Negative Impact of Daily Screen Use on Inhibitory Control Network in Preadolescence: A Two Year Follow-Up Study

Ya-Yun Chen[1], Hyungwook Yim[2], & Tae-Ho Lee[1,3]

[1]Department of Psychology, Virginia Tech, Blacksburg, VA
[2]Department of Cognitive Sciences, Hanyang University, Seoul, Republic of Korea
[3]School of Neuroscience, Virginia Tech, Blacksburg, VA

Correspondence should be addressed to Tae-Ho Lee, Department of Psychology at Virginia Tech, 890 Drillfield Drive, Virginia Tech, VA 24060 (email: taehol@vt.edu) or Hyungwook Yim, Department of Cognitive Sciences, Hanyang University, 222 Wangsimni-ro, Seoul, 04763, South Korea (email: hwyim@hanyang.ac.kr)

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Abstract

The COVID 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 online environment rapidly substitutes in-person experience, understanding children's neuropsychological trajectories associated with screen experiences is important. Given previous findings suggesting that excessive screen use can lead children to seek more immediate rewards over delayed outcomes, we hypothesized that the increased screen time delays the development of inhibitory control. By analyzing neuropsychological data for 8,334 children (9-11ys) from the ABCD Study Data, we found that children with longer screen time showed a higher reward orientation and a weaker inhibitory control system (i.e., fronto-striatal circuitry) in the brain. Importantly, the interaction of screen experience with the reward sensitivity negatively influences the development of inhibitory control system in the brain over two years, implying possible long-term negative impacts of increased daily screen time on neuropsychological development in children. The results further demonstrated that screen time especially influences the dorsal striatum connectivity, which suggests that the effect of daily screen use is more of a habitual seeking behavior. The results together provide neural and behavioral evidence on the negative impact of daily screen use on developing children.

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 & Kern, 2011) and focus on long-term goals, change significantly along with their related 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 & Campbell, 2018) by highlighting the nature of the platform, which offers immediate benefits with negligible costs (Frey et al., 2007). For example, most screen platforms allow users to pause and skip any session that they are less interested in and to choose contents that please them more. This increased information accessibility allows children to pursue immediate rewards and feedback (Tricomi & Fiez, 2012), and, in turn, this increased reward-seeking tendency can further weaken the development of IC (Burton et al., 2021).

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

Recent evidence suggest that the underlying neural mechanisms linked to the failure of IC may be associated with the imbalance between the executive networks and the reward-related nucleus (Casey, 2015; Lee & Telzer, 2016; McClure et al., 2004; Metcalfe & Mischel, 1999). Although non-clinical daily screen behaviors are understudied, research in 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 frontal executive networks and the striatum (Balleine et al., 2007; Brand et al., 2014). For example, studies report that young adults with SDD have dysfunctions in the dorsolateral prefrontal cortex (DLPFC) and frontoparietal

network (FPN) (Dong et al., 2015; Liu et al., 2014). During the inhibitory task, the SDD group exhibited a lower inhibition efficiency with lower activation and connectivity in the FPN regulatory regions compared to the control group, which suggests that the inhibitory function was impaired in the disorder group. Developmentally, adolescents who excessively play computer games have been reported to have higher gray matter volume and higher activation in the striatum compared to those who play computer games infrequently (Kühn et al., 2011).

Although the critical role of a certain brain regions such as the frontal executive network or the striatum in the inhibitory control processing has been investigated extensively as a single region or network, recent studies highlight the importance of neural connectivity in inhibitory processing at the large-scale brain systems level. In particular, recent neural circuitry research from both animal and human studies suggest that it is more comprehensive to consider the between-level neural connectivity as a system (Figure 1A). The frontal executive networks 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, subserving inhibitory control (Alexander et al., 1986; Haber, 2016; Leh et al., 2007; Rubia et al., 2006; Sigman, 2017; Zhang & Iwaki, 2020). For example, functional MRI (fMRI) studies using diverse task-based indices demonstrated a progressive maturation for IC functions within the fronto-striatal circuitry, where the level of activation in the circuitry increases along with inhibition efficiency across development (Rubia et al., 2006). The findings suggest that the neural maturation of IC can be examined by measuring functional coupling between the frontal executive networks and the striatum, and that the regions should be considered together when considering IC.

