminal offending and substance dependence in adulthood (Moffitt et al., 2011). Lower IC ability in the developing period increases the risk of obesity (Schlam et al., 2013), the vulnerability to substantial gambling addiction (see Verdejo-García et al., 2008 for review), and moves up the age of earliest onset for marijuana, alcohol, or cigarette use (Lee & Telzer, 2016), which lead to adverse health outcomes later in life. In contrast, individuals with higher IC ability in the developing period have higher grades and more successful achievements in school and work (Tangney et al., 2018), more satisfaction and lower conflict in intimate relationships (Allemand et al., 2019), and longevity (Kern & Friedman, 2008).

Screen Exposure and Inhibitory Control

The development of IC is bidirectional. On one hand, it is malleable by practicing and training. For instance, the daily practices that are required to inhibit one’s emotions, thoughts, and behaviors when confronting temptations and impulses, such as avoiding sweets (Muraven, 2010) and forcing exercise (Oaten & Cheng, 2006), have been shown to improve IC strength. On the other hand, one’s ability of IC would decline due to problematic behaviors: Excessive screen use is one of them. The nature of screen use includes that user can switch modes easily and make information accessibility increase. Users may pause and skip any session they are less interested

in to choose content that pleases them more, which offers immediate benefits and the negligible marginal cost (Frey et al., 2007). In other words, excessive screen use may weaken the ability of inhibitory control. Developmental studies demonstrated that individuals' impulsiveness and attention problems are associated with excessive screen use. Gentile and colleagues (2012) tracked children and adolescents over 3 years for the adverse effect of playing video games and found that those who spent more time on playing video games were more impulsive or had more attention problems subsequently (Gentile et al., 2012). Besides, a large cohort study which examined consequences of digital media activities on healthy adolescents reported that those who had a higher frequency of digital media use showed higher odds of having subsequent symptoms of attention-deficit/hyperactivity disorder (ADHD) throughout 5 waves (Ra et al., 2018). Furthermore, the deleterious effects of excessive screen use on adolescence are not limited to certain contents or devices. A growing body of literature has provided considerable evidence that a wide variety of excessive screen use impairs IC, including television viewing (David Acevedo-Polakovich et al., 2007; Swing et al., 2010), violent video gaming (Coyne et al., 2018; Swing et al., 2010), mobile phone usage (Seo et al., 2016), binge-watching (Shim et al., 2018), and social media use (Du et al., 2019; Ra et al., 2018). However, the existing literature of daily screen use remains focusing on the impact on behavioral development.

Neurocircuitry Underlying Screen Exposure and Inhibitory Control

Childhood is a period where the brain changes strikingly (Casey et al., 2000; Rapoport & Gogtay, 2008), with neural circuits underlying IC also rapidly developing (Padmanabhan et al., 2011). Thus, it is possible that daily screen exposure would influence the developmental trajectory of the IC circuits.

Recent evidence suggests that the underlying neural mechanisms linked to the failure of IC may be associated with imbalanced functional and structural developments between the reward-related nucleus and the executive networks (Casey, 2015; Lee & Telzer, 2016; McClure et al., 2004; Metcalfe & Mischel, 1999). Although non-clinical daily screen behaviors are understudied, research in the screen dependency disorders (SDDs; Sigman, 2017) shows that the reward-related nucleus and the executive networks that may be affected by daily screen behaviors are the striatum and the frontal executive networks (Balleine et al., 2007; Brand et al., 2014).

Striatum. The striatum is composed of three nuclei, caudate, putamen, and ventral striatum, integrating input from the brainstem and a variety of subcortical and cortical regions, and functioning in motor planning, decision-making, motivation, and reward perception and responses (Taylor et al., 2013; Yager et al., 2015). Both animal and human studies have revealed that the striatum serves a key role in habit formation and addictive processes (Corbit et al., 2012; Everitt et al., 2008; Everitt & Robbins, 2013; Schwendt et al., 2009; Volkow et al., 2006). For example, in rodents, long-access to self-administered methamphetamine gradually decreased dopamine transporter protein levels in the striatum (Schwendt et al., 2009). Similarly, a human imaging study using positron emission tomography (PET) revealed that the metabolism in striatal regions were decreased when the individual with cocaine addiction saw the cocaine-cue compared with a neutral cue, and the magnitude of the reduction positively correlated with their craving (Volkow et al., 2006). A task-based functional MRI (fMRI) also showed that patients with internet addiction exhibited less activation in the striatum compared to controls when they continuously won in a competitive task (Dong et al., 2013). In regards to volumetric comparison, increased striatal volume was found in youth smokers compared to nonsmokers (Li et al., 2015)

and in youth with SDD (Cai et al., 2016). This volumetric difference was further correlated with the error rate in the Stroop task. Developmentally, adolescents who excessively play computer games showed the higher gray matter volume size and the more increased neural activation in the striatum compared to those who play computer games infrequently (Kühn et al., 2011). These findings suggest that the striatum is associated with both inhibitory control and screen dependency.

Frontal Executive Networks. The frontoparietal network (FPN) and the dorsolateral prefrontal cortex (DLPFC) are also investigated extensively in the context of inhibitory control and dependency behaviors since they are involved in executive and regulatory processes in the brian (Brand et al., 2014; Hare et al., 2009; Hayashi et al., 2013; Lopez et al., 2019; Vincent et al., 2008). For example, Lopez and colleagues (2019) used an elegant two-session study to reveal that the dieters that have to recruit greater DLPFC activation in the first IC exertion session showed less FPN activity in the subsequence food-cue task and tended to consume more ice-cream when the diets were broken (Lopez et al., 2019). Similarly, a study on cigarette smokers showed the positive association between the DLPFC activation the level of craving (McBride et al., 2006). These findings imply the DLPFC and FPN functioning in craving regulation. Importantly, a recent study demonstrated that the young adults with SDD showed more DLPFC dysfunctions (Liu et al., 2014). This study used Go/NoGo tasks combined with distracting gaming pictures to demonstrated that the control group exhibited a higher inhibitory control ability with higher activation of DLPFC during distracting tasks compared to original non-distracted tasks but not in the SDD group, suggesting the inhibitory function was impaired in the disorder group. Consistently, a study using resting-state functional connectivity approach reported that the SDD group showed more within-network connectivity reduction in FPN

compared to the control group (Dong et al., 2015). They further reported that the strength of the connectivity was negatively correlated with the Stroop effect, suggesting that the higher functional connectivity in FPN may underpin the better control ability.

Frontostriatal Circuitry. Although most screen-related studies only focused on either the striatum or the frontal executive networks separately, both animal and human studies have revealed that the striatum and the frontal executive networks are structurally interconnected (Alexander et al., 1986; Haber, 2016; Leh et al., 2007; Zhang & Iwaki, 2020), being a part of the frontostriatal circuitry (Haber, 2016) and functioning on IC (Figure 1). Developmentally, functional MRI (fMRI) studies using diverse task-based indices demonstrated a progressive maturation for IC functions within the frontostriatal circuitry, such that children show lower inhibition efficiency and lower activations in the circuitry, which switches to better inhibition efficiency and higher activations in the circuitry by adulthood (Rubia et al., 2006). A diffusion tensor imaging (DTI) study further supports this progressive maturation finding by showing that the tracts within the frontostriatal circuitry became more restricted over developing and the ability of IC was enhanced parallelly (Liston et al., 2006). Thus, the negative coupling between these regions is an index of dysfunction of neural networks of the brain in IC. Furthermore, a study reported consistent findings by using both the DTI and functional connectivity techniques to explore the fronto-striatal network on smokers (Yuan et al., 2017). The functional connectivity analysis revealed a negative functional coupling of the fronto-striatal connection during smoking cue-induced craving and this coupling was negatively correlated with the fiber tract integrity of fronto-striatal connection. Although similar exploration in screen-related behaviors has not been reported yet, the change in fronto-striatal connection is possible and can exist in the individuals with screen dependency.

Taken together, the literature suggests that daily screen behavior may change the connectivity strength between the regions in the frontostriatal circuitry (i.e., FPN-striatum) and that the frontal and striatal regions should be considered as a whole system.

Personality Characteristics in Screen Exposure and Inhibitory Control

The current designs of screen devices and platforms make user to switch modes easily and increase information accessibility. The users, therefore, are easy to gain feedback and reward, which may boost the reward-seeking tendency (Tricomi & Fiez, 2012) and may delay the development of the inhibitory control networks in children, who are vulnerable to immediate reward-orientated tendencies and not yet capable of controlling their impulsivity (Burton et al., 2021; Casey, 2015).

The Behavioral Inhibition and Behavioral Approach Systems (BIS/BAS) scales is a broadly used biological-based personality measure, capturing individual differences in the sensitivity to stimulus. The difference in sensitivity may differ one's perception toward the environment, which in turn changes one's motivation and strength of desire (Hofmann et al., 2012). The BIS/BAS scales were designed to measure two broad motivational systems, the behavioral inhibition system (BIS) and the behavioral activation system (BAS; Motzkin et al., 2014). The BIS corresponds to motivation to avoid aversive outcomes. On the contrary, the behavioral activation system (Motzkin et al., 2014) corresponds to motivation to approach goal-oriented outcomes, which can be allocated to three facets: BAS Drive, BAS Fun-seeking, and BAS Reward Responsiveness. The BIS/BAS scales have been reported as being related to both screen-related addictions and IC problems (Fino et al., 2014; Kim et al., 2016). Specifically, a higher BIS and BAS fun-seeking level are related to increased internet addiction (Yen et al., 2009), BAS drive level is able to predict internet gaming disorder (IGD) (Rho et al., 2018), and

BAS total, a sum score of all BAS subscores, is related to impulsivity (Miller et al., 2004) and is significantly higher in adolescents with IGD and smartphone addiction than controls (Kim et al., 2016; Li et al., 2020). Taken together, these findings suggest that when studying IC and screen-related behaviors, it is necessary to consider their reward-sensativity for a more comprehensive exploration.

The Present Study

The present study was to delineate how screen exposure time influences the development of neurocircuitry engaging in IC of children's brains. Recent literature has shown that excessive screen time exposure, especially screen-related additions, may impair the development of IC, a crucial index to predict future physical and psychological well-being. However, given that virtual movement is irreversible in modern and future life, it is critical to track the influences of non-clinical daily screen exposure on IC. Moreover, rather than simply investigating the direct relationship between screen time and IC, personality traits would be an important piece when doing such investigation since personality traits are significantly linked to both screen dependency and IC in personality-focused research. Importantly, the present study would focus on the influence on the neural level. Although the current studies on various screen-related addictions suggest that the severe screen exposure may alter the reward-related nucleus and executive networks, the current investigation on the non-clinical screen behaviors is scarce in the field. In sum, the current study would examine whether the non-clinical screen exposure time may explain the link between children's personality traits and the change of IC related networks, i.e., reward-related nucleus and executive networks.

Given previous evidence indicating that the maturation of the brain can be indexed by the degree of functional coupling between the frontal executive networks and the striatum (Balleine et al., 2007; Brand et al., 2014; Casey, 2015; Liston et al., 2006; Rubia et al., 2006), the main goal of the thesis was to explore the effect of screen exposure time on developing children's intrinsic neural coupling that underlies IC. This study used the first two waves of the Adolescent Brain Cognitive Development study (Casey et al., 2018) to examine the intrinsic functional connectivity estimated from resting-state fMRI, focusing on the functional connectivity between

the fronto-parietal network and striatum. The specific aims of this study were to 1) Examine the effects of screen exposure time on the neurocircuitry underlying inhibitory control. 2) Examine screen exposure time as a mediator in the relationship between personality traits and the neurocircuitry underlying inhibitory control. 3) Examine the relationship between the neurocircuitry underlying inhibitory control and behavioral indices of inhibitory control.

Hypotheses

Consistent with the study aims, the hypotheses were:

1. There would be an alteration of the fronto-striatal connectivity in children with longer daily screen exposure time.
2. The daily screen exposure time in the baseline year (i.e., 1st-year/wave1) can predict the strength of the fronto-striatal connectivity two years after (i.e., 2nd-year/wave2) as well as the strength change between waves.
3. In addition to the effect of daily screen exposure time on the IC circuit, this study further predicted that as children become more exposed to screens, their reward sensitivity will be augmented, leading to a delay in the development of the inhibitory neural circuit (Johnson et al., 2003; Kim et al., 2016; Kim-Spoon et al., 2016; Miller et al., 2004).
4. The striegth of fronto-striatal connectivity is possitively correlated with behaviroal indecies of inhibitory control.

