



## Original Investigation | Pediatrics

## Association of Video Gaming With Cognitive Performance Among Children

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## Abstract

**IMPORTANCE** Although most research has linked video gaming to subsequent increases in aggressive behavior in children after accounting for prior aggression, findings have been divided with respect to video gaming's association with cognitive skills.

**OBJECTIVE** To examine the association between video gaming and cognitive performance in children using data from the Adolescent Brain Cognitive Development (ABCD) study.

**DESIGN, SETTING, AND PARTICIPANTS** In this cross-sectional study, cognitive performance and blood oxygen level-dependent (BOLD) signal were compared in video gamers (VGs) and non-video gamers (NVGs) during response inhibition and working memory using task-based functional magnetic resonance imaging (fMRI) in a large data set of 9- and 10-year-old children from the ABCD study. A sample from the baseline assessment of the ABCD 2.0.1 release in 2019 was largely recruited across 21 sites in the US through public, private, and charter elementary schools using a population neuroscience approach aiming to mirror demographic variation in the US population. Children with valid neuroimaging and behavioral data were included, with adjustments performed for demographic, behavioral, and psychiatric confounding factors. Some exclusions included common MRI contraindications, history of major neurologic disorders, and history of traumatic brain injury. Collected data were analyzed between October 2019 and October 2020, with additional analyses in 2023.

**EXPOSURES** Participants completed a self-reported screen time survey, including an item asking children to report the time specifically spent on video gaming. All fMRI tasks were performed by all participants.

**MAIN OUTCOMES AND MEASURES** Cognitive performance, assessed with stop signal tasks (SST) and n-back tasks; and BOLD signal on fMRI during the tasks. Mental health symptoms were evaluated using the Child Behavior Checklist and included raw scores of behavioral (anxiety, depression, somatic, social, attention, rule breaking, and aggression concerns) and psychiatric categories (*Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition*, diagnoses of depression, anxiety, somaticism, attention-deficit/hyperactivity disorder, oppositional-defiant disorder, and conduct disorder).

**RESULTS** A total of 2217 children (mean [SD] age, 119 [7.6] months; 9.91 [0.62] years; 1399 [63.1%] female) participated in this study. The final sample used in the stop signal task analyses consisted of 1128 NVGs (0 gaming hours per week) and 679 VGs who played at least 21 hours per week. The final sample used in the n-back analyses consisted of 1278 NVGs who had never played video games (0 hours per week of gaming) and 800 VGs who played at least 21 hours per week. The NVG vs VG groups did not differ on age but did differ on sex, race and ethnicity, combined parental income, body mass index, and IQ. There were no differences in body mass index and IQ after adjusting for sociodemographic variables. The Child Behavior Checklist behavioral and mental health scores were

(continued)

## Key Points

**Question** What is the association between video gaming and cognitive performance in children?

**Findings** As part of the national Adolescent Brain Cognitive Development study and after controlling for confounding factors, results of this cross-sectional study of 2217 children showed very small levels of enhanced cognitive performance measured on inhibitory control and working tasks in children who played video games vs those who did not, although the video gamers had significantly higher attention problems, depression, and attention-deficit/hyperactivity disorder scores compared with the those who did not play video games. Functional MRI obtained clear blood oxygen level-dependent signal differences were associated with video gaming in task-related brain regions during inhibition control and working memory.

**Meaning** These findings suggest that video gaming may be associated with very small cognitive performance enhancement involving response inhibition and working memory, and with alterations in underlying cortical pathways, but concerns about the association with mental health may warrant further study.

This article was retracted and replaced on April 10, 2023. See supplemental content for versions that show errors and corrections.

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Abstract (continued)