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 present study is to delineate how daily screen exposure time influences the development of children's intrinsic neurocircuitry that underlies IC (i.e., fronto-stratal circuitry, FPN-striatum). We 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 the striatum. We hypothesized that (1) there would be an alteration of the fronto-striatal connectivity in children with longer daily screen exposure time, and (2) the daily screen exposure time in the baseline year (i.e., 1st-year/wave-1) can predict the strength of the fronto-striatal connectivity two years after (i.e., 2nd-year/wave-2) as well as the strength change between waves. In addition to the effect of daily screen exposure time in the inhibitory control network, we further predicted that (3) 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).

Materials and 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 to11 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*), and the MRI related measures include the processed resting-state fMRI data (ABCD rsfMRI Network to Subcortical ROI Correlations, *mrirscor02*). After removing the missing value, the final sample size was 8,327 for the first year (interview date from 09/2016 to 10/2018) and 3,891 for the second year (interview date from 07/2018 to 01/2020). The age range of children in this sample in their first year was 108-131 months old (*M* = 119.28, *SD* = 7.47) and 49.65% of them were female. Children were primarily identified as White (76.99%), 18.69% as African American, and 4.32% as Others. Caregiver ages ranged from 23 to 80 years (*M* = 40.21, *SD* = 6.75). See Table S1 for more demographic information.

Demographic and behavioral data

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

*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. 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. 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. When discard individuals with missing values, 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, take out all data points that have the same value on months per year and then calculate the median of days per week of those data points for replacing the missing values. For example, if soccer: days per week is missing and the months per year is 2, then all other months per year that are 2 under soccer will be taken out and then the median of days per week of them will be calculated. The median value will be used to replace the missing values in this example. 2) for missing values of minutes per session, take out all data points that have the same value of months per year and then calculate 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 is different from the scale of the screen time survey, daily average activity time was calculated by the following steps: 1) convert the minutes per session of a single type of activity to hour per session; 2) multiply the hour per session and days per week of a single type of activity and divided by seven; and 3) add 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 spends 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 (Bissett et al.) and the behavioral activation system (Motzkin et al.). 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 the 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 indication of overall reward sensitivity (Kelley et al., 2019).

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 et al. (Hagler Jr et al., 2019).

Data analysis

Because of 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.

Data analyses were performed by combining a 50,000 permutation resampling method and the robust method (Pernet), 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, 2006). 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 (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 & 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). 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, reflecting the belief of a medium effect size.

Results

Association between screen exposure and the fronto-striatal connectivity. The correlation analysis showed a significant negative association between the screen-activity proportion and the fronto-striatal connectivity of first-year data (r = -0.040, 95% $CI^{50,000}$ bootstrap = [-0.0605, -0.0186], BF_{10} = 13.10). As the strength of the fronto-striatal connectivity reflects the maturation quality of the inhibitory control system (Rubia et al., 2006), the results suggest that a longer screen exposure time was significantly related to the underdevelopment of the inhibitory control system in the brain (Figure 1B).

An additional group-level comparison with children who had a Screen-Activity Proportion (SAP) greater than the 90th percentile (SAP = 1, N = 785) and children who had a 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 showed a significantly lower fronto-striatal connectivity, compared to children with shorter screen time (Figure 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).