Methods

Participants and Data Preprocessing

The present study was performed by using data retrieved from the Adolescent Brain Cognitive Development (ABCD) Data Repository (https://abcdstudy.org). The ABCD Data Repository tracks 11,878 individuals aged 9 to 11 years from 21 data collection sites around the United States (Casey et al., 2018). The dataset was downloaded on 11/2020 from the NIH Data Archive (NDA, https://nda.nih.gov/). The present study included the ABCD Youth Screen Time Survey (STQ, *abcd_stq01*), the Sports and Activities Survey (*abcd_spacss01*), the processed resting-state fMRI data (ABCD rsfMRI Network to Subcortical ROI Correlations, *mrirscor02*), ADHD score from the Child Behavior Checklist Scores (CBCL, *abcd_cbcls01*), and behavioral performance in the Stop Signal Task (SST, *abcd_sst02*).

Demographic and Behavioral Data

Demographics Survey. In a parent-report questionnaire (*pdem02* and *abcd_lpds01*), caregivers reported the race and gender of themselves and their child, family structure, total household income, and education.

Screen Time Assessment. Screen time was assessed using a child self-report measure consisting of 14 items (Barch et al., 2018; Sharif et al., 2010). The main 12 items measured different types of screen utilization, such as watching TV shows or movies, watching videos, and playing video games, on a typical weekday and weekend day. The scale is as follows: 0 = None; .25 = < 30 minutes; 0.5 = 30 minutes; 1 = 1 hour; 2 = 2 hours; 3 = 3 hours; and 4 = 4+ hours. Additionally, the survey included two items related to the experiences in playing mature-rated video games and watching R-rated movies (See Appendix A). Daily average screen time was calculated by averaging the sum of weekday screen time and the sum of weekend time.

Non-Screen Activities Time Assessment. The activities time refers to all sports and activities other than screen time, which was measured by the parent-reported Sports and Activities Involvement Questionnaire (Huppertz et al., 2016). The items in the questionnaire included 31 different types of sports, music, art and hobbies. Parents had to report how many years, how many months per year, how many days per week, and how many minutes per session their child participated in a certain activity (See Appendix B). The activities time data was processed in two steps: missing value remedy and final score calculating.

The data set had several missing values on various types of activity and was scattered on different participants. If the samples with missing data were simply discarded, 2,075 samples (25%) had to be removed. Thus the remedy rules that were applied were: 1) for missing values of days per week items, took out all data points that have the same value on months per year and then calculated the median of days per week of those data points for replacing the missing values. For example, if soccer: days per week was missing and the months per year was 2, then all other months per year that were 2 under soccer were taken out, and then the median of days per week of them was calculated. The median value was used to replace the missing values in this example. 2) for missing values of minutes per session, took out all data points that have the same value of months per year and then calculated the median of minutes per session of those data points for replacing the missing point. After dealing with the missing values, because the scale of this survey was different from the scale of the screen time survey, daily average activity time was calculated by the following steps: 1) converted the minutes per session of a single type of activity to hour per session; 2) multiplied the hour per session and days per week of a single type of activity and divided by seven; and 3) added up all types of activities.

Screen-Activity Proportion Score. In the examinations, the non-screen activities time was used to control the screen exposure time by the following calculation:

$$SAP\ score = \frac{Daily\ Screen\ Time}{Daily\ Screen\ Time + Daily\ Activity\ Time}$$

The Screen-Activity Proportion (SAP) score reflects how much individuals are exposed to the screen on a daily basis compared to non-screen activities. For example, the higher SAP score over 0.5 means that an individual spent more time with screens daily than non-screen activities.

Behavioral Inhibition/Behavioral Approach System (BIS/BAS) Scales. Carver and White (Carver & White, 1994) suggested two motivation systems, the behavioral inhibition system (BIS) and the behavioral activation system (BAS; Motzkin et al., 2014). The BIS corresponds to the motivation to avoid aversive outcomes. The BAS corresponds to the motivation to approach reward outcomes, which can be allocated to three facets: BAS Drive, BAS Fun-seeking, and BAS Reward Responsiveness (See Appendix C). To examine the relationship between individual behavioral traits in reward sensitivity, the degree of screen time exposure, and the neural development, the BAS scores were included. Although the BAS is divided into three subscales, it was found to load onto one single dimension significantly when a factor analysis was conducted (Miller et al., 2004). Thus, in the current analysis, the sum of the three BAS subscales (i.e., BAS Total) was adopted, as an indication of overall reward sensitivity (Kelley et al., 2019).

Behavioral indecies of inhibitory control. The ADHD traits and the performences of SST were used as behavioral indices of inhibitory control. The ADHD Scale (t-score) scale of the child behavior checklist (CBCL) was use as the measure of ADHD traits, with a higher scores indicating more behavioral problems (Achenbach & Edelbrock, 1991; Owens et al., 2021). The SST (Logan, 1994) measures impulsivity and ability of impulse control. It requires participants to withhold their motor responses to a “Go” stimulus when an unpredictable “Stop” is presented.

Participants were instructed to respond as quickly and accurately as possible when a "Go" signal is presented. They were also instructed to withhold the motor response when a delayed "Stop" signal is presented. If participants are able to withhold the motor response while "Stop" is shown, the trial is counted as successful inhibition, whereas if participants still respond, the trial is counted as unsuccessful inhibition. Of the total 180 trials in each run of the task, 30 of the trials (16.67%) were "Stop" trials. To ensure that there were about 50% successful and 50% unsuccessful inhibition trials, a tracking algorithm varied the interval between the "Go" signal onset and the "Stop" signal onset. This interval is called Stop Signal Delay (SSD), which initial setup was 50 ms. Following an unsuccessful inhibition, the SSD would be decreased by 50 ms on the next "Stop" trial to make the withhold easier. Following a successful inhibition, the SSD would be increased by 50 ms on the next "Stop" trial to make the withhold harder. Although most studies use the stop-signal reaction time (SSRT) as the dependent variable of the SST, it is indicated that the SSRT in the ABCD study is problematic (for the detailed see Bissett et al., 2021) so instead of only using the SSRT, the mean SSD was used as the main index of impulsivity in the present study. A shorter SSD corresponds to a higher impulsivity (Logan & Cowan, 1984; Logan et al., 2014). More details about the design of SST is available in Casey et al. (2018).

Neuroimaging Data

Imaging protocol. The ABCD imaging protocol was integrated from three 3T scanner platforms (i.e., Siemens Prisma, General Electric/GE 750, and Philips), which used standard adult-size multi-channel coils that are capable of multiband echo-planar imaging (EPI) acquisitions. More information about the protocols, such as scanning parameters and motion correction processing, are available in Casey et al. (2018) and Hagler et al. (2019).

Resting-State Intrinsic connectivity between the Inhibitory Control Network to Subcortical ROI connectivity. The ABCD dataset provides processed resting-state intrinsic network connectivity with various subcortical regions based on the subcortical segmentation with the FreeSurfer's automated brain segmentation (aseg) atlas (Bruce, 2012) to the cortical networks' that extracted by the Gordon parcellation approach (Gordon et al., 2016). For the present study, the values representing the strength of the frontoparietal network (FPN) to striatum connectivity (Figure. 1A) were generated by averaging the scores of the FPN-bilateral caudate, the FPN-bilateral putamen, and the FPN-bilateral accumbens connectivities. More details about the MRI processing pipeline and ROI extraction are available in Hagler Jr et al. (2019).

Data Analysis Plan

Data Preparation

The Robust Correlation Toolbox under Matlab was used for outlier detection and data cleaning (Pernet et al., 2013; Rousselet & Pernet, 2012). Using this toolbox, a scatter plot and normalized histograms with the corresponding Gaussian curves was plotted in the first step to overview the distribution of the data. Secondly, bivariate normality and heteroscedasticity were tested by using Henze-Zirkler's Multivariate Normality Test (Henze & Zirkler, 1990; Trujillo-Ortiz et al., 2007) and by comparing variances using a 95% percentile bootstrap CI, respectively. The outliers were determined using the 1.5 Interquartile Rule (IQR).

Correlation and Mediation Model Testing

Data analyses were performed by combining a 50,000 permutation resampling method and the robust method (Pernet et al., 2013), unless otherwise noted. By performing the resampling with replacement (boostrapping and permutation) techniques, ordinary least squares (OLS) models can be used without needing assumptions of normality and homoscedasticity (Efron & Tibshirani, 1994; Manly & Alberto, 2020). The statistical results from both Frequentist (i.e., *p*-value) and Bayesian approaches were reported to ensure robustness of the results. Bayesian approaches are able to evaluate the relative plausibility of the alternative hypothesis and the null hypothesis simultaneously, which can avoid the inflated false positive rate due to the large sample size (i.e., more than 10,000 in the ABCD data; c.f., Sullivan & Feinn, 2012). The Bayes factors (BF_{10}) were adopted as support for the alternative hypothesis (H_1) over the null hypothesis (H_0). A BF_{10} larger than 3 is interpreted as moderate favor for H_1 and a value larger than 10 is interpreted as a strong favor for H_1 (Matzke, 2014). For the Bayesian test, because the previous ABCD neural correlate studies reported significant results with a small effect size (*r*‘s

range from 0.037 to 0.07) (Cheng et al., 2020; Karcher et al., 2019; Paulus et al., 2019; Rosenberg et al., 2020), in the present study, a conservative stretched beta prior width of 0.3 was set in JASP 0.14.1 version (JASP Team, 2021), reflecting the belief of a medium effect size.

Results

After removing the missing value, the final sample size for the first year was 8,324 (interview date from 09/2016 to 10/2018). For the second year (interview date from 07/2018 to 01/2020) only 3,891 children from the first-year data were included in the current analyses as the second-year data has not yet fully released. The age range of children in this sample in their first year was 107-133 months old (M = 119.32, SD = 7.52) and 49.64% of them were female. Children were primarily identified as White (66.61%, race alone), 13.69% as African American, and 11.85% as Multiracial population. Caregiver ages ranged from 23 to 80 years (M = 40.21, SD = 6.75). See Table 1 for more demographic information.

The range of children's daily screen time is from 0 to 24 hours (M = 3.85, SD = 3.01, *Median* = 3); whereas the range of children's daily non-screen activities time is from 0 to 12.57 hours (M = 1.31, SD = 1.22, *Median* = 1.04). When converting them into SAP scores (M = .71, SD = .23, *Median* = .75), the results showed that 838 children (10%) didn't have non-screen activities (SAP = 1) and only 25 children (0.3%) didn't have screen activities (SAP = 0). The distributions of children's daily screen time, non-screen activities time, and SAP scores are shown in Figure 2 to Figure 4 and their correlation with demographic variables are shown in Table 2.

Association between screen exposure and the fronto-striatal connectivity.

The correlation analysis showed a significant negative correlation between the screen-activity proportion and the fronto-striatal connectivity of first-year data (n = 7881, r = -0.040, 95% $CI^{5,000}$ bootstrap = [-0.0605, -0.0186], BF_{10} = 13.10). As the stronger strength of the fronto-striatal connectivity is considered an index of maturation of the inhibitory control system, the

results suggest that a longer screen exposure time was associated with a underdeveopmental inhibitory control system in the brain (Figure. 5A).

An additional group-level comparison was conducted by comparing the children who had a SAP greater than the 90th percentile (SAP = 1, n = 785) and to the children who had a SAP less than the 10th percentile (SAP < 0.39, n = 788, M_{SAP} = 0.29, SD = 0.07). Results supported that children with higher SAP scores, who were children that only used screen but did not report to have non-screen activity, had a significant weaker fronto-striatal connectivity (Figure 5C in grey; M_{high} = 0.021, M_{low} = 0.027, independent t-test: $t_{(1571)}$ = 3.043, p = 0.002, Cohen's d = 0.153, BF_{10} = 5.487).

Association between screen exposure and the development of fronto-striatal connectivity.

