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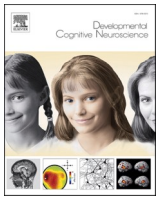

Negative impact of daily screen use on inhibitory control network in preadolescence: A two-year follow-up study

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ABSTRACT

The COVID-19 pandemic has made an unprecedented shift in children's daily lives. Children are increasingly spending time with screens to learn and connect with others. As the online environment rapidly substitutes in-person experience, understanding children's neuropsychological trajectories associated with screen experiences is important. Previous findings suggest that excessive screen use can lead children to prefer more immediate rewards over delayed outcomes. We hypothesized that increased screen time delays a child's development of inhibitory control system in the brain (i.e., fronto-striatal circuitry). By analyzing neuropsychological data from 8324 children (9–11ys) from the ABCD Study, we found that children who had more screen time showed a higher reward orientation and weaker fronto-striatal connectivity. Importantly, we found that the daily screen exposure mediated the effect of reward sensitivity on the development of the inhibitory control system in the brain over a two year period. These findings suggest possible negative long-term impacts of increased daily screen time on children's neuropsychological development. The results further demonstrated that screen time influences dorsal striatum connectivity, which suggests that the effect of daily screen use is a habitual seeking behavior. The study provides neural and behavioral evidence for the negative impact of daily screen use on developing children.

1. Introduction

Childhood is a critical period for the development of inhibitory control (IC) (Williams et al., 1999), where the ability to resist impulsive behaviors (Carlson et al., 2002; Duckworth and Kern, 2011) and focus on long-term goals undergoes significant changes along with the associated neural circuits (Padmanabhan et al., 2011). Studies have demonstrated the negative impact of excessive screen exposure on the development of children's inhibitory control (Carson et al., 2016; Domingues-Montanari, 2017; Twenge and Campbell, 2018) by highlighting the nature of the screen platform, which often offers immediate benefits with negligible costs (Frey et al., 2007). For example, most screen platforms allow users to pause and skip sessions that they are less interested in and select content that they enjoy more. This increased accessibility to information allows children to pursue immediate rewards and feedback (Tricomi and Fiez, 2012), and, in turn, this increased reward-seeking tendency may further weaken IC development (Burton et al., 2021).

Although social organizations and governments offer guidelines to limit screen time for school-age children to mitigate its negative effects (Communications, C. o., Media, and MBE, 2016; Okely et al., 2019), the average use of screen time entertainment for children is continuously increasing (Tsiros et al., 2017; Twenge and Campbell, 2018), and has been amplified since the COVID-19 pandemic. For example, screen exposure time has been escalated by at least 50% as virtual experiences replaced in-person interactions during the period of the Stay-at-Home Order (SuperAwesome, 2020).

Recent evidence suggests that the underlying neural mechanisms linked to the failure of IC may be associated with the imbalance between the executive networks and the regions involved in reward-related processing (e.g., amygdala, striatum, ventral tegmental area) (Casey, 2015; Lee and Telzer, 2016; McClure et al., 2004; Metcalfe and Mischel, 1999). Although non-clinical daily screen behaviors are understudied, research on screen dependency disorders (SDD) with various age groups (from children aged 5–11, adolescents aged 9–17, to college-aged young adults) suggests that the regions involved in reward-related processing

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and central executive networks that may be affected by daily screen behaviors are the striatum and the frontoparietal network (FPN) (Balleine et al., 2007; Brand et al., 2014).

The striatum, consisting of the caudate, putamen, and ventral striatum, integrates input from the brainstem and various subcortical and cortical regions. It plays a role 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 and 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) showed that the metabolism in the striatum was decreased when individuals with cocaine addiction saw a 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) showed that young adult 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). When compared volumetrically, increased striatal volume was found in young adult smokers compared to nonsmokers (Li et al., 2015) and in young adults with SDD (Cai et al., 2016). Developmentally, it has been reported that adolescents who play computer games excessively have greater gray matter volume and higher 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 reward processing and screen dependency.