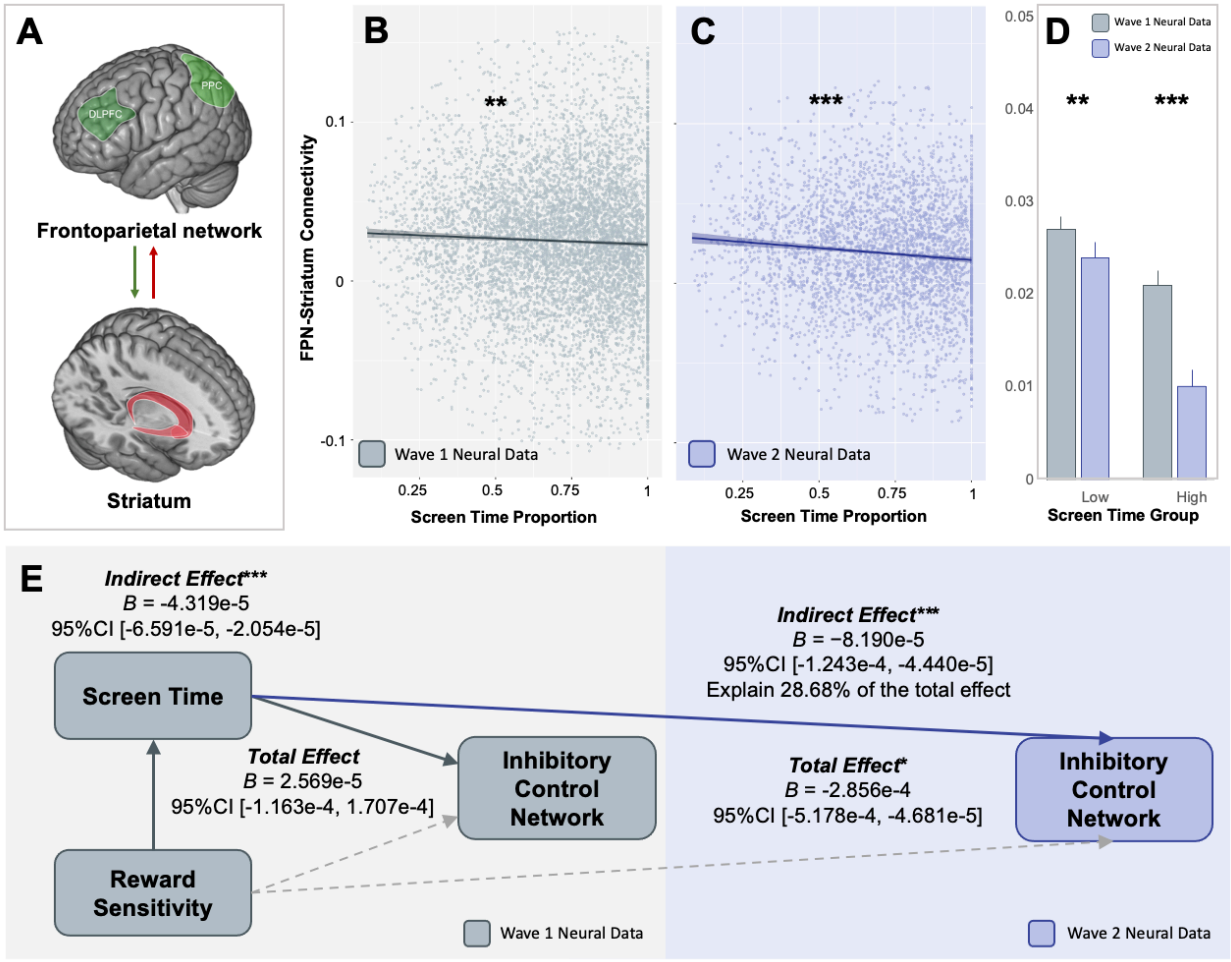

Figure 1. *Association between screen exposure, brain, and reward sensitivity.* ***A:*** *Illustrations of the ROIs examined.* ***B:*** *Correlation between the first year Screen-Activity Proportion (SAP) and the FPN-Striatum Connectivity from the first-year neural data.* ***C:*** *Correlation between first year SAP and the FPN-Striatum Connectivity from second-year 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 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 $BF_{10} > 30$.*

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 association between the screen-activity proportion and the fronto-striatal connectivity than with the first-year neural data (r = -0.0933, 95% $CI^{50,000}$ bootstrap = [-0.1231, -0.0635], BF_{10} = 428995.74; Figure 1C). In addition, the first year daily screen exposure time predicted the connectivity strength change between the first and the second year (wave-2 minus wave-1) (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) in the second-year data. This strong group effect confirmed that the longer screen activity is strongly associated with the development of the inhibitory control system in the brain (Figure 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 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.

Association between reward sensitivity, screen exposure, and brain.

The pairwise correlations between reward sensitivity trait, screen exposure and inhibitory control imply that screen exposure time may mediate the relationship between reward sensitivity trait 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 & 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 (indirect effect: B = −8.190e-5, SE = 1.981e-5, p < 0.001, 95% $CI^{5,000}$ bootstrap = [-1.243e-4, -4.440e-5]; total effect: B = -2.856e-4, SE = 1.150e-4, p < 0.05, 95% $CI^{5,000}$ bootstrap = [-5.178e-4, -4.681e-5]), explaining 28.68% of the total effect. This mediation effect was also shown when using the first-year fronto-striatal connectivity (indirect effect: B = -4.319e-

5, *SE* = 1.229e-5, $p < 0.001$, 95% $CI^{5,000}$ bootstrap = [-6.591e-5 -2.054e-5]; total effect: *B* = 2.569e-5, *SE* = 7.196e-5, $p = 0.721$, 95% $CI^{5,000}$ bootstrap = [-1.163e-4 1.707e-4]). 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 S2. We also tested the model the with BAS as mediator and yielded a non-significant result (See *Supplemental Materials Section D* for more details).