A correlation analysis using the second-year neural data demonstrated a stronger significant negative correlation between the screen-activity proportion and the fronto-striatal connectivity than with the first-year neural data (n = 3711, r = -0.0933, 95% $CI^{50,000}$ bootstrap = [-0.1231, -0.0635], BF_{10} = 428995.74; Figure 5B). In addition, the first year daily screen exposure time prediced the strength change between the first and second year (year 2 minus year 1) (n = 3707, r = -0.0340, 95% $CI^{50,000}$ bootstrap = [-0.0645, -0.0035], BF_{10} = 0.349).

As conducted in the first year data, there was a statistically significant difference in fronto-striatal connectivity between the high SAP group (n = 329) and the low SAP group (n = 382, M_{SAP} = 0.28, SD = 0.08). This strong group effect confirmed again that the longer screen activity is strongly associated with the development of the inhibitory control system in the brain (Figure. 5C in blue; M_{high} = 0.010, M_{low} = 0.024, $t_{(709)}$ = 5.675, p < 0.001, Cohen's d = 0.427, BF_{10} = 439537.31).

Along with the result of the first year neural correlates, the results of the developmental data suggest that a longer screen exposure time may negatively affect the development of the inhibitory control system in the brain.

Bayes factor robustness check for the correlation analyses

Although a conservative stretched beta prior width of 0.3 was used in the present study to reflect the belief of a medium effect size. Robustness checks were applied to make sure the current correlation findings were stable even a different prior was used. As the robustness checks shown in Figure 6, the screen time effect on both the first-year and second-year neural data results were robust. However, the strength change between the first- and the second-year neural data, however, was located in the anecdotal range.

Association between reward sensitivity, screen exposure, and brain.

The pairwise correlations between reward sensitivity trait, screen exposure and inhibitory control imply a mediation relationship among them, such that screen exposure time mediates the relationship between reward sensitivity trait and inhibitory control. However, this possible mediation relationships and progression among children have not been studied. Therefore, it was further hypothesized that screen exposure time mediates the relationship between the BAS score and the strength of the fronto-striatal connectivity.

A bootstrapping mediation analysis was used (Biesanz et al., 2010; Preacher & Hayes, 2008) to test the hypothesis that screen-activity proportion mediates the relationship between the BAS score and the strength of the fronto-striatal connectivity. The results showed that the screen-activity proportion significantly mediated the effect between the BAS score and the second year fronto-striatal connectivity (Figure 7 in blue, indirect effect: $B = -8.190\text{e-}5$, $SE = 1.981\text{e-}5$, $p < 0.001$, 95% $CI^{5,000}$ bootstrap = [-1.243e-4, -4.440e-5]) explaining 28.68% of the

total effect. The results remained significant after controlling for the children's sex, age and family socioeconomic status. This mediation effect was also shown when using the first-year fronto-striatal connectivity (Figure 7 in gray, indirect effect: B = -4.319e-5, SE = 1.229e-5, $p <$ 0.001, 95% $CI^{5,000}$ bootstrap = [-6.591e-5 -2.054e-5]). The results suggest that the screen exposure effect augments the aversive reward sensitivity effect on the inhibitory control network development. The results with nuisance regressors (sex, age, household income, and parental education level) are shown in Table 3.

Association between screen exposure and the subdivisions of the striatum.

In addition to deeming the striatum as a whole, it was also valuable to further examine the screen exposure effect on different striatal regions. Drug seeking and addiction studies showed that there is an activation shift from the ventral (nucleus accumbens, Nacc) to the dorsal striatum (caudate and putamen) along with the behavioral shift from voluntary to habitual drug seeking and then to addiction (Everitt & Robbins, 2013; Zhou et al., 2018). It was suspected that the longer daily screen exposure time was not simply voluntary but close to habitual seeking behavior. The results supported our argument, where a longer screen exposure was more associated with the dorsal striatum especially in the second year, $r_{caudate}$ = -0.0597, 95% $CI^{50,000}$ = [-0.0902, -0.0292], $BF_{10,caudate}$ = 15.738; $r_{putamen}$ = -0.0710, 95% $CI^{50,000}$ = [-0.1010, -0.0414], $BF_{10,putamen}$ = 245.716; r_{Nacc} = -0.0257, 95% $CI^{50,000}$ = [-0.0560, 0.0047], $BF_{10,Nacc}$ = 0.070 (See Figure 8 and Table 4 for more details).

Association between brain and behavioral indices.

Given that the ABCD data did not release the two-year follow up of the ADHD score (instead, the one-year follow up was released), the current analyses only included the first wave

of ADHD score but two waves of SST performences in order to make the logic of analysis consistent.

The correlation analyses showed that there was no significant association between the strength of fronto-striatal connectivities and children's ADHD traits nor significant correlation between the strength of fronto-striatal connectivities and children's performance in the stop signal task (i.e., SSD and SSRT), suggesting that there was no association between the intrinsic neural network activity and inhibitory performences. The detailed values are shown in Table 5.

Discussion

This thesis study examined how daily screen exposure time can influence the inhibitory control network (ICN) in children's brains using the first two years of data from the ABCD study. The results demonstrated that a longer screen exposure time was negatively associated with the strength of the fronto-striatal connectivity. The results further demonstrated that a longer screen exposure time predicts a protracted development of the ICN supported by a negative correlation to the wave2 strength of the fronto-striatal connectivity and the strength change between two waves. Finally, the results showed that a longer screen exposure mediated the effect between the reward sensitivity and the wave2 fronto-striatal connectivity, indicating that a longer screen exposure may augment the aversive reward sensitivity effect on the ICN development. Importantly, this screen exposure effect was more associated with the dorsal striatum, which is involved in habitual seeking behavior, suggesting that the screen exposure effect is similar to addictive effects.

Focusing on the striatum, the core of reward-related processing region, and the frontal executive network, functioning in executive control mechanism (Balleine et al., 2007; Brand et al., 2014), our results extend previous work by showing that the screen exposure effect was not only linked to a single region but can influence the interaction between regions and systems, that is an inverse fronto-striatal connectivity in both cross sectional data and the longitudinal data. Previous screen dependency research paid attention to the striatum and the frontal executive network separately. They showed that the striatum, especially the dorsal striatum (i.e., caudate and putamen in humans), serves a role in screen dependency with its function in reward and addictive processes (Corbit et al., 2012; Everitt et al., 2008; Everitt & Robbins, 2013; Schwendt et al., 2009; Volkow et al., 2006). Studies have also demonstrated that youth with IGD had

volumetric alternation in the striatum (Cai et al., 2016) and patients with internet addiction exhibited less activation in the striatum in a competitive task (Dong et al., 2013) compared to controls, suggesting the reward process changed in the screen dependency group. Moreover, frontal executive networks of the IGD group had a resting within-network connectivity reduction in the FPN (Dong et al., 2015), and lower activation in the DLPFC during inhibitory tasks (Liu et al., 2014) compared to the control group, suggesting that the inhibitory function was impaired in the screen dependency group.

However, for a more comprehensive view, it is better to investigate these two systems together given that they are coupling together structurally and functionally. Between the striatum and the frontal executive network, both DTI and fMRI studies revealed more restricted fiber tracts and increased positive connectivity across development as neural networks become more specialized and efficient in IC (Liston et al., 2006; Rubia et al., 2006). Thus, the negative fronto-striatal connectivity among longer screen exposure users in the current study may, therefore, reflect decreasing sophistication of functional coupling between these networks as the brain matures throughout childhood and adolescence. Although similar exploration in screen-related behaviors has not been reported yet, this view can be supported by substance addiction research. Yuan and Colleague (2017) used both the DTI and functional connectivity techniques to explore the frontostriatal network on smokers. Results showed a negative functional coupling of the fronto-striatal connectivity during smoking cue-induced craving and this coupling was negatively correlated with the fiber tract integrity of fronto-striatal connection. Becker et al. (2017) also reported a decreased fronto-striatal connectivity in alcohol dependent patients relative to healthy controls. Thus, in the same vein, the excessive screen exposure can weaken the development of the fronto-striatal network such that the present study demonstrated that the changes in the

fronto-striatal connectivity exist in the individuals with increased screen dependency. Thus, examining neural responses at the network level can provide an integrated contribution.

Our findings are is congruent with previous findings from resting-state (Becker et al., 2017; Kohno et al., 2014; Motzkin et al., 2014; Wang et al., 2013) and task-based fMRI studies (Becker et al., 2017; Kohno et al., 2014; Yuan et al., 2017) in terms of the detrimental effect of negative fronto-striatal coupling. However, it should be noted that there is contradictory evidence from resting-based studies as well (Hu et al., 2015; Koehler et al., 2013) showing that a longer exposure to addictive stimuli was associated with a positive fronto-striatal connectivity. For example, there was an increased connectivity between ventral striatum and the superior/middle frontal gyrus found in the pathological gambling patients (Koehler et al., 2013) and an increased fronto-striatal connectivity in cocaine addiction patients (Hu et al., 2015). However, given the heterogeneity of study populations and approaches, these inconsistent findings in fronto-striatal coupling are not unexpected. Some of the diverse reports may be due to the distinct addictive behaviors and the status of those behaviors, such as the period of at risk, current dependence, and the period of recovery (Pariyadath et al., 2016). Moreover, differences of the target regions within the frontostriatal circuits may show these seemingly contradictory findings. For instance, the study of Koehler et al. (2013) showed a positive coupling by using the ventral striatum as the region representing the striatum, whereas Wang et al. (2013) showed a negative coupling by employing the caudate, dorsal striatum, to represent the striatum.

Importantly, the current study showed a difference in the connectivity between each subdivision of the striatum and the frontal executive network. Results showed that a longer screen exposure resulted in a more negative dorsal striatum coupling to the frontal executive network relative to the ventral striatum especially in the second-year data. Evidence from both

rodent and human studies have shown a functional shifting from the ventral to the dorsal striatum underlying the voluntary behaviors becoming compulsion, suggesting a dysfunction of the IC (Everitt et al., 2008; Everitt & Robbins, 2013; Zhou et al., 2018). In the rodent model, dopamine release was increased only in the dorsal but not the ventral striatum while rats' cocaine seeking became habitual (Everitt et al., 2008). Similary, a study with cannabis-dependent male using resting-state fMRI showed that the additive group had a lower dorsal striatum connectivity to frontal regions relative to the controls (Zhou et al., 2018). Thus, the finding of stronger association to the dorsal striatum imply the effect of screen exposure is similar to the consequences of the substance use.

The current analyses focused on the screen exposure effect on the striatum and frontoparietal network connectivity. However, there are other regions within the frontostriatal network and may be involved in inhibitory control and possibly be altered by the excessive screen exposure, such as connectivity between the striatum and the ventromedial prefrontal cortex (Kim & Kang, 2018) or between the striatum and the orbitofrontal cortex (Chun et al., 2018). In addition, previous addictive behavior studies suggest that the fronto-limbic system (Lee & Telzer, 2016; van Duijvenvoorde et al., 2016) and the salience network (Vincent et al., 2008) also contribute to inhibitory control. For example, the SN is engaged in the stimuli detection and can switch to couple with the default-mode network (DMN) or the frontoparietal network (FPN) to reflect an appropriate attention configuration (see Uddin et al., 2010 for review). In other words, from SN, the moment-by-moment connectivity changes between different networks may play an important role in enhancing inhibitory control in the brains. Although remaining in the static functional connectivity approach, studies have shown that the interactions between the SN, DMN and excessive networks were disrupted in individuals with substance-use disorder (Liang

et al., 2015; Volkow et al., 2012) and in adolescents with Internet addiction (Wang et al., 2017). These results suggest that the daily excessive screen exposure may also change the switching function of SN. Therefore, further investigation of dynamic functional connectivity between the SN and other networks with a link to excessive screen behavior will increase our understanding of the inhibitory control network in developing brains.

As the COVID-19 pandemic forces virtual experiences to rapidly substitute for a significant proportion of in-person interactions, future research has to pay more attention to the daily screen exposure rather than only focusing on screen-related disorders, such as internet gaming disorder. In fact, children spending considerable time on screen for noneducational content, such as a simple television viewing (David Acevedo-Polakovich et al., 2007; Swing et al., 2010), mobile phone usage (Seo et al., 2016), and active social media use (Du et al., 2019; Ra et al., 2018). These contents have been reported to have deleterious effects on inhibitory control. Fortunately, inhibitory control is malleable by engaging in the tasks that are required to inhibit one's emotions, thoughts, and behaviors in the face of temptations and impulses. For instance, the daily practices on avoiding sweets (Muraven, 2010), forcing exercise (Oaten & Cheng, 2006) and game-based go/nogo program (Liu et al., 2015), have been shown to improve the strength of inhibitory control. Therefore, children should be encouraged to spend more time on such activities to strengthen their inhibitory control.