The FPN, primarily comprised of the dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (Uddin et al., 2019), and its DLPFC node have been extensively investigated in the context of inhibitory control and dependency behaviors as it plays a role in executive and regulatory processes in the brain (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) conducted an elegant two-session study and found that the dieters who had 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 their diets were broken (Lopez et al., 2019). Studies on screen dependency disorders (SDD) have also reported dysfunctions in the DLPFC and FPN in young adults with SDD during both resting-state and task-based scans (Dong et al., 2015; Liu et al., 2014). During inhibitory tasks, the SDD group exhibited lower inhibition efficiency with lower activation and connectivity in the FPN regulatory regions, compared to the control group, suggesting that the inhibitory function was impaired in the disorder group. Consistently, using the resting-state functional connectivity approach, studies have also reported that the SDD group showed a greater reduction in within-network connectivity in the 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. Taken together, these studies suggest that the function of the FPN is crucial for one's control ability during reward-related processing and is also related to screen use.

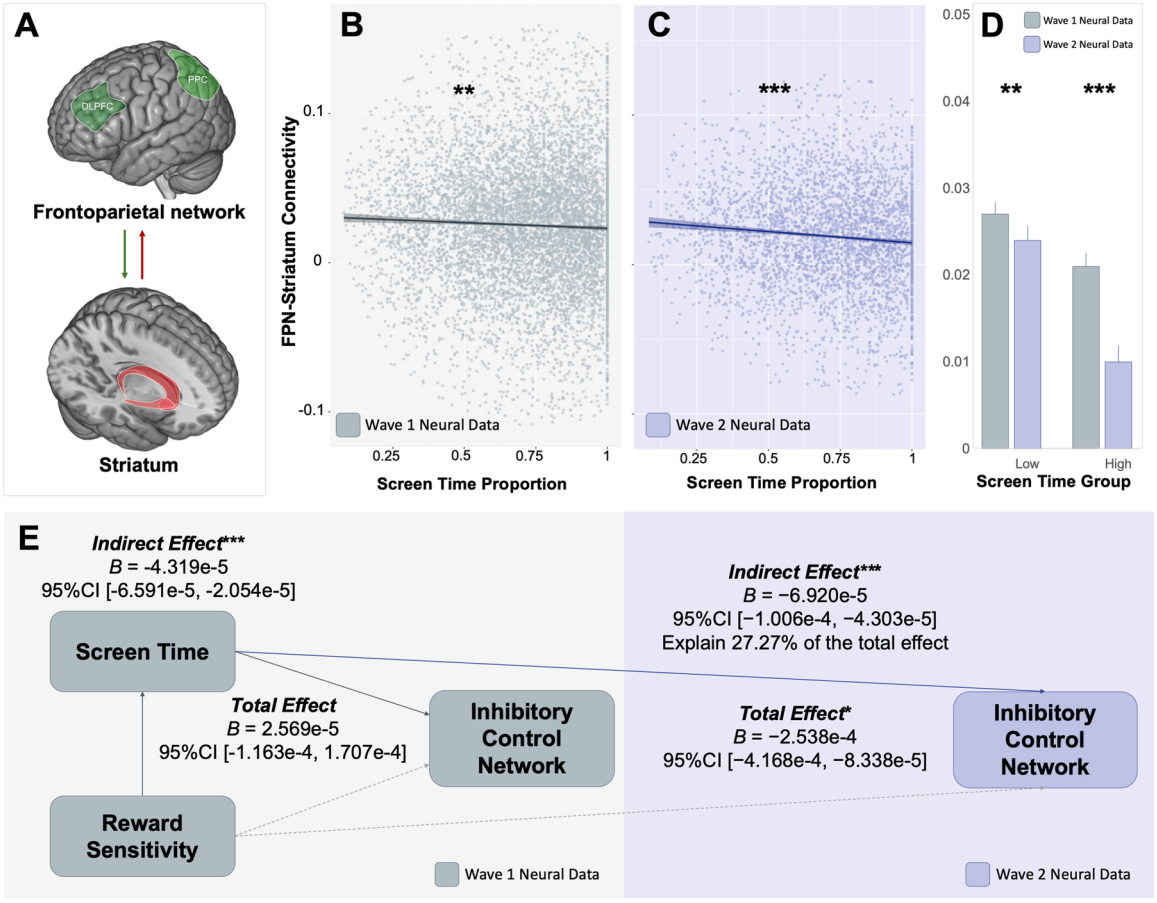

Fig. 1. *Associations between screen exposure, brain, and reward sensitivity.* A: Illustrations of the ROIs examined. B: Correlation between the baseline year Screen-Activity Proportion (SAP) and the FPN-Striatum Connectivity from the baseline year neural data. C: Correlation between the baseline year SAP and the FPN-Striatum Connectivity from the year 2 neural data. D: The group comparisons between high SAP and low SAP in FPN-Striatum Connectivity for both years. E: Association between reward sensitivity (BAS score), screen time (SAP), and the inhibitory control network (FPN-Striatum Connectivity) from the baseline data (in grey) and the year 2 data (in blue). * $p < 0.05$ or $BF_{10} > 3$;** $p < 0.01$ or $BF_{10} > 10$; *** $p < 0.001$ or $BF_{10} > 30$.

Although the critical role of a particular brain region, such as the FPN, DLPFC, or striatum, in inhibitory control processing has been extensively investigated as a single region or network, recent studies highlight the importance of neural connectivity in inhibitory processing at the level of large-scale brain systems. In particular, recent neural circuitry research from both animal and human studies suggests that it is more comprehensive to consider the between-network neural connectivity as a system (Fig. 1A). The FPN and the striatum can also be viewed from a brain-systems level, as they are structurally and functionally interconnected, being part of the fronto-striatal circuit, serving inhibitory control through the DLPFC node (Alexander et al., 1986; Haber, 2016; Leh et al., 2007; Rubia et al., 2006; Sigman, 2017; Zhang and Iwaki, 2020). For example, functional MRI (fMRI) studies using various task-based indices have demonstrated a progressive maturation for IC functions within the fronto-striatal circuitry, with the level of activation in the circuitry increasing along with inhibition efficiency across development (Rubia et al., 2006). The findings suggest that the neural maturation of IC can be assessed by measuring functional coupling between the FPN and the striatum, and that these regions should be considered together when investigating IC.