higher in VGs, with attention problems, depression, and attention-deficit/hyperactivity disorder scores significantly higher in the VGs compared with the NVGs. The VGs performed better on both fMRI tasks compared with the NVGs; the differences were statistically significant but very small. VGs had significantly faster stop signal reaction times compared with NVGs (adjusted means [SE]; 287.3 [9.8] vs 300.1 [9.6], standardized mean difference [SMD] 0.04 milliseconds;  $P = .018$ ) and correct go reaction times (adjusted means [SE], 514 [2.9] vs 552 [2.2] milliseconds; SMD 0.05;  $P = .002$ ). Following a similar pattern, O-back D' measures of the n-back task were significantly higher in VGs compared with NVGs (adjusted means [SE], 2.33 [0.03] vs 2.18 [0.03]; SMD, 0.15;  $P < .001$ ). Similarly, adjusted means (SE) 2-back D' scores were significantly higher in VGs relative to NVGs (1.87 [0.03] vs 1.72 [0.02]; SMD 0.15;  $P < .002$ ), and reaction times for correct responses during the 2-back conditions were faster in VGs relative to NVGs (adjusted means [SE]; 1025 [4.8] vs 1069 [3.7] milliseconds;  $P < .002$ ). Nonparametric analyses of fMRI data demonstrated a greater BOLD signal in VGs in the precuneus during inhibitory control. During working memory, a smaller BOLD signal was observed in VGs in parts of the occipital cortex and calcarine sulcus and a larger BOLD signal in the cingulate, middle, and frontal gyri and the precuneus.

**CONCLUSIONS AND RELEVANCE** In this study, compared with NVGs, VGs were found to exhibit faster reaction times in measures of cognitive performance involving response inhibition and working memory and differences in fMRI BOLD signals in key regions of the cortex responsible for visual, attention, and memory processing. The very small differences in reaction times lack clinical relevance but were consistent with a potential association between videogaming and cognitive performance that involve response inhibition and working memory and the underlying cortical pathways. Concerns about the association with mental health symptoms may warrant further study.

JAMA Network Open. 2022;5(10):e2235721.

Retracted and replaced on April 10, 2023.

Corrected on August 8, 2023. doi:10.1001/jamanetworkopen.2022.35721

## Introduction

Ask any parent how they feel about their child's videogaming and you will almost certainly hear concerns about hours spent in a virtual world and the possibility of adverse effects on cognition, mental health, and behavior. A contributing factor to these concerns is the growth of video gaming within the last 20 years. In tandem, the demographic makeup of gamers has also been rapidly changing. In children aged 2 to 17 years, a large 2022 survey in the US showed that 71% play video games, an increase of 4 percentage points since 2018.<sup>1</sup> Given the substantial brain development that occurs during childhood and adolescence, these trends have led researchers to investigate associations between gaming and cognition and mental health. Most psychological and behavioral studies<sup>2</sup> suggest detrimental associations of video gaming, linking it to subsequent increases in depression, violence, and aggressive behavior in children after accounting for prior aggression. However, researchers have been divided with respect to whether playing video games is associated with cognitive skills and brain function. In contrast to the negative associations with mental health, video gaming has been proposed to enhance cognitive flexibility by providing skills that can be transferred to various cognitive tasks relevant for everyday life. One formulation for this broad transfer is that video gaming shares a number of perceptual and attentional demands (such as multiple object tracking, rapid attentional switches, and peripheral vision) with common cognitive tasks and can enhance reaction time (RT), creativity, problem solving, and logic.<sup>3,4</sup>

In a previous review investigating video gaming and cognitive tasks,<sup>3</sup> gaming was found to be associated with attentional benefits, including improvements in bottom-up and top-down attention, optimization of attentional resources, integration between attentional and sensorimotor areas, and

improvements in selective and peripheral visual attention. Video gamers (VGs) may also benefit from an enhanced visuospatial working memory capacity according to Boot et al,<sup>5</sup> who found that VGs outperformed non-VGs (NVGs) on various visuospatial working memory tasks, such as multiple object tracking, mental rotation, and change detection. Working memory improvements were similarly found after video game training in experimental vs control group research designs.<sup>5-7</sup> This finding is consistent with other studies suggesting that even short video game training paradigms can enhance cognitive control-related functions for long durations, such as reading abilities in dyslexic children<sup>8</sup> and, more particularly, working memory.<sup>3</sup>