The present study used the longitudinal data to demonstrate that the daily screen exposure preceded the functional connectivity patterns, suggesting that the screen exposure may affect the development of the ICN and augment the reward-seeking tendency. However, this study can only examine the change at the intrinsic neural network level and fail to find any significant correlation between intrinct neural connectiviy and any behavioral indices. Limited by the

currently released processed data in the ABCD study, it is difficult to gain the processed inhibitory task-based cortical networks to subcortical regions data. In future studies, it will be necessary to examine how daily screen exposure influences the connectivity in the frontostriatal network while the inhibitory processing is activating. Moreover, limited by the heterogeneous nature of the neural data of the ABCD study, the effect sizes represented by *r* of the current study are small. Several ABCD neural correlate studies were reported with a small effect size as the current study (Cheng et al., 2020; Karcher et al., 2019; Paulus et al., 2019; Rosenberg et al., 2020),. To ensure the robustness of the results, the current study applied Bayesian approach and Bootstrap Hypothesis Testing (Dick et al., 2021) to confirm the findings are robust.

Conclusion

In brief, the present thesis study showed that with longer daily screen exposure, the neural coupling between the frontoparietal (frontal executive networks) and the striatum (nucli for reward and addictive process) is decreased in children. This connectivity strength deduction is greater in the second year suggesting that the screen exposure may impair the development of the inhibitory control system in children's brains. Importantly, this daily screen exposure may augment the reward-seeking tendency and the neural consiquences of daily screen exposure were close to impulsive addictive behavior rather than a voluntary use. Given that virtual movement is irreversible in modern and future life, there should be an increase of attention in this research field of daily screen exposure.

References

Achenbach, T. M., & Edelbrock, C. (1991). Child behavior checklist. *Burlington (Vt)*, *7*, 371-392.

Alexander, G. E., DeLong, M. R., & Strick, P. L. (1986). Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annual review of neuroscience*, *9*(1), 357-381.

Allemand, M., Job, V., & Mroczek, D. K. (2019). Self-control development in adolescence predicts love and work in adulthood. *Journal of personality and social psychology*, *117*(3), 621.

Balleine, B. W., Delgado, M. R., & Hikosaka, O. (2007). The role of the dorsal striatum in reward and decision-making. *Journal of Neuroscience*, *27*(31), 8161-8165.

Barch, D. M., Albaugh, M. D., Avenevoli, S., Chang, L., Clark, D. B., Glantz, M. D., . . . Yurgelun-Todd, D. (2018). Demographic, physical and mental health assessments in the adolescent brain and cognitive development study: Rationale and description. *Developmental cognitive neuroscience*, *32*, 55-66.

Becker, A., Kirsch, M., Gerchen, M. F., Kiefer, F., & Kirsch, P. (2017). Striatal activation and frontostriatal connectivity during non-drug reward anticipation in alcohol dependence. *Addiction biology*, *22*(3), 833-843.

Biesanz, J. C., Falk, C. F., & Savalei, V. (2010). Assessing mediational models: Testing and interval estimation for indirect effects. *Multivariate Behavioral Research*, *45*(4), 661-701.

Bissett, P. G., Hagen, M. P., Jones, H. M., & Poldrack, R. A. (2021). Design issues and solutions for stop-signal data from the Adolescent Brain Cognitive Development (ABCD) study. *Elife*, *10*, e60185.

Brand, M., Young, K. S., & Laier, C. (2014). Prefrontal control and Internet addiction: a theoretical model and review of neuropsychological and neuroimaging findings. *Frontiers in human neuroscience*, *8*, 375.

Bruce, F. (2012). Freesurfer. *Neuroimage*, *62*(2), 774-781.

Burton, S., Knibb, G., & Jones, A. (2021). A meta-analytic investigation of the role of reward on inhibitory control. *Quarterly Journal of Experimental Psychology*, 17470218211008895.

Cai, C., Yuan, K., Yin, J., Feng, D., Bi, Y., Li, Y., . . . Tian, J. (2016). Striatum morphometry is associated with cognitive control deficits and symptom severity in internet gaming disorder. *Brain imaging and behavior*, *10*(1), 12-20.

Carlson, S. M., Moses, L. J., & Breton, C. (2002). How specific is the relation between executive function and theory of mind? Contributions of inhibitory control and working memory. *Infant and Child Development: An International Journal of Research and Practice*, *11*(2), 73-92.

Carson, V., Hunter, S., Kuzik, N., Gray, C. E., Poitras, V. J., Chaput, J.-P., . . . Connor Gorber, S. (2016). Systematic review of sedentary behaviour and health indicators in school-aged children and youth: an update. *Applied physiology, nutrition, and metabolism*, *41*(6), S240-S265.

Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: the BIS/BAS scales. *Journal of personality and social psychology*, *67*(2), 319.

Casey, B. (2015). Beyond simple models of self-control to circuit-based accounts of adolescent behavior. *Annual review of psychology*, *66*, 295-319.

Casey, B., Cannonier, T., Conley, M. I., Cohen, A. O., Barch, D. M., Heitzeg, M. M., . . . Garavan, H. (2018). The adolescent brain cognitive development (ABCD) study: imaging acquisition across 21 sites. *Developmental cognitive neuroscience*, *32*, 43-54.

Casey, B., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological psychology*, *54*(1-3), 241-257.

Cheng, W., Rolls, E., Gong, W., Du, J., Zhang, J., Zhang, X.-Y., . . . Feng, J. (2020). Sleep duration, brain structure, and psychiatric and cognitive problems in children. *Molecular psychiatry*, 1-12.

Chun, J.-W., Choi, J., Cho, H., Choi, M.-R., Ahn, K.-J., Choi, J.-S., & Kim, D.-J. (2018). Role of frontostriatal connectivity in adolescents with excessive smartphone use. *Frontiers in psychiatry*, *9*, 437.

Communications, C. o., Media, & MBE. (2016). Media use in school-aged children and adolescents. *Pediatrics*, *138*(5), e20162592.

Corbit, L. H., Nie, H., & Janak, P. H. (2012). Habitual alcohol seeking: time course and the contribution of subregions of the dorsal striatum. *Biological psychiatry*, *72*(5), 389-395.

Coyne, S. M., Warburton, W. A., Essig, L. W., & Stockdale, L. A. (2018). Violent video games, externalizing behavior, and prosocial behavior: A five-year longitudinal study during adolescence. *Developmental psychology*, *54*(10), 1868.

David Acevedo-Polakovich, I., Lorch, E. P., & Milich, R. (2007). Comparing television use and reading in children with ADHD and non-referred children across two age groups. *Media Psychology*, *9*(2), 447-472.

Dick, A. S., Lopez, D. A., Watts, A. L., Heeringa, S., Reuter, C., Bartsch, H., . . . Marshall, A. (2021). Meaningful associations in the adolescent brain cognitive development study. *Neuroimage*, 118262.

Domingues-Montanari, S. (2017). Clinical and psychological effects of excessive screen time on children. *Journal of paediatrics and child health*, *53*(4), 333-338.

Dong, G., Hu, Y., Lin, X., & Lu, Q. (2013). What makes Internet addicts continue playing online even when faced by severe negative consequences? Possible explanations from an fMRI study. *Biological psychology*, *94*(2), 282-289.

Dong, G., Lin, X., & Potenza, M. N. (2015). Decreased functional connectivity in an executive control network is related to impaired executive function in Internet gaming disorder. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *57*, 76-85.

Du, J., Kerkhof, P., & van Koningsbruggen, G. M. (2019). Predictors of social media self-control failure: Immediate gratifications, habitual checking, ubiquity, and notifications. *Cyberpsychology, Behavior, and Social Networking*, *22*(7), 477-485.

Duckworth, A. L., & Kern, M. L. (2011). A meta-analysis of the convergent validity of self-control measures. *Journal of research in personality*, *45*(3), 259-268.

Efron, B., & Tibshirani, R. J. (1994). *An introduction to the bootstrap.* CRC press.

Everitt, B. J., Belin, D., Economidou, D., Pelloux, Y., Dalley, J. W., & Robbins, T. W. (2008). Neural mechanisms underlying the vulnerability to develop compulsive drug-seeking habits and addiction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1507), 3125-3135.

Everitt, B. J., & Robbins, T. W. (2013). From the ventral to the dorsal striatum: devolving views of their roles in drug addiction. *Neuroscience & Biobehavioral Reviews*, *37*(9), 1946-1954.

Fino, E., Melogno, S., Iliceto, P., D'Aliesio, S., Pinto, M. A., Candilera, G., & Sabatello, U. (2014). Executive functions, impulsivity, and inhibitory control in adolescents: A structural equation model. *Advances in Cognitive Psychology*, *10*(2), 32.

Frey, B. S., Benesch, C., & Stutzer, A. (2007). Does watching TV make us happy? *Journal of Economic psychology*, *28*(3), 283-313.

Gentile, D. A., Swing, E. L., Lim, C. G., & Khoo, A. (2012). Video game playing, attention problems, and impulsiveness: Evidence of bidirectional causality. *Psychology of popular media culture*, *1*(1), 62.

Gordon, E. M., Laumann, T. O., Adeyemo, B., Huckins, J. F., Kelley, W. M., & Petersen, S. E. (2016). Generation and evaluation of a cortical area parcellation from resting-state correlations. *Cerebral Cortex*, *26*(1), 288-303.

Haber, S. N. (2016). Corticostriatal circuitry. *Dialogues in clinical neuroscience*, *18*(1), 7.

Hagler Jr, D. J., Hatton, S., Cornejo, M. D., Makowski, C., Fair, D. A., Dick, A. S., . . . Harms, M. P. (2019). Image processing and analysis methods for the Adolescent Brain Cognitive Development Study. *Neuroimage*, *202*, 116091.

Hare, T. A., Camerer, C. F., & Rangel, A. (2009). Self-control in decision-making involves modulation of the vmPFC valuation system. *Science*, *324*(5927), 646-648.

Hayashi, T., Ko, J. H., Strafella, A. P., & Dagher, A. (2013). Dorsolateral prefrontal and orbitofrontal cortex interactions during self-control of cigarette craving. *Proceedings of the national Academy of Sciences*, *110*(11), 4422-4427.

Henze, N., & Zirkler, B. (1990). A class of invariant consistent tests for multivariate normality. *Communications in statistics-Theory and Methods*, *19*(10), 3595-3617.

Hofmann, W., Baumeister, R. F., Förster, G., & Vohs, K. D. (2012). Everyday temptations: an experience sampling study of desire, conflict, and self-control. *Journal of personality and social psychology*, *102*(6), 1318.

Hu, Y., Salmeron, B. J., Gu, H., Stein, E. A., & Yang, Y. (2015). Impaired functional connectivity within and between frontostriatal circuits and its association with compulsive drug use and trait impulsivity in cocaine addiction. *JAMA psychiatry*, *72*(6), 584-592.

Huppertz, C., Bartels, M., de Zeeuw, E. L., van Beijsterveldt, C. E., Hudziak, J. J., Willemsen, G., . . . de Geus, E. J. (2016). Individual differences in exercise behavior: stability and change in genetic and environmental determinants from age 7 to 18. *Behavior Genetics*, *46*(5), 665-679.

JASPTeam. (2021). *JASP (Version 0.16)[Computer software].* In (Version 0.14.1) https://jasp-stats.org/

Johnson, S. L., Turner, R. J., & Iwata, N. (2003). BIS/BAS levels and psychiatric disorder: An epidemiological study. *Journal of psychopathology and behavioral assessment*, *25*(1), 25-36.

Karcher, N. R., O'Brien, K. J., Kandala, S., & Barch, D. M. (2019). Resting-state functional connectivity and psychotic-like experiences in childhood: results from the adolescent brain cognitive development study. *Biological psychiatry*, *86*(1), 7-15.

Kelley, N. J., Kramer, A. M., Young, K. S., Echiverri-Cohen, A. M., Chat, I. K.-Y., Bookheimer, S. Y., . . . Zinbarg, R. E. (2019). Evidence for a general factor of behavioral activation system sensitivity. *Journal of research in personality*, *79*, 30-39.