Given previous evidence indicating that the maturation of the brain can be indexed by the degree of functional coupling between the FPN 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 present study is to delineate how daily screen exposure time influences the development of the intrinsic neurocircuitry that underlies IC (i.e., fronto-stratal circuitry, FPN-striatum) in children. To achieve this, we used the baseline and post-baseline year 2 follow-up 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 frontoparietal network and the striatum. We hypothesized that (1) there would be an alteration in the fronto-striatal connectivity in children with longer daily screen exposure time, and (2) the daily screen exposure time in the baseline year (year of enrollment) would predict the strength of fronto-striatal connectivity in year 2 (i.e., post-baseline year 2 follow-up) as well as the change in strength between the two waves. In addition to the effect of daily screen exposure time in the inhibitory control network. Furthermore, the present study also explored (3) how reward sensitivity affects the development of the inhibitory neural circuitry (Johnson et al., 2003; Kim et al., 2016; Kim-Spoon et al., 2016; Miller et al., 2004) as children become more exposed to screens.

2. Materials and methods

2.1. Participants and data preprocessing

The current study utilized data from the Adolescent Brain Cognitive Development (ABCD) Data Repository (https://abcdstudy.org), which tracks 11,878 individuals aged 9–11 years from 21 data collection sites across the United States (Casey et al., 2018). The dataset was obtained from the ABCD 2.0 release from the NIH Data Archive (NDA, https://nda.nih.gov/) in November 2020. The present study included the ABCD Youth Screen Time Survey (STQ, *abcd_stq01*), the Sports and Activities Survey (*abcd_spacss01*), the ABCD Youth Behavioral Inhibition/Behavioral Approach System Scales (*abcd_bisbas01*), and the MRI-related measures include the processed resting-state fMRI data (ABCD rsfMRI Network to Subcortical ROI Correlations, *mrirscor02*). The final sample size after removing missing values was 8324 for the baseline year (interview date: 09/2016–10/2018) and 3891 for the year 2 follow-up (interview date: 07/2018–01/2020). The children in the sample were between the ages of 108–131 months old ($M = 119.28$, $SD = 7.47$) in the baseline year, with 49.65% of them being female. The majority of children were identified as White (76.99%), followed by African American (18.69%), and Others (4.32%). The ages of caregivers ranged from 23 to 80 years ($M = 40.21$, $SD = 6.75$). Further demographic information can be found in Table S1.