Task-based functional magnetic resonance imaging (fMRI) studies<sup>4,9-11</sup> have compared brain activity between VGs and NVGs. When presented with a complex visuomotor task, Granek et al<sup>4</sup> found that VGs exhibited more blood oxygen level-dependent (BOLD) activity in the prefrontal cortex but less overall brain activity compared with NVGs. In 1 study using an fMRI attentional letter detection task, Richlan et al<sup>9</sup> found no significant behavioral performance differences between 14 VGs and 14 NVGs, but VGs showed more brain activation in multiple frontoparietal regions and different activation patterns, suggesting that VGs may recruit different regions of the brain to perform attentional tasks. In the same study,<sup>9</sup> no differences between the 2 groups were observed during a working memory visuospatial task in overall performance (in accuracy or RT) or in brain activation. In a more recent study, Trisolini and colleagues<sup>10</sup> investigated sustained performance between VGs and NVGs in 2 attentional tasks. The results indicated that although VGs displayed significantly stronger performance at the beginning of the task, a substantial decrease in performance was observed over time. By the end of the task, NVGs performed more accurately and quicker. Moreover, in a study<sup>11</sup> investigating the short-term impact of different activities performed during a break before an n-back working memory test in an fMRI scan, 27 young adults who played video games during the break displayed poorer working memory task performance and less BOLD activity in the supplementary motor area compared with those who had listened to music. However, VGs showed neither performance nor BOLD differences compared with those who spent the break resting. The authors reasoned that the video-gaming demands may have fatigued specific cognitive resources that rely on the supplementary motor area and reduced the ability of VGs to focus attention on the subsequent working memory task.<sup>11</sup> This finding is in contrast with another study<sup>3</sup> that suggested that even short video game training paradigms can enhance cognitive control-related functions, particularly working memory, with the enhancement linked to activity changes in prefrontal areas, such as the dorsolateral prefrontal cortex and the orbitofrontal cortex.

In brief, although several studies have investigated the association between video gaming and cognitive behavior, the neurobiological mechanisms underlying the associations are not well understood because only a handful of neuroimaging studies have addressed this topic. In addition, findings from fMRI studies on video gaming in children and adolescents have not been replicated, which could be in part attributable to the relatively small sample sizes included in the analyses (N<80). In this study, we assess video-gaming associations with cognitive performance and brain activation during response inhibition and working memory using task-based fMRI in a large data set of 9- and 10-year-old children from the Adolescent Brain Cognitive Development (ABCD) study,<sup>12</sup> the largest long-term study of brain development and child health in 21 research sites across the US. We hypothesized, based on the literature, that VGs would perform better on the tasks and have altered cortical activation patterns compared with NVGs in key areas of the brain involved in inhibitory control and working memory.

## Methods

This cross-sectional study used data from the baseline assessment of the ABCD study 2.0.1 release in 2019, which recruited a large sample of 9- to 10-year-old children from whom neuroimaging and behavioral data were acquired and quality controlled according to standard operating procedures for the ABCD study consortium.<sup>5</sup> All measurements were collected at enrollment in the ABCD study. The

fMRI paradigms were preprocessed with standard automated pipelines using Analysis of Functional NeuroImages and included the stop signal task (SST) and the n-back task. Children were asked to report how many hours per week they play video games on a computer, console, smart phone, or other devices. Consent (parents) and assent (children) were obtained from all participants. The ABCD study was approved by the appropriate institutional review boards: most ABCD research sites rely on a central Institutional Review Board at the University of California, San Diego for the ethical review and approval of the research protocol, with a few sites obtaining local IRB approval.

## Sample

The ABCD sample was largely recruited through public, private, and charter elementary schools. The ABCD study adopted a population neuroscience approach to recruitment<sup>13,14</sup> by using epidemiologically informed procedures to ensure demographic variation in its sample that would mirror the variation in the US population of 9- and 10-year-olds.<sup>15</sup> A probability sampling of schools was conducted within the defined catchment areas of the study's nationally distributed set of 21 recruitment sites in the US. All children in each sampled school were invited to participate after classroom-based presentations, distribution of study materials, and telephone screening for eligibility. Exclusions included common MRI contraindications (such as stainless steel braces, cardiac pacemakers and defibrillators, internal pacing wires, cochlear and metallic implants, and Swan-Ganz catheters), inability to understand or speak English fluently, uncorrected vision, hearing or sensorimotor impairments, history of major neurologic disorders, gestational age less than 28 weeks, birth weight less than 1200 g, birth complications that resulted in hospitalization for more than 1 month, current diagnosis of schizophrenia, moderate or severe autism spectrum disorder, history of traumatic brain injury, or unwillingness to complete assessments. The ABCD study sample also includes 2105 monozygotic and dizygotic twins. The ABCD study's anonymized data, including all assessment domains, are released annually to the research community. Information on how to access ABCD study data through the National Institute of Mental Health Data Archive is available on the ABCD study data-sharing webpage.<sup>16</sup>