Kern, M. L., & Friedman, H. S. (2008). Do conscientious individuals live longer? A quantitative review. *Health psychology*, *27*(5), 505.

Kim, J., & Kang, E. (2018). Internet game overuse is associated with an alteration of fronto-striatal functional connectivity during reward feedback processing. *Frontiers in psychiatry*, *9*, 371.

Kim, Y., Jeong, J.-E., Cho, H., Jung, D.-J., Kwak, M., Rho, M. J., . . . Choi, I. Y. (2016). Personality factors predicting smartphone addiction predisposition: Behavioral inhibition and activation systems, impulsivity, and self-control. *PloS one*, *11*(8), e0159788.

Kim-Spoon, J., Deater-Deckard, K., Holmes, C., Lee, J., Chiu, P., & King-Casas, B. (2016). Behavioral and neural inhibitory control moderates the effects of reward sensitivity on adolescent substance use. *Neuropsychologia*, *91*, 318-326.

Koehler, S., Ovadia-Caro, S., van der Meer, E., Villringer, A., Heinz, A., Romanczuk-Seiferth, N., & Margulies, D. S. (2013). Increased functional connectivity between prefrontal cortex and reward system in pathological gambling. *PloS one*, *8*(12), e84565.

Kohno, M., Morales, A. M., Ghahremani, D. G., Hellemann, G., & London, E. D. (2014). Risky decision making, prefrontal cortex, and mesocorticolimbic functional connectivity in methamphetamine dependence. *JAMA psychiatry*, *71*(7), 812-820.

Kühn, S., Romanowski, A., Schilling, C., Lorenz, R., Mörsen, C., Seiferth, N., . . . Büchel, C. (2011). The neural basis of video gaming. *Translational psychiatry*, *1*(11), e53-e53.

Lee, T.-H., & Telzer, E. H. (2016). Negative functional coupling between the right fronto-parietal and limbic resting state networks predicts increased self-control and later substance use onset in adolescence. *Developmental cognitive neuroscience*, *20*, 35-42.

Leh, S. E., Ptito, A., Chakravarty, M. M., & Strafella, A. P. (2007). Fronto-striatal connections in the human brain: a probabilistic diffusion tractography study. *Neuroscience letters*, *419*(2), 113-118.

Li, Q., Wang, Y., Yang, Z., Dai, W., Zheng, Y., Sun, Y., & Liu, X. (2020). Dysfunctional cognitive control and reward processing in adolescents with Internet gaming disorder. *Psychophysiology*, *57*(2), e13469.

Li, Y., Yuan, K., Cai, C., Feng, D., Yin, J., Bi, Y., . . . von Deneen, K. M. (2015). Reduced frontal cortical thickness and increased caudate volume within fronto-striatal circuits in young adult smokers. *Drug and alcohol dependence*, *151*, 211-219.

Liang, X., He, Y., Salmeron, B. J., Gu, H., Stein, E. A., & Yang, Y. (2015). Interactions between the salience and default-mode networks are disrupted in cocaine addiction. *Journal of Neuroscience*, *35*(21), 8081-8090.

Liston, C., Watts, R., Tottenham, N., Davidson, M. C., Niogi, S., Ulug, A. M., & Casey, B. (2006). Frontostriatal microstructure modulates efficient recruitment of cognitive control. *Cerebral Cortex*, *16*(4), 553-560.

Liu, G.-C., Yen, J.-Y., Chen, C.-Y., Yen, C.-F., Chen, C.-S., Lin, W.-C., & Ko, C.-H. (2014). Brain activation for response inhibition under gaming cue distraction in internet gaming disorder. *The Kaohsiung Journal of Medical Sciences*, *30*(1), 43-51.

Liu, Q., Zhu, X., Ziegler, A., & Shi, J. (2015). The effects of inhibitory control training for preschoolers on reasoning ability and neural activity. *Scientific reports*, *5*(1), 1-11.

Logan, G. D. (1994). On the ability to inhibit thought and action: A users' guide to the stop signal paradigm.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological review*, *91*(3), 295.

Logan, G. D., Van Zandt, T., Verbruggen, F., & Wagenmakers, E.-J. (2014). On the ability to inhibit thought and action: general and special theories of an act of control. *Psychological review*, *121*(1), 66.

Lopez, R. B., Courtney, A. L., & Wagner, D. D. (2019). Recruitment of cognitive control regions during effortful self-control is associated with altered brain activity in control and reward systems in dieters during subsequent exposure to food commercials. *PeerJ*, *7*, e6550.

Manly, B. F. & Alberto, J. A. N. (2020). *Randomization, Bootstrap and Monte Carlo Methods in Biology.* CRC press.

Matzke, D. (2014). *Bayesian explorations in mathematical psychology*. Universiteit van Amsterdam [Host].

McBride, D., Barrett, S. P., Kelly, J. T., Aw, A., & Dagher, A. (2006). Effects of expectancy and abstinence on the neural response to smoking cues in cigarette smokers: an fMRI study. *Neuropsychopharmacology*, *31*(12), 2728-2738.

McClure, S. M., Laibson, D. I., Loewenstein, G., & Cohen, J. D. (2004). Separate neural systems value immediate and delayed monetary rewards. *Science*, *306*(5695), 503-507.

Metcalfe, J., & Mischel, W. (1999). A hot/cool-system analysis of delay of gratification: dynamics of willpower. *Psychological review*, *106*(1), 3.

Miller, E., Joseph, S., & Tudway, J. (2004). Assessing the component structure of four self-report measures of impulsivity. *Personality and Individual differences*, *37*(2), 349-358.

Mills, K. L. (2016). Possible effects of internet use on cognitive development in adolescence. *Media and Communication*, *4*(3), 4-12.

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Ross, S. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the national Academy of Sciences*, *108*(7), 2693-2698.

Motzkin, J. C., Baskin-Sommers, A., Newman, J. P., Kiehl, K. A., & Koenigs, M. (2014). Neural correlates of substance abuse: reduced functional connectivity between areas underlying reward and cognitive control. *Human brain mapping*, *35*(9), 4282-4292.

Muraven, M. (2010). Building self-control strength: Practicing self-control leads to improved self-control performance. *Journal of experimental social psychology*, *46*(2), 465-468.

Oaten, M., & Cheng, K. (2006). Longitudinal gains in self-regulation from regular physical exercise. *British journal of health psychology*, *11*(4), 717-733.

Okely, A., Ghersi, D., Loughran, S., Cliff, D., Shilton, T., Jones, R., . . . Eckermann, S. (2019). Australian 24-hour movement guidelines for children and young people (5-17 years): An integration of physical activity, sedentary behaviour and sleep–research report. *Australian Government Department of Health*.

Owens, M. M., Allgaier, N., Hahn, S., Yuan, D., Albaugh, M., Adise, S., . . . Potter, A. (2021). Multimethod investigation of the neurobiological basis of ADHD symptomatology in children aged 9-10: baseline data from the ABCD study. *Translational psychiatry*, *11*(1), 1-11.

Padmanabhan, A., Geier, C. F., Ordaz, S. J., Teslovich, T., & Luna, B. (2011). Developmental changes in brain function underlying the influence of reward processing on inhibitory control. *Developmental cognitive neuroscience*, *1*(4), 517-529.

Pariyadath, V., Gowin, J. L., & Stein, E. A. (2016). Resting state functional connectivity analysis for addiction medicine: from individual loci to complex networks. *Progress in brain research*, *224*, 155-173.

Paulus, M. P., Squeglia, L. M., Bagot, K., Jacobus, J., Kuplicki, R., Breslin, F. J., . . . Bartsch, H. (2019). Screen media activity and brain structure in youth: evidence for diverse structural correlation networks from the ABCD study. *Neuroimage*, *185*, 140-153.

Pernet, C. R., Wilcox, R. R., & Rousselet, G. A. (2013). Robust correlation analyses: false positive and power validation using a new open source matlab toolbox. *Frontiers in psychology*, *3*, 606.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior research methods*, *40*(3), 879-891.

Ra, C. K., Cho, J., Stone, M. D., De La Cerda, J., Goldenson, N. I., Moroney, E., . . . Leventhal, A. M. (2018). Association of digital media use with subsequent symptoms of attention-deficit/hyperactivity disorder among adolescents. *Jama*, *320*(3), 255-263.

Rapoport, J. L., & Gogtay, N. (2008). Brain neuroplasticity in healthy, hyperactive and psychotic children: insights from neuroimaging. *Neuropsychopharmacology*, *33*(1), 181-197.

Rho, M. J., Lee, H., Lee, T.-H., Cho, H., Jung, D. J., Kim, D.-J., & Choi, I. Y. (2018). Risk factors for internet gaming disorder: Psychological factors and internet gaming characteristics. *International journal of environmental research and public health*, *15*(1), 40.

Rosenberg, M. D., Martinez, S. A., Rapuano, K. M., Conley, M. I., Cohen, A. O., Cornejo, M. D., . . . Wager, T. D. (2020). Behavioral and neural signatures of working memory in childhood. *Journal of Neuroscience*, *40*(26), 5090-5104.

Rousselet, G. A., & Pernet, C. R. (2012). Improving standards in brain-behavior correlation analyses. *Frontiers in human neuroscience*, *6*, 119.

Rubia, K., Smith, A. B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., & Brammer, M. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Human brain mapping*, *27*(12), 973-993.

Schlam, T. R., Wilson, N. L., Shoda, Y., Mischel, W., & Ayduk, O. (2013). Preschoolers' delay of gratification predicts their body mass 30 years later. *The Journal of pediatrics*, *162*(1), 90-93.

Schwendt, M., Rocha, A., See, R. E., Pacchioni, A. M., McGinty, J. F., & Kalivas, P. W. (2009). Extended methamphetamine self-administration in rats results in a selective reduction of dopamine transporter levels in the prefrontal cortex and dorsal striatum not accompanied by marked monoaminergic depletion. *Journal of Pharmacology and Experimental Therapeutics*, *331*(2), 555-562.

Seo, D. G., Park, Y., Kim, M. K., & Park, J. (2016). Mobile phone dependency and its impacts on adolescents' social and academic behaviors. *Computers in human behavior*, *63*, 282-292.

Sharif, I., Wills, T. A., & Sargent, J. D. (2010). Effect of visual media use on school performance: a prospective study. *Journal of Adolescent Health*, *46*(1), 52-61.

Shim, H., Lim, S., Jung, E. E., & Shin, E. (2018). I hate binge-watching but I can't help doing it: The moderating effect of immediate gratification and need for cognition on binge-watching attitude-behavior relation. *Telematics and Informatics*, *35*(7), 1971-1979.

Sigman, A. (2017). Screen Dependency Disorders.

Sullivan, G. M., & Feinn, R. (2012). Using effect size—or why the P value is not enough. *Journal of graduate medical education*, *4*(3), 279-282.

SuperAwesome. (2020). *Everyone is a kids and family brand now: Data, observations and recommendations for companies interacting with kids and families during lockdown.* https://www.superawesome.com/everyone-is-a-kids-and-family-brand-now/

Swing, E. L., Gentile, D. A., Anderson, C. A., & Walsh, D. A. (2010). Television and video game exposure and the development of attention problems. *Pediatrics*, *126*(2), 214-221.

Tangney, J. P., Boone, A. L., & Baumeister, R. F. (2018). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Self-regulation and self-control*, 173-212.

Taylor, S. B., Lewis, C. R., & Olive, M. F. (2013). The neurocircuitry of illicit psychostimulant addiction: acute and chronic effects in humans. *Substance abuse and rehabilitation*, *4*, 29.

Tricomi, E., & Fiez, J. A. (2012). Information content and reward processing in the human striatum during performance of a declarative memory task. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(2), 361-372.

Trujillo-Ortiz, A., Hernandez-Walls, R., Barba-Rojo, K., & Cupul-Magana, L. (2007). HZmvntest: Henze-Zirkler's Multivariate Normality Test. *A MATLAB file. URL http://www. mathworks. com/matlabcentral/fileexchange/loadFile. do*.

Tsiros, M. D., Samaras, M. G., Coates, A. M., & Olds, T. (2017). Use-of-time and health-related quality of life in 10-to 13-year-old children: not all screen time or physical activity minutes are the same. *Quality of Life Research*, *26*(11), 3119-3129.