2.2. Demographic and behavioral data

2.2.1. Demographics survey

The demographic information was collected through a parent-report questionnaire, in which caregivers reported the race and gender of both themselves and their child, family structure, socioeconomic status (SES, based on total household income), education level, and religious beliefs. The results of this survey can be found in Table S1.

2.2.2. Screen time assessment

Screen time was measured using a child self-report questionnaire 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 min; 0.5 = 30 min; 1 = 1 h; 2 = 2 h; 3 = 3 h; and 4 = 4 + hours. Additionally, the questionnaire included two items related to the experiences in playing mature-rated video games and watching R-rated movies. Daily average screen time was calculated by averaging the sum of weekday screen time and the sum of weekend time.

2.2.3. Non-screen activities time assessment

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. The parents reported the number of years, months per year, days per week, and minutes per session that their child spent on each activity. The activities time data was processed in two steps: missing value imputation and final score calculation.

The data set had several missing values for various types of activity which were dispersed amongst participants. When discarding individuals with missing values, 2075 samples (25%) had to be removed. Thus, to handle the missing values in the data set, the following treatment rules were applied: 1) for missing values of the number of days per week spent on an activity, those data points with the same number on months per year were taken to calculate the median of days per week. This median number was used to replace the missing values. For example, in the case of soccer, if the number of days per week is missing and the number of months per year is 2, then all other data points where soccer is played for 2 months per year will be considered and the median of the number of days per week for these data will be calculated. This median score would be put into the cell of missing value. 2) for missing values of the number of minutes per session, all data points with the same number of months per year were taken to calculate the median score of minutes per session for missing value imputation.

After treating the missing values, since the scale of the survey was different from the scale of the screen time survey, the daily average activity time was calculated by: 1) converting the minutes per session of each type of activity to hours per session; 2) multiplying the hours per session and days per week of that activity, and dividing the result by seven. This was done for each type of activity; and then 3) all the activity times were added up to get the total daily average activity time.

2.2.4. Screen-activity proportion score

In the examinations, the non-screen activities time was used to control the screen exposure time by the following calculation:

$$SAPscore = \frac{DailyScreenTime}{DailyScreenTime + DailyActivityTime}$$

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

2.2.5. Behavioral inhibition/behavioral activation system (BIS/BAS) scales

Carver and White (Carver and White, 1994) suggested two motivation systems, the behavioral inhibition system (BIS) and the behavioral activation system (BAS). 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. To examine the relationship between individual behavioral traits in reward sensitivity, the degree of screen time exposure, and neural development, we included BAS scores, provided by the ABCD dataset. 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, we used the sum of the three BAS subscales (i.e., BAS Total), as an indicator of overall reward sensitivity (Kelley et al., 2019).

2.3. Neuroimaging data

2.3.1. Imaging protocol

The ABCD imaging protocol was integrated from three 3 T scanner platforms (i.e., Siemens Prisma [66.87%], General Electric/GE 750 [20.48%], and Philips [18.06%]), which used standard adult-size multichannel coils that are capable of multiband echo-planar imaging (EPI) acquisitions with repetition time (TR) = 0.8 s, voxel size = 2.4 mm isotropic, 60 slices, field of view (FoV) = 216 × 216 mm, echo time (TE) = 30 ms, flip angle = 52 degrees. The twenty minutes resting-state data was acquired with eyes open and passive viewing of a crosshair. Briefly, the resting-state data was processed with motion correction, B0 distortion correction, resampled to isotropic, rigidly coregistered to the structural image, and spatially normalized. Additional details about the scanning protocols and motion correction processing can be found in Casey et al. (2018) and Hagler et al. (2019).