## Screen Time Survey

Participants were administered a screen time survey that asked how much time they spend engaged in different types of screen time on a typical weekday and a typical weekend day. The different screen time categories were as follows: "Watch TV shows or movies?"; "Watch videos (such as YouTube)?"; "Play video games on a computer, console, phone, or other device (Xbox, Play Station, iPad)?"; "Text on a cell phone, tablet, or computer (eg, GChat, Whatsapp, etc.)?"; "Visit social networking sites like Facebook, Twitter, Instagram, etc?"; and "Video chat (Skype, Facetime, etc)?" For each of these activities, the participants responded with how much time they spent per day doing them. They could answer none, less than 30 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, or 4 hours. Answers were mostly none for the texting, social networking, and video chatting categories, as expected for this age range. For each participant, a total weekly video-gaming score was derived as the sum of (video-gaming hours per weekday  $\times$  5) + (video-gaming hours per weekend day  $\times$  2). A total weekly watching videos score was also derived for each participant. Using the video-gaming score, we defined a group of NVGs who never played video games (0 gaming hours per week) and a group of VGs who played a minimum of 3 hours per day (21 hours per week) or more. This threshold was selected because it exceeds the American Academy of Pediatrics screen time guidelines,<sup>17</sup> which recommends that video-gaming time be limited to 1 to 2 hours per day for older children.

## Demographic Characteristics and Mental Health Measures

The child's age, sex, and race and ethnicity were reported by the parent at the baseline assessment. Race and ethnicity categories included Asian, Black, Hispanic, White, and other (which included American Indian, Alaska Native, Native Hawaiians, Pacific Islander, and multiple racial and ethnic categories). A trained researcher measured children's height (to the nearest inch) and weight (to the

nearest 0.1 lb). Height and weight were assessed 2 times, and means were recorded. Height and weight were converted to body mass index (BMI) scores (according to the Centers for Disease Control and Prevention BMI cutoffs<sup>18</sup>). IQ scores were derived from the National Institutes of Health Toolbox cognition battery<sup>19</sup> as the mean of crystallized intelligence and fluid intelligence composite, age-corrected scores. The Pubertal Development Scale (PDS)<sup>20</sup> was used to assess the child's pubertal stage. The PDS is a noninvasive measure that assesses current pubertal status in females and males, in which higher scores indicate further progression in puberty. Mental health symptoms were evaluated using the Child Behavior Checklist (CBCL)<sup>21</sup>, and included raw scores of behavioral (anxiety, depression, somatic, social, attention, rule-breaking, and aggression concerns) and psychiatric categories (*Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition*, diagnoses of depression, anxiety, somaticism, attention-deficit/hyperactivity disorder [ADHD], oppositional-defiant disorder, and conduct disorder).

### Task fMRI Acquisition

The ABCD imaging protocol was designed to extend the benefits of high temporal and spatial resolution of imaging protocols of the Human Connectome Project<sup>22</sup> with the multiple scanner systems of participating sites.<sup>23</sup> High spatial and temporal resolution simultaneous multislice and multiband echo-planar imaging task-based fMRIs, with fast integrated distortion correction, were acquired to examine functional activity. For the 3-T scanners (Siemens and GE), the scanning parameters were as follows: matrix, 90 × 90; 60 slices; field of vision, 216 × 216; echo time/repetition time, 800/30 milliseconds; flip angle, 52°; and resolution, 2.4 × 2.4 × 2.4 mm. The fMRI acquisitions (2.4-mm isotropic with repetition time of 800 milliseconds) used multiband echo-planar imaging with slice acceleration factor 6. The order of fMRI tasks was randomized across participants. The fMRI preprocessing pipeline included a within-volume head motion estimation and correction and a correction for image distortions. Estimates of task-related activation strength (measured with BOLD activity levels of 10242 vertices/hemisphere) were computed at the individual participant level using a general linear model implemented in Analysis of Functional NeuroImages 3dDeconvolve, with additional nuisance regressors and motion estimates. Hemodynamic response functions were modeled in Analysis of Functional NeuroImages with 2 parameters using a γ-variate basis function plus its temporal derivative.