Twenge, J. M., & Campbell, W. K. (2018). Associations between screen time and lower psychological well-being among children and adolescents: Evidence from a population-based study. *Preventive medicine reports*, *12*, 271-283.

Uddin, L. Q., Supekar, K., & Menon, V. (2010). Typical and atypical development of functional human brain networks: insights from resting-state FMRI. *Frontiers in systems neuroscience*, *4*, 21.

van Duijvenvoorde, A. C., Achterberg, M., Braams, B. R., Peters, S., & Crone, E. A. (2016). Testing a dual-systems model of adolescent brain development using resting-state connectivity analyses. *Neuroimage*, *124*, 409-420.

Verdejo-García, A., Lawrence, A. J., & Clark, L. (2008). Impulsivity as a vulnerability marker for substance-use disorders: review of findings from high-risk research, problem gamblers and genetic association studies. *Neuroscience & Biobehavioral Reviews*, *32*(4), 777-810.

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. *Journal of neurophysiology*, *100*(6), 3328-3342.

Volkow, N. D., Wang, G.-J., Fowler, J. S., & Tomasi, D. (2012). Addiction circuitry in the human brain. *Annual review of pharmacology and toxicology*, *52*, 321-336.

Volkow, N. D., Wang, G.-J., Telang, F., Fowler, J. S., Logan, J., Childress, A.-R., . . . Wong, C. (2006). Cocaine cues and dopamine in dorsal striatum: mechanism of craving in cocaine addiction. *Journal of Neuroscience*, *26*(24), 6583-6588.

Wang, L., Shen, H., Lei, Y., Zeng, L.-L., Cao, F., Su, L., . . . Hu, D. (2017). Altered default mode, fronto-parietal and salience networks in adolescents with Internet addiction. *Addictive Behaviors*, *70*, 1-6.

Wang, Y., Zhu, J., Li, Q., Li, W., Wu, N., Zheng, Y., . . . Wang, W. (2013). Altered fronto-striatal and fronto-cerebellar circuits in heroin-dependent individuals: a resting-state FMRI study. *PloS one*, *8*(3), e58098.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental psychology*, *35*(1), 205.

Yager, L. M., Garcia, A. F., Wunsch, A. M., & Ferguson, S. M. (2015). The ins and outs of the striatum: role in drug addiction. *Neuroscience*, *301*, 529-541.

Yen, J. Y., Ko, C. H., Yen, C. F., Chen, C. S., & Chen, C. C. (2009). The association between harmful alcohol use and Internet addiction among college students: comparison of personality. *Psychiatry and clinical neurosciences*, *63*(2), 218-224.

Yuan, K., Yu, D., Bi, Y., Wang, R., Li, M., Zhang, Y., . . . Lu, X. (2017). The left dorsolateral prefrontal cortex and caudate pathway: New evidence for cue-induced craving of smokers. *Human brain mapping*, *38*(9), 4644-4656.

Zhang, F., & Iwaki, S. (2020). Correspondence Between Effective Connections in the Stop-Signal Task and Microstructural Correlations. *Frontiers in human neuroscience*, *14*, 279.

Zhou, F., Zimmermann, K., Xin, F., Scheele, D., Dau, W., Banger, M., . . . Becker, B. (2018). Shifted balance of dorsal versus ventral striatal communication with frontal reward and regulatory regions in cannabis-dependent males. *Human brain mapping*, *39*(12), 5062-5073.

Tables

Table 1. *Demographic table*

	Wave 1	Wave 2
Sample size (*N*)	8,324	3,891
Interview date	09/2016 - 10/2018	07/2018 - 01/2020
Female percentage	49.64%	46.94%
Age (in month)	119.32 (107-133)	143.49 (127-163)
Caregiver's age (in year)	40.21 (23-80)	42.35 (25-82)
Race alone		*(from wave 1 data)*
White	66.61%	71.34%
African American	13.69%	10.80%
Native American[a]	0.46%	0.46%
Asian	1.92%	1.59%
Others	3.99%	3.50%
Multiracial population	11.85%	11.11%
Caregiver's marital status		
Married	70.16%	71.21%
Living with partner	5.22%	5.76%
Others	24.01%	22.39%
Total combined family income[b]		
< $25,000	11.51%	8.30%
$25,000 - $49,999	12.79%	11.03%
$50,000 - $99,999	26.33%	26.25%
$100,000 - $199,999	30.19%	33.68%
>=$200,000	11.37%	13.42%

Refuse to answer or don't know	7.83%	7.30%
Parental Education[c]		*(from wave 1 data)*
<High school diploma	5.55%	4.19%
High school Diploma or GED	9.87%	8.66%
Some college or associate degree	28.23%	28.89%
Bachelor's degree	29.68%	31.90%
Post graduate degree	26.54%	26.22%
Refuse to answer	0.13%	0.13%

All demographic variables were parent-reported. For example, for the race attribute, the question was: "What race do you consider the child to be?."

[a]*Native American included American Indian, Alaska Native, and Native Hawaiian.*

[b]What is your total combined highest income for the past 12 months?

[c]*What is the highest grade or level of school you have completed or the highest degree you have received?*

Table 2. *Simple zero-order correlation (r score) between interested variables and demographic variables without removing outlier.*

	SAP (Wave 1)	Striatum (Wave 1)	Striatum (Wave 2)	BAS
Age	-0.0516	-0.0113	-0.0028	-0.0213
Sex (M=1, F=0)	0.0347	0.0120	0.0187	0.0871
Caregiver's age	-0.1870	0.0026	0.0515	-0.0742
Total combined family income	-0.3786	0.0421	0.0827	-0.1330
Parental Education	-0.3745	0.0459	0.0828	-0.1175

All correlations were matched for wave except for the parental education. BAS: Behavioral approach system. Striatum: FPN-Striatum Connectivity.

Table 3. *The results of Mediation analysis*

	B	***SE***	***p***	***95% CI^{5,000} bootstrap***
Main model (Wave1)				
Indirect effect	-4.319e-5	1.229e-5	< 0.001	[-6.591e-5 -2.054e-5]
Total effect	2.569e-5	7.196e-5	0.721	[-1.163e-4 1.707e-4]
Controlling for sex and age				
Indirect effect	-4.436e-5	1.264e-5	< 0.001	[-6.932e-5 -2.120e-5]
Total effect	1.909e-5	7.516e-5	0.800	[-1.228e-4 1.723e-4]
Controlling for household income				
Indirect effect	-1.443e-5	9.582e-6	0.132	[-3.273e-5 3.336e-6]
Total effect	8.937e-5	7.535e-5	0.236	[-5.849e-5 2.363e-4]
Controlling for parental education				
Indirect effect	-2.180e-5	1.044e-5	0.037	[-4.243e-5 -2.968e-6]
Total effect	6.995e-5	7.521e-5	0.355	[-7.671e-5 2.176e-5]
Main model (Wave2)				
Indirect effect	-8.190e-5	1.981e-5	< 0.001	[-1.243e-4, -4.440e-5]
Total effect	-2.856e-4	1.150e-4	0.004	[-5.178e-4, -4.681e-5]
Controlling for sex and age				
Indirect effect	-6.008e-5	1.463e-5	< 0.001	[-9.068e-5, -3.539e-5]
Total effect	-2.650e-4	9.143e-5	0.004	[-4.442e-4, -9.474e-5]
Controlling for household income				
Indirect effect	-3.155e-5	1.057e-5	0.003	[-5.649e-5, -1.473e-5]
Total effect	-1.934e-4	9.174e-5	0.035	[-3.620e-4, -1.804e-5]
Controlling for parental education				
Indirect effect	-3.629e-5	1.171e-5	0.002	[-6.275e-5, -1.630e-5]
Total effect	-2.072e-4	9.133e-5	0.023	[-3.841e-4, -3.251e-5]

Table 4. *The results of the association between screen exposure and the subdivisions of the striatum connectivities to the frontoparietal network (FPN).*

	r	$CI^{50,000}$ bootstrap	BF_{10}
Wave 1			
Caudate	-0.0273	[-0.0481, -0.0066]	0.535
Putamen	-0.0215	[-0.0423, -0.0004]	0.173
Nucleus Accumbens	-0.0246	[-0.0456, -0.0039]	0.303
Wave 2			
Caudate	-0.0597	[-0.0902, -0.0292]	15.738**
Putamen	-0.0710	[-0.1010, -0.0414]	245.716***
Nucleus Accumbens	-0.0257	[-0.0560, 0.0047]	0.070

Caudate: FPN-Caudate connectivity; Putamen: FPN-Putamen connectivtiy; Nucleus Accumbens: FPN-Nucleus Accumbens connectivity.

** $BF_{10} > 3$;** $BF_{10} > 10$; *** $BF_{10} > 30$.*

Table 5. *The results of the association between screen exposure, brain, and behavioral indices of inhibitory function in r and [CI^{50,000}bootstrap].*

	Striatum (Wave 1)	Striatum (Wave 2)	Striatum Change[a]	SAP
ADHD (Wave 1)	-0.0105 [-0.0343, 0.0134]	-	-	0.0778*** [0.0554, 0.0997]
SSD (Wave 1)	0.0156 [-0.0069, 0.0379]	-	-	-0.0073 [-0.0287, -0.0142]
SSRT (Wave 1)	-0.0247 [-0.0478, -0.0018]	-	-	0.0022 [-0.0194, -0.0238]
SSD (Wave 2)	0.0118 [-0.0206, 0.0446]	-0.0207 [-0.0527, 0.0114]	-0.0228 [-0.0560, 0.0104]	-0.0061 [-0.0386, -0.0261]
SSRT (Wave 2)	-0.0060 [-0.0377, 0.0256]	0.0281 [-0.0073, 0.0627]	0.0233 [-0.0105, 0.0571]	0.0250 [-0.0066, 0.0566]

ADHD: Attention Deficit Hyperactivity Disorder ; Striatum: FPN-Striatum Connectivity; SAP: Screen-Activity Proportion score; SSD: Stop Signal Delay; SSRT: Stop Signal Reaction Time. [a]*Striatum Change: Wave 2 FPN-Striatum Connectivity minus Wave 1 FPN-Striatum Connectivity.*

** BF_{10} > 3;** BF_{10} > 10; *** BF_{10} > 30.*

Figures

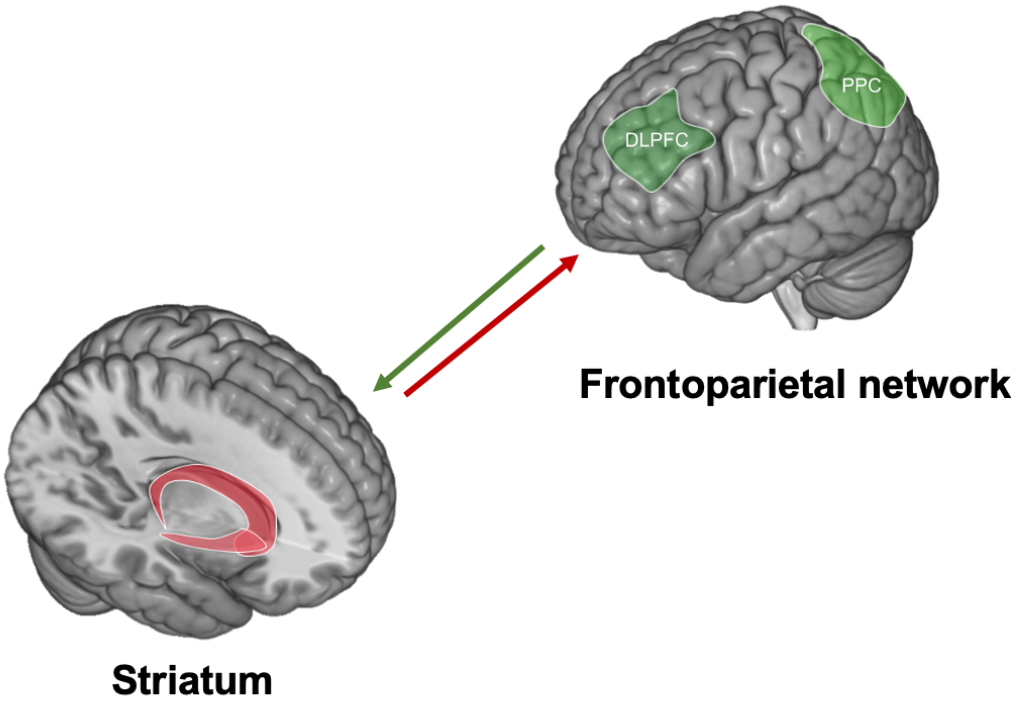

Figure 1. *A schematic view of the relationship between the striatum and the frontoparietal network. The frontoparietal network (FPN) is composed of the dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (PPC). There is a direct biological projection between the striatum (red) and the frontoparietal network (green).*