2.3.2. 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 were extracted by the Gordon parcellation approach (Gordon et al., 2016). More information on the MRI processing pipeline and ROI extraction can be found in Hagler et al. (2019). For the present study, the values representing the strength of the frontoparietal network (FPN) to striatum connectivity (Fig. 1A) were generated by averaging the connectivity values of the FPN to bilateral caudate, FPN to bilateral putamen, and FPN to bilateral accumbens.

2.4. Data analysis

Given the heterogeneous nature of the neural data of the ABCD study, the effect sizes represented by correlation coefficient (r) in the current study are relatively small. This is in line with previous ABCD neural correlate studies that have also reported small effect sizes (e.g., Cheng et al., 2020; Karcher et al., 2019; Paulus et al., 2019; Rosenberg et al., 2020). To ensure the robustness of the brain-behavior effect (Marek et al., 2022), the current study applied both Bayesian and Bootstrap Hypothesis Testing approaches (Dick et al., 2021) to ensure the robustness of the results.

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 (bootstrapping and permutation) techniques, ordinary least squares (OLS) models can be used without meeting assumptions of normality and homoscedasticity (Efron and Tibshirani, 1994; Manly, 2006). The statistical results from both Frequentist (i.e., p-value) and Bayesian approaches were reported. Bayesian approaches are able to evaluate the relative plausibility of the alternative hypothesis (H_1) and the null hypothesis (H_0) at the same time, 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 and Feinn, 2012). We used Bayes factors (BF_{10}) 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). In the Bayesian test, due to previous ABCD neural correlate studies reporting significant results with small effect sizes (r's ranging from 0.037 to 0.07) (Cheng et al., 2020; Karcher et al., 2019; Paulus et al., 2019; Rosenberg et al., 2020), a conservative stretched beta prior width of 0.3 was set in the present study to reflect the belief of a medium effect size.

3. Results

3.1. Association between screen exposure and fronto-striatal connectivity

The results of the correlation analysis showed a significant negative association between the Screen-Activity Proportion (SAP) and the fronto-striatal connectivity in the baseline year ($r = -0.040$, 95% $CI^{50,000}$ bootstrap = [−0.0605, −0.0186], $BF_{10} = 13.10$). As the strength of the fronto-striatal connectivity is considered to reflect the maturation quality of the inhibitory control system (Rubia et al., 2006), the results suggest that a longer screen exposure time was significantly associated with the underdevelopment of the inhibitory control system in the brain (Fig. 1B).

The additional results from the group-level comparison between children with an SAP greater than the 90th percentile (SAP = 1, $N = 785$) and children with an SAP less than the 10th percentile (SAP < 0.39, $N = 788$, $M_{SAP} = 0.29$, $SD = 0.07$) confirmed that children with longer screen time had significantly lower fronto-striatal connectivity, compared to children with shorter screen time (Fig. 1D in grey; $M_{high} = 0.021$, $M_{low} = 0.027$, independent t-test: $t_{(1571)} = 3.043$, $p = 0.002$, Cohen's $d = 0.153$, $BF_{10} = 5.487$).

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

The results of a correlation analysis using the year 2 neural data showed a stronger and significantly negative association between the SAP and the fronto-striatal connectivity than with the baseline neural data ($r = -0.0933$, 95% $CI^{50,000}$ bootstrap = [−0.1231, −0.0635], $BF_{10} = 428995.74$; Fig. 1C). In addition, the daily screen exposure time during the baseline year was found to predict changes in connectivity strength between the baseline and year 2 (year 2 minus baseline) ($r = -0.0340$, 95% $CI^{50,000}$ bootstrap = [−0.0645, −0.0035], $BF_{10} = 0.349$), although these changes in connectivity strength were not as robust as when examining baseline and year 2 separately (See Supplemental Materials *Section B* for more details on the Bayes Factor Robustness Check).