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 & 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. 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 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). 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).

Discussion

In our two-year follow-up study, we examined how daily screen exposure time can influence the neural inhibitory control network (ICN) in children. The results demonstrated that a longer screen exposure time was negatively associated with the strength of the fronto-striatal circuitry. The results further demonstrated that a longer screen exposure time predicts a protracted development of the ICN supported by a negative correlation with the strength of the fronto-striatal connectivity in wave-2, and the strength change between the 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, longer screen exposure was associated with the dorsal striatum, which is involved in habitual seeking behavior and addictive behavior.

Our findings on the inverse fronto-striatal connectivity in both cross-sectional and longitudinal data 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 (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 are associated with an enhanced efficiency of IC across development (Liston et al., 2006; Rubia et al., 2006). Thus, negative fronto-striatal connectivity among children who have longer screen exposure may reflect decreasing sophistication of functional coupling between these networks as the brain matures. This novel finding can be supported by studies in 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 relative to healthy controls (Becker et al., 2017). Similarly, a longer daily screen exposure can weaken the development of the fronto-striatal network supported by our findings showing that the fronto-striatal connectivity changes for individuals with increased screen dependency.

Consistent with the previous findings (Becker et al., 2017; Kohno et al., 2014; Motzkin et al., 2014; Wang et al., 2013; Yuan et al., 2017), we found the detrimental effect of negative fronto-striatal coupling in inhibitory process. However, it should be noted that there is contradictory evidence, showing that a longer exposure to addictive stimuli was associated with a positive fronto-striatal connectivity (Hu et al., 2015; Koehler et al., 2013). For example, a recent resting-state fMRI study showed that an increased connectivity between ventral striatum and the superior/middle frontal gyrus is related to the pathological gambling patients (Koehler et al., 2013) and an increased fronto-striatal connectivity in cocaine addiction patients (Hu et al., 2015). Furthermore, the study of Lee and Telzer (2016) showed that the negative coupling between frontal and limbic networks is associated with better self-control ability (Lee & Telzer, 2016).

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 fronto-striatal 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 (Koehler et al., 2013), whereas Wang et al. (2013) showed a negative coupling by employing the caudate, dorsal striatum, to represent the striatum (Wang et al., 2013).

Importantly, the current study showed a difference in the connectivity between each subdivision of the striatum and the frontal executive network. 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-wave data. Evidence from both rodent and human studies have shown a functional shifting from ventral to 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 ventral striatum while rats' cocaine seeking became habitual (Everitt et al., 2008). Similarly, a study with cannabis-dependent male showed that the additive group had a lower dorsal striatum connectivity to frontal regions relative to the controls (Zhou et al., 2018). Therefore, it is possible that a consequence of long-term extensive screen exposure would be similar to the effect of the addictive behaviors (Dong et al., 2021). Individual who has excessive screen exposure induces frontal network connectivity shifting from ventral to dorsal, leading them to be more vulnerable to impulses and addictions.

The current two-year follow-up study demonstrate that the excessive daily screen exposure can shift the functional connectivity patterns, suggesting that the long-term screen exposure may affect the development of the ICN and can excessively augment the reward-seeking tendency. However, we can only examine the change at the intrinsic neural network level. Limited by the currently released processed data in the ABCD study, we have difficulty in gaining the processed inhibitory task-based cortical network

to subcortical regions data. In future studies, it will be necessary to examine how daily screen exposure influences the connectivity in the fronto-striatal network while the inhibitory processing is activating.

In summary, we showed that with longer daily screen exposure the neural coupling between the frontoparietal and striatum is decreased in children. Importantly, we also found that this excessive daily screen exposure may augment the reward-seeking tendency and close to impulsive addictive behavior rather than a voluntary use. Given that the virtual movement is irreversible in modern and future life, we appeal for increasing research attention to the daily screen exposure.

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DATA AVAILABILITY:

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

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