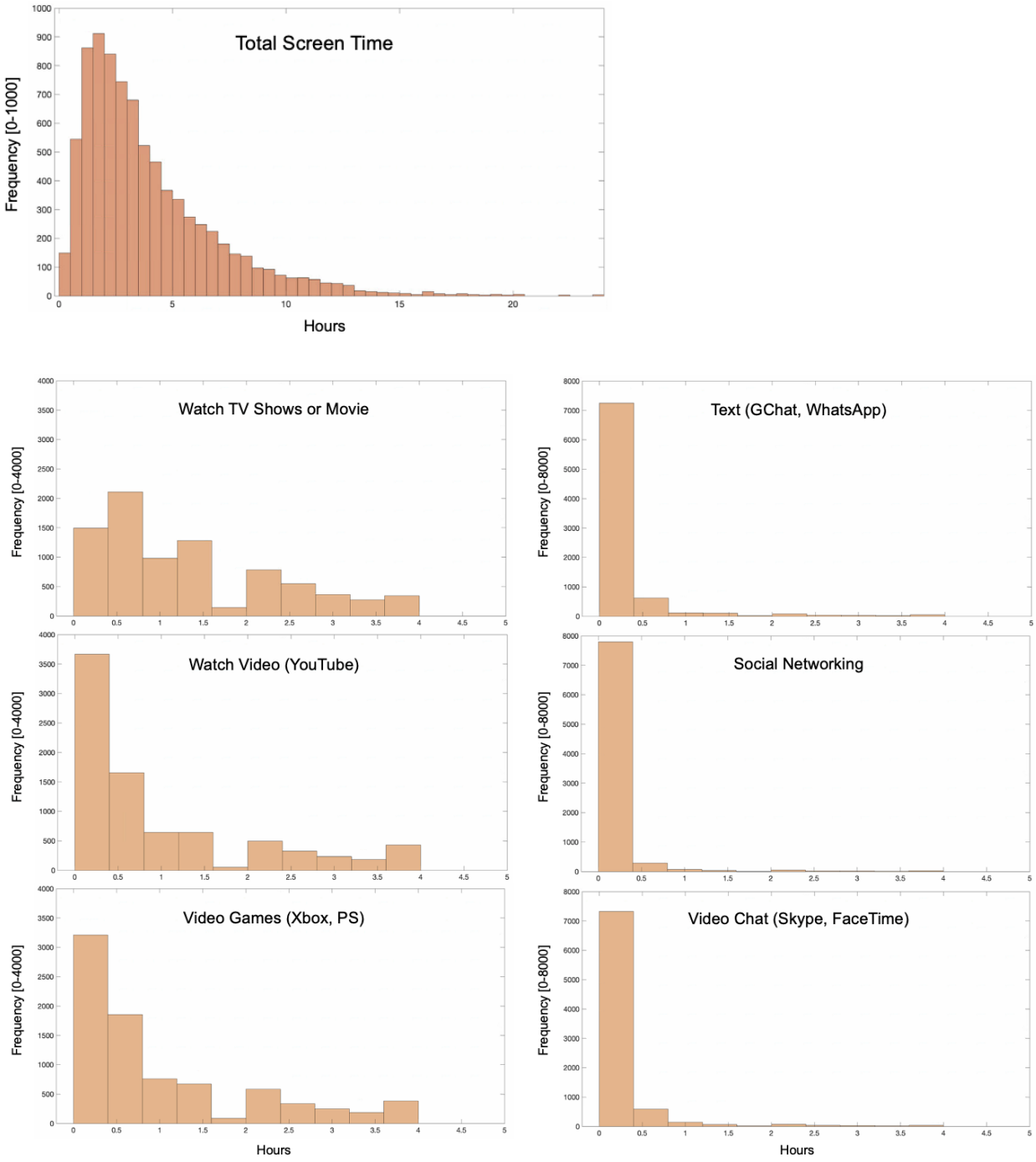

Figure 2. *The distributions of children's total daily screen time and time spent on each subitem.*

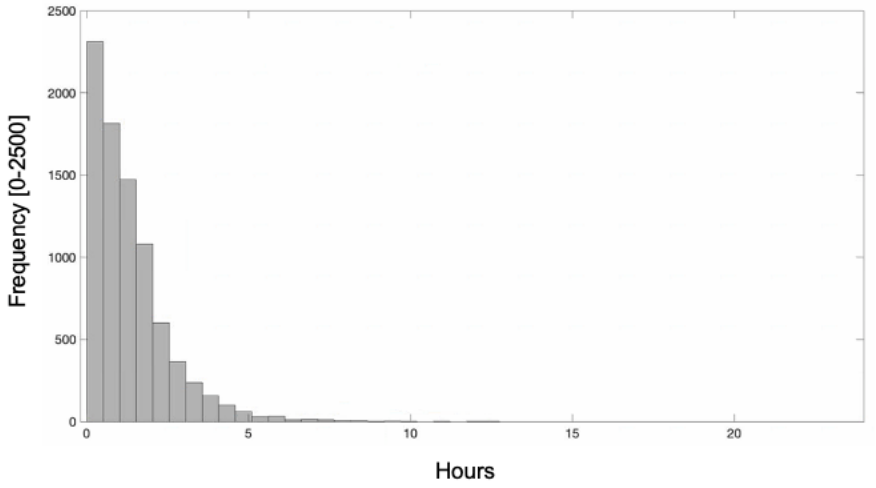

Figure 3. *The distributions of children's total daily non-screen activity time.*

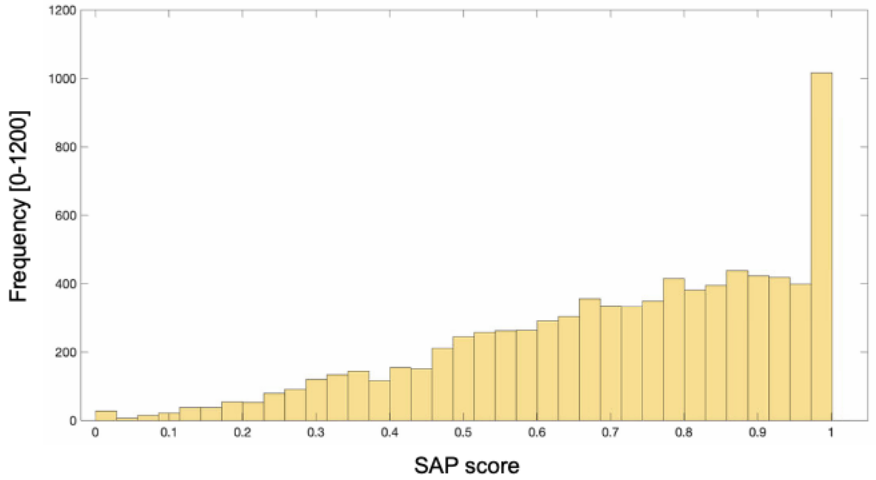

Figure 4. *The distributions of the Screen-Activity Proportion (SAP) score.*

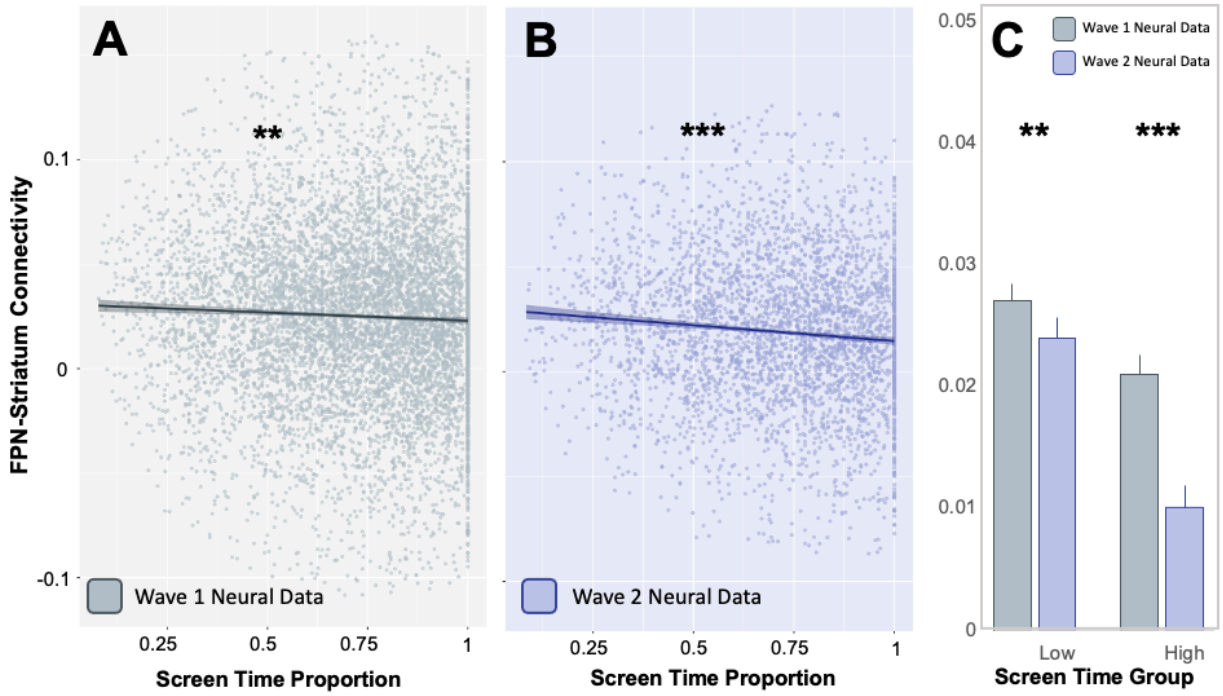

Figure 5. *Correlation results.* ***A:*** *Correlation between the first year Screen-Activity Proportion (SAP) and the FPN-Striatum Connectivity from the first-year neural data.* ***B:*** *Correlation between first year SAP and the FPN-Striatum Connectivity from second-year neural data.* ***C:*** *The group comparisons between high SAP and low SAP in FPN-Striatum Connectivity for both years. * $p < .05$ or $BF_{10} > 3$;** $p < .01$ or $BF_{10} > 10$; *** $p < .001$ or $BF_{10} > 30$.*

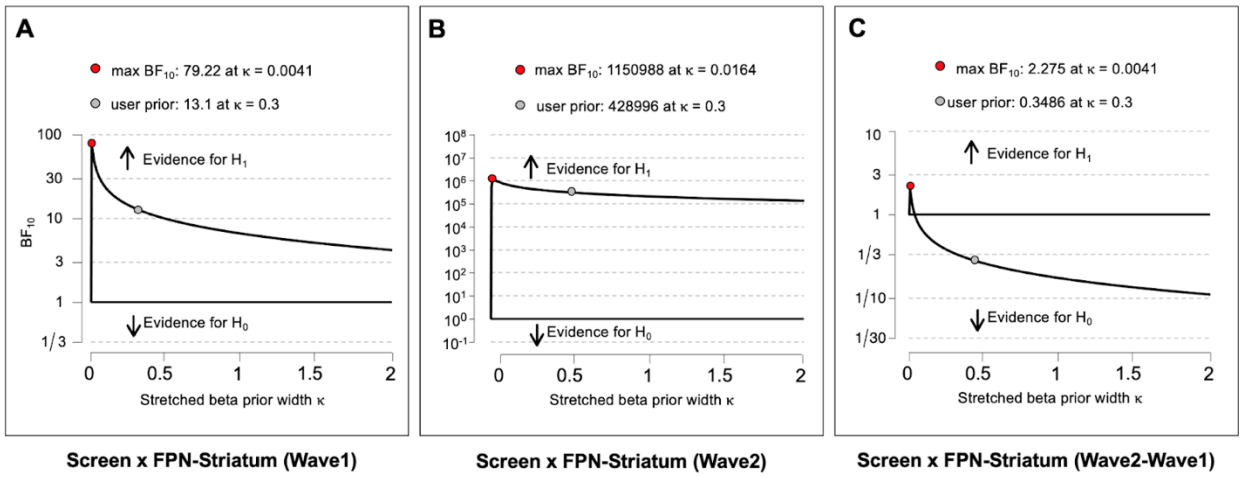

Figure 6. *Robustness check graphs for three basyan examinations.* ***A:*** *Robustness check for correlation between the first year Screen-Activity Proportion (SAP) and the FPN-Striatum Connectivity from the first-year neural data.* ***B:*** *Robustness check for correlation between the first year SAP and the FPN-Striatum Connectivity from the second-year neural data.* ***C:*** *Robustness check for correlation between the first year SAP and the difference between the second-year and first-year FPN-Striatum Connectivity.*