As was conducted in the analysis using baseline data, there was a statistically significant difference in fronto-striatal connectivity between the high SAP group ($N = 329$) and the low SAP group ($N = 382$, $M_{SAP} = 0.28$, $SD = 0.08$) in the year 2 data. The group effect confirmed that the longer screen activity is associated with a delayed development of the inhibitory control system in the brain (Fig. 1D 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 baseline 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.

3.3. Association between reward sensitivity, screen exposure, and the brain

The pairwise correlations between reward sensitivity trait, screen exposure, and inhibitory control (Table S4) imply that screen exposure time may mediate the relationship between trait reward sensitivity and inhibitory control. Therefore, we 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 and 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 SAP significantly mediated the effect between the BAS score and the year 2 fronto-striatal connectivity (indirect effect: $B = -6.920e\text{-}5$, $SE = 1.504e\text{-}5$, $p < 0.001$, 95% CI^{5000} bootstrap = [−1.006e-4, −4.303e-5]; total effect: $B = -2.538e\text{-}4$, $SE = 8.746e\text{-}5$, $p = 0.004$, 95% CI^{5000} bootstrap = [−4.168e-4, −8.338e-5]), explaining 27.27% of the total effect. This mediation effect was also shown when using the baseline fronto-striatal connectivity (indirect effect: $B = -4.319e\text{-}5$, $SE = 1.229e\text{-}5$, $p < 0.001$, 95% CI^{5000} bootstrap = [−6.591e-5 −2.054e-5]; total effect: $B = 2.569e\text{-}5$, $SE = 7.196e\text{-}5$, $p = 0.721$, 95% CI^{5000} bootstrap = [−1.163e-4 1.707e-4]). The results suggest that the effect of screen exposure amplifies the negative impact of reward-seeking tendencies on the development of inhibitory control. The results with the inclusion of nuisance variables (sex, age, household income, and parental education level) are shown in Table S2. We also evaluated the model with BAS as a mediator, which yielded a non-significant result (See Supplemental Materials *Section D* for more details).

3.4. Association between screen exposure and the subdivisions of the striatum

Previous studies suggest that the ventral striatum (i.e., nucleus accumbens, Nacc) is more related to simple voluntary behaviors whereas the dorsal striatum (i.e., caudate and putamen) plays a major role in habitual seeking and addictive behaviors (Everitt and Robbins, 2013; Zhou et al., 2018). Thus, we additionally hypothesized that the longer daily screen exposure time leads children to the more habitual seeking behavior associated with increased dorsal striatum activation, and thus showing lower connectivity to FPN. To test this hypothesis, we also examined the screen exposure effect for each striatal subregion and found that the longer screen exposure was more associated with the decreased dorsal striatum-FPN connectivity, especially in the year 2, $r_{caudate} = -0.0597$, 95% $CI^{50,000} = [-0.0902, -0.0292]$, $BF_{10,caudate} = 15.738$; $r_{putamen} = -0.0710$, 95% $CI^{50,000} = [-0.1010, -0.0414]$, $BF_{10,putamen} = 245.716$). In contrast, there was no such association with the ventral striatum ($r_{Nacc} = -0.0257$, 95% $CI^{50,000} = [-0.0560, 0.0047]$, $BF_{10,Nacc} = 0.070$. (See Supplemental Materials *Section E* for more details).

3.5. Validating the association between intrinsic FPN-striatum connectivity and the function of inhibitory control

The current study adopted FPN-striatum to represent the intrinsic neurocircuitry that underlies inhibitory control. Several behavioral indices of inhibitory control were utilized, including the behavioral performances in the Flanker Inhibitory Control and Attention Test (Eriksen and Eriksen, 1974), the Monetary Incentive Delay Task (Everitt et al., 2008), the Stop Signal Task (Logan, 1994), ADHD trait (Achenbach and Edelbrock, 1991), and the Cash Choice Task. The task descriptions and details of results can be found in the Supplemental Materials *Section G*. Although the associations between the strength of FPN-striatum connectivity and the behavioral indices of inhibitory function had a small effect size, the direction of the coefficients was consistent across all variables. This implies that the resting-state FPN-Striatum connectivity and the effect of screen exposure were able to anchor to the behavioral indices of inhibitory function.