The SST and n-back task were selected from the ABCD imaging battery to probe inhibitory control and working memory, respectively. Participants practiced the 2 tasks before scanning to ensure they understood the instructions and were familiar with the response collection device. These 2 tasks yield robust neural activation patterns as demonstrated previously.<sup>24</sup> Quality control criteria included excluding participants based on poor image quality, motion, or task performance. The full details of the tasks and fMRI acquisition, preprocessing, and quality control are described in the eMethods in [Supplement 1](#) and by Hagler et al.<sup>22</sup>

### Behavioral Task Performance

The adaptive algorithm used in the SST allowed for calculation of the stop signal RT (SSRT; the time required to inhibit the motor response<sup>24</sup>), which was used as the performance variable in analyses that assessed individual differences in response inhibition ability. The SSRT was computed by subtracting the median stop signal delay of all successful stop trials from the *n*th percentile go RT, where *n* represents the percentage of successful inhibitions (for details on the theoretical underpinnings for this estimation, see the study by Logan and Cowan<sup>25</sup>). To evaluate behavioral task performance in the n-back task, *D'* (calculated as the z-transformed hit rate minus the z-transformed false alarm rate) was computed for both the 2-back and 0-back conditions by calculating each participant's hit rate (the proportion of targets for which the participant correctly indicated a match) and the false alarm rate (the proportion of nontargets for which the participant incorrectly indicated a match or did not respond). The hit and false alarm rates were then z transformed. Cognitive performance was also assessed with tasks not relying on visual-motor coordination (list sorting

working memory task and Rey Auditory Verbal Learning Test), as described in the eMethods in [Supplement 1](#).

### Participant Inclusion Criteria

Participants were included if they had (1) 2 fMRI runs per task, (2) cortical vertex and subcortical voxel data available at the time of analysis, (3) hemispheric mean BOLD signal within 2 SDs of the sample mean for each task, (4) at least 200 *df* during the 2 scan runs, (5) mean framewise displacement less than 0.9 mm for both runs, (6) met task-specific performance criteria (described in the eMethods in [Supplement 1](#)), and (7) had complete information on the screen time survey and for all other variables (CBCL, age, sex, scanner serial number, puberty, race and ethnicity, and combined parental income).

### Statistical Analysis

Collected data were analyzed between October 2019 and October 2020, with additional analysis in 2023. Unadjusted demographic characteristics (age, sex, race and ethnicity, household income), BMI and IQ, and scanner manufacturer were compared between VGs and NVGs using 2-tailed *t* tests and  $\chi^2$  analyses. To compare the 2 groups on IQ, BMI, and mental health as outcome measures, we use linear mixed models, controlling for sociodemographic factors (age, sex, puberty, race and ethnicity, and household income), and including site as a random effect. Linear mixed models were also used to compare VG and NVG on the 4 task-performance measures: SSRT, correct go RT in the SST, and O-back and 2-back D' in the n-back. These models included age, sex, race and ethnicity, IQ, puberty, and combined parental income as adjustment variables, and site as a random effect. Based on the fits of these models, group-specific estimated marginal means (referred to as adjusted means), standard errors and standardized mean differences (SMDs) were calculated for each performance measure. Analyses were carried out in SPSS (version 28.0).

Cortical task-fMRI BOLD signal contrasts (10242 vertices/hemisphere) were compared between VGs and NVGs using vertexwise permutation analyses via the fit of a Permutation Analysis of Linear Models (PALM) general linear model.<sup>26</sup> Task-fMRI contrasts included correct stop vs correct go and incorrect stop vs correct go conditions of the SST, as well as O-back vs fixation and 2-back vs fixation conditions of the n-back test. Throughout age (months), sex, scanner serial number, race and ethnicity, IQ, puberty, and combined parental income were included as adjustment variables. Furthermore, nonindependence of siblings was acknowledged using sibling status as a nested covariate in the model using PALM's exchangeability blocks,<sup>27</sup> which restrict the shuffling to only occur among the observations that share the same family index (ie, number of siblings). Note, sibling status was only included in the neuroimaging analyses because the permutation design with exchangeability blocks allows for optimal modeling of nested covariates, such as sibling status and site.

Additional task measurements not relying on visuomotor coordination included a list sorting working memory task and the Rey Auditory Verbal Learning Test and are described in the eMethods in [Supplement 1](#).

All statistical tests were 2-sided. False discovery rate (FDR) was assessed with the Benjamini and Hochberg procedure, and corrected *P* values and statistical maps were considered significant