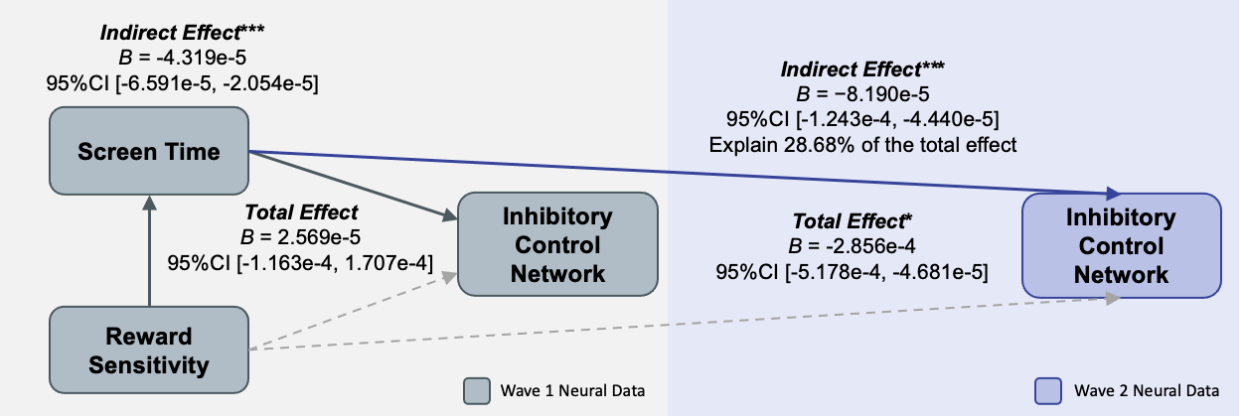

Figure 7. *Mediation results. Association between reward sensitivity (BAS score), screen time (SAP), and the inhibitory control network (FPN-Striatum Connectivity) from the first-year data (in grey) and the second-year data (in blue). * $p < .05$ or $BF_{10} > 3$;** $p < .01$ or $BF_{10} > 10$; *** $p < .001$ or $BF_{10} > 30$.*

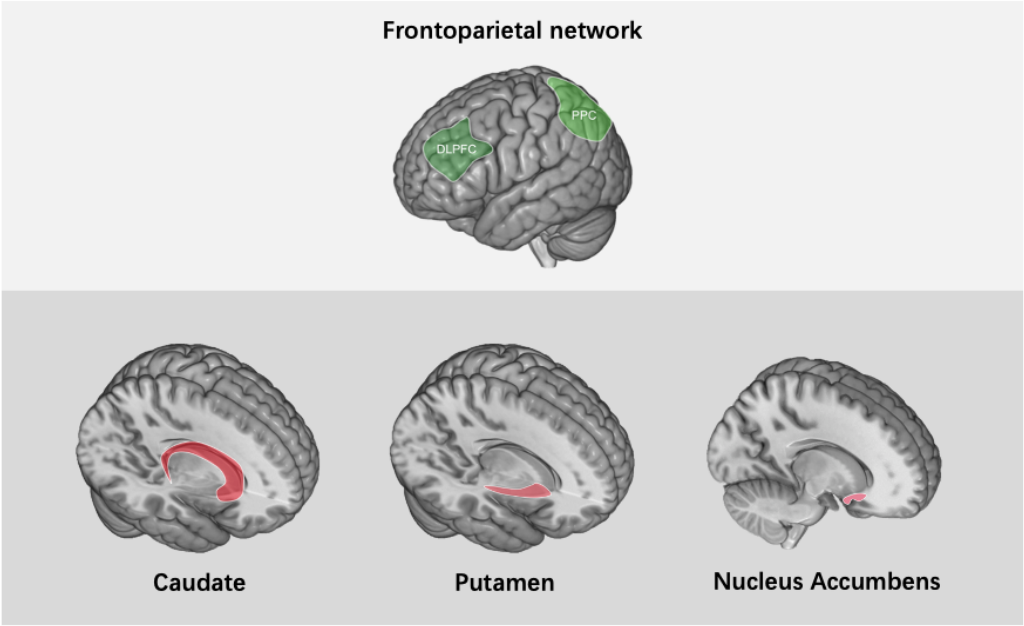

Figure 8. *Illustrations of the ROIs examined in the subdivision connectivity test.*

Appendices

Appendix A. ABCD Youth Screen Time Survey (STQ)

ABCD Youth Screen Time Survey (STQ)

0 = None; .25 = < 30 minutes; 0.5 = 30 minutes; 1 = 1 hour; 2 = 2 hours; 3 = 3 hours; 4 = 4+ hours. **Example: 1½ hours would be coded as 1 hour, rather than 2 hours.**

	Hour(s)						
1. On a typical weekday, how many hours do you: Watch TV shows or movies?	0	.25	0.5	1	2	3	4
2. On a typical weekday, how many hours do you: Watch videos (such as YouTube)?	0	.25	0.5	1	2	3	4
3. On a typical weekday, how many hours do you: Play video games on a computer, console, phone or other device (Xbox, Play Station, iPad)?	0	.25	0.5	1	2	3	4
4. On a typical weekday, how many hours do you: Text on a cell phone, tablet, or computer (e.g. GChat, WhatsApp, etc.)?	0	.25	0.5	1	2	3	4
5. On a typical weekday, how many hours do you: Visit social networking sites like Facebook, Twitter, Instagram, etc.?	0	.25	0.5	1	2	3	4
6. On a typical weekday, how many hours do you: Video chat (Skype, Facetime, etc.)?	0	.25	0.5	1	2	3	4
7. On a typical weekend day, how many hours do you: Watch TV shows or movies?	0	.25	0.5	1	2	3	4
8. On a typical weekend day, how many hours do you: Watch videos (such as YouTube)?	0	.25	0.5	1	2	3	4
9. On a typical weekend day, how many hours do you: Play video games on a computer, console, phone or other device (Xbox, Play Station, iPad)?	0	.25	0.5	1	2	3	4
10. On a typical weekend day, how many hours do you: Text on a cell phone, tablet, or computer (GChat, WhatsApp, etc.)?	0	.25	0.5	1	2	3	4
11. On a typical weekend day, how many hours do you: Visit social networking sites like Facebook, Twitter, Instagram, etc.?	0	.25	0.5	1	2	3	4
12. On a typical weekend day, how many hours do you: Video chat (Skype, Facetime, etc.)?	0	.25	0.5	1	2	3	4
13. How often do you play mature-rated video games (e.g., Call of Duty, Grand Theft Auto, Assassin's Creed, etc.)?	0	.25	0.5	1	2	3	4
14. How often do you watch R-rated movies?	0	.25	0.5	1	2	3	4

Appendix B. ABCD Summary Scores Sports Activity

ABCD Summary Scores Sports Activity

During the most active period, about how many months per year did your child participate?
Fill in 0 ; 1 ; 2 ; 3 ; 4 ; 5 ; 6 ; 7 ; 8 ; 9 ; 10 ; 11 ; 12
About how many days per week?
Fill in 0 ; 1 ; 2 ; 3 ; 4 ; 5 ; 6 ; 7 ; 8 ; 9 ; 10,
8 = Once every 2 weeks; 9 = One day every month; 10 = Less than one day per month
About how many minutes per session?
Fill in 0 ; 1 ; 2 ; 3 ; 4 ; 5 ; 6 ; 7 ; 8 ; 9
0 = 0; 1 = less than 30 minutes; 2 = 30; 3 = 45; 4 = 60 (1 hr); 5 = 90 (1.5 hrs); 6 = 120 (2 hrs); 7 = 150 (2.5 hrs); 8 = 180 (3 hrs); 9 = greater than 3 hours

Activity	During the most active period, about how many months per year did your child participate?	About how many days per week?	About how many minutes per session?
Ballet, Dance			
Baseball, Softball			
Basketball			
Climbing			
Field Hockey			
Football			
Gymnastics			
Ice Hockey			
Horseback Riding, Polo			
Ice or Inline Skating			
Martial Arts			
Lacrosse			
Rugby			
Skateboarding			
Skiing, Snowboarding			
Soccer			
Surfing			
Swimming, Water Polo			

Activity	During the most active period, about how many months per year did your child participate?	About how many days per week?	About how many minutes per session?
Tennis			
Track, Running, Cross-country			
Wresting, Mixed Martial Arts			
Volleyball			
Yoga, Tai Chi			
Musical Instrument			
Drawing, Painting, Graphic Art, Photography, Pottery, Sculpting			
Crafts like Knitting, Building Model Cars or Airplanes			
Competitive Games like Chess, Cards, or Darts			
Hobbies like collecting stamps or coins			

Appendix C. BIS/BAS

BIS/BAS

Each item of this questionnaire is a statement that a person may either agree with or disagree with. For each item, indicate how much you agree or disagree with what the item says. Please respond to all the items; do not leave any blank. Choose only one response to each statement. Please be as accurate and honest as you can be. Respond to each item as if it were the only item. That is, don't worry about being "consistent" in your responses.

	Very true for me	Somewhat true for me	Somewhat false for me	Very false for me
1. Even if something bad is about to happen to me, I rarely experience fear or nervousness.	1	2	3	4
2. I go out of my way to get things I want.	1	2	3	4
3. When I'm doing well at something I love to keep at it.	1	2	3	4
4. I'm always willing to try something new if I think it will be fun.	1	2	3	4
5. When I get something I want, I feel excited and energized.	1	2	3	4
6. Criticism or scolding hurts me quite a bit.	1	2	3	4
7. When I want something I usually go all-out to get it.	1	2	3	4
8. I will often do things for no other reason than that they might be fun.	1	2	3	4
9. If I see a chance to get something I want I move on it right away.	1	2	3	4
10. I feel pretty worried or upset when I think or know somebody is angry at me.	1	2	3	4
11. When I see an opportunity for something I like I get excited right away.	1	2	3	4
12. I often act on the spur of the moment.	1	2	3	4
13. If I think something unpleasant is going to happen I usually get pretty "worked up."	1	2	3	4
14. When good things happen to me, it affects me strongly.	1	2	3	4
15. I feel worried when I think I have done poorly at something important.	1	2	3	4
16. I crave excitement and new sensations.	1	2	3	4
17. When I go after something I use a "no holds barred" approach.	1	2	3	4
18. I have very few fears compared to my friends.	1	2	3	4
19. It would excite me to win a contest.	1	2	3	4
20. I worry about making mistakes.	1	2	3	4

Appendix D. IRB Approval Letter

VIRGINIA TECH

Division of Scholarly Integrity and Research Compliance
Institutional Review Board
North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
http://www.research.vt.edu/sirc/hrpp

MEMORANDUM

DATE: September 22, 2021

TO: Tae-Ho Lee, Tai-Jung Chen, Joshua Neal, Ya-Yun Chen

FROM: Virginia Tech Institutional Review Board (FWA00000572)

PROTOCOL TITLE: Big data and small brain: Functional connectivity analysis using open-source big dataset for adolescent brain

IRB NUMBER: **18-769**

Thank you for your submission. The Virginia Tech Human Research Protection Program (HRPP), has received and reviewed your Progress Report.

Your next Progress Report will be due on Aug 31, 2024. You will receive automated reminders through the IRB Protocol Management online system.

If your study is complete before then and is eligible to be reported as Closed, please proceed to close the study by accessing the appropriate link in Virginia Tech's IRB Protocol Management online system. If you have any questions or require any additional information, please contact the protocol coordinator that has been assigned to the protocol. If a coordinator has not been assigned, please contact irb@vt.edu for assistance.

Appendix E. Data Availability

Source Data: https://osf.io/z9dcp/?view_only=bb229c96747a4213ad36ada37651ec28