4. Discussion

In our two-year follow-up study, we examined the impact of daily screen exposure time on the neural inhibitory control network (ICN) in children. Our findings indicated that a longer daily screen exposure time was negatively associated with the strength of the fronto-striatal circuitry. In addition, we found that a longer screen exposure time predicted a protracted development of the ICN, as evidenced by a negative correlation between screen exposure time and the strength of the fronto-striatal connectivity at year 2 and the change in strength between the two waves. Moreover, our results revealed that screen exposure time played a mediating role in the effect of reward sensitivity on the two waves of fronto-striatal connectivity, suggesting that longer screen exposure may amplify the negative effect of reward sensitivity on ICN development. Notably, longer screen exposure was associated with reduced connectivity between the FPN and the dorsal striatum in year 2, which is implicated in habitual addictive seeking behavior.

Our findings on the inverse fronto-striatal connectivity in both cross-sectional and longitudinal data extend previous work by demonstrating that the screen exposure effect is not linked only to a single region, but can influence the interaction between regions and systems (Balleine et al., 2007; Brand et al., 2014). Previous studies using fMRI and DTI suggest that increased positive functional connectivity between the striatum and the frontal executive network is associated with enhanced efficiency of IC across development (Liston et al., 2006; Rubia et al., 2006). Thus, negative fronto-striatal connectivity among children with higher screen exposure may indicate a decreased sophistication of functional coupling between these networks as the brain matures. This novel finding is supported by studies on substance addiction. For example, both DTI and functional connectivity techniques revealed a negative functional coupling of the fronto-striatal connectivity during smoking cue-induced craving (Yuan et al., 2017) and in alcohol-dependent patients compared to healthy controls (Becker et al., 2017). In a similar manner, increased daily screen time may undermine the development of the fronto-striatal network, as our findings showed a negative change in the fronto-striatal connectivity in individuals with relatively increased daily screen time.

Consistent with previous findings (Becker et al., 2017; Kohno et al., 2014; Motzkin et al., 2014; Wang et al., 2013; Yuan et al., 2017), we found a detrimental effect of the negative fronto-striatal coupling in the inhibitory process. However, it should be noted that there is contradictory evidence indicating that longer exposure to addictive stimuli was associated with positive fronto-striatal connectivity (Hu et al., 2015; Koehler et al., 2013). For example, a recent resting-state fMRI study showed that pathological gambling patients have increased connectivity between ventral striatum and the superior/middle frontal gyrus (Koehler et al., 2013), and cocaine addiction patients showed an increased fronto-striatal connectivity (Hu et al., 2015). Furthermore, it has been demonstrated that the negative coupling between frontal and limbic networks is associated with better self-control ability (Lee and Telzer, 2016). However, given the heterogeneity of study populations and approaches, these inconsistent findings in fronto-striatal coupling are not unexpected. Some of the disparate reports may be due to distinct addictive behaviors or the status of those behaviors, such as the period of 'at risk', current dependence, and the period of recovery (Pariyadath et al., 2016). Moreover, the use of different target regions within fronto-striatal circuits may explain these contradictory findings. For instance, one study showed a positive coupling by using the ventral striatum, whereas another showed a negative coupling by employing the caudate and dorsal striatum (Wang et al., 2013).

Importantly, the current study revealed a difference in the connectivity between each subdivision of the striatum and the frontal executive network. High screen exposure resulted in a more negative dorsal

striatum coupling to the frontal executive network relative to the ventral striatum, particularly in the year 2 data. Evidence from both rodent and human studies has shown a functional shift from the ventral to the dorsal striatum underlying the transformation of voluntary behaviors into compulsions, suggesting a dysfunction of the IC (Everitt et al., 2008; Everitt and Robbins, 2013; Zhou et al., 2018). In the rodent model, as cocaine seeking became habitual for the rats, dopamine release was increased in the dorsal, but not the ventral, striatum (Everitt et al., 2008). Similarly, a study with cannabis-dependent males showed lower dorsal striatum connectivity in the frontal regions compared to controls (Zhou et al., 2018). Therefore, it is possible that the consequence of long-term prolonged daily screen exposure may have a similar effect to that of habitual addictive seeking behaviors (Dong et al., 2021), leading to a shift in frontal network connectivity from the ventral to the dorsal striatum.

We also demonstrated the generalizability of the negative effect of screen exposure by controlling the sex and age of the children as well as their parental SES and education level. Previous studies have shown that there are demographic differences in screen exposure in children and adolescents, for example, boys reported higher overall screen use than girls (Nagata et al., 2022), and youth from lower SES and minority backgrounds engaged in more screen activity (Reid Chassiakos et al., 2016). Additionally, literatures also suggests associations between parental SES and both children's executive function (Lawson et al., 2018) and the development of the fronto-striatal circuitry during adolescence (Li et al., 2022). By taking these factors into account, the current study demonstrated that the delaying effect of screen exposure on the development of the ICN is a general phenomenon that exists in children during preadolescence.

Due to the heterogeneous nature of the neural data in the ABCD study, the effect sizes represented by the correlation coefficient in the current study are relatively small, particularly for the baseline year. However, it has been reported that the true size of brain-behavior effects is smaller than what has been previously reported and anticipated (Dick et al., 2021; Marek et al., 2022). In addition, the small effect size of the present study could be due to the target behavior (i.e., daily screen use), as it is expected that the effect of daily behavior is smaller compared to the effect of addictive behaviors (e.g., sampling from the population with SDD). Interestingly, the present study suggests that the impact of daily screen use may be growing, although it was relatively small to begin with. This is indicated by the larger effect size of the year 2 data ($r = -0.093$) compared to the baseline year ($r = -0.040$). The children in the current study were approximately 10 years old at the baseline, marking the beginning of early adolescence. According to theoretical models and empirical studies (Casey, 2015; Rubia et al., 2006), the development of the fronto-striatal circuitry occurs throughout adolescence. Taken together, it is hypothesized that the habit of daily screen use may have a long-term and cumulative effect on adolescents. However, further examination of this hypothesis requires additional data from future waves of the ABCD study.

The current two-year follow-up study demonstrates that prolonged daily screen exposure can alter functional connectivity patterns, suggesting that it may have long-term effects on the development of the ICN and can amplify the negative impact of reward-seeking tendencies on the development of the ICN in adolescents. Despite the relatively small effect found in the intrinsic brain-behavior associations, the results consistently showed that the intrinsic fronto-striatal connectivity was negatively associated with behavioral measures of inhibitory control outcomes. At present, we are limited by the currently released processed data in the ABCD study, as we have not been able to access the processed inhibitory task-based cortical network to subcortical regions data, which would allow us to observe how this altered intrinsic ICN works during inhibitory tasks. In future studies, it will be important to examine how daily screen exposure influences connectivity in the fronto-striatal network during actively inhibitory processing.

In conclusion, the present study found that the neural coupling between the frontoparietal network and the striatum decreases in children with prolonged daily screen exposure. Importantly, we also found that this excessive daily screen exposure may augment the impact of children's reward-seeking tendencies on the inhibitory control network, and the consequence of prolonged daily screen exposure has a similar effect to that of habitual addictive seeking behaviors on the inhibitory control system in the brain. Given that the virtual movement is irreversible and expanding in the modern and future life, it is imperative to conduct more research on the impact of daily screen exposure.

Authorship contribution statement

Y.-Y. Chen developed the study concept. Y.-Y. Chen analyzed and interpreted data under the supervision of T.-H. Lee and H. Yim. Y.-Y. Chen drafted the manuscript, and T.-H. Lee and H. Yim provided critical revisions. All authors approved the final version of the manuscript for submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

I have shared the link of my data in the article. Source Data: https://osf.io/z9dcp/?view_only=bb229c96747a4213ad36ada37651ec28

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2023.101218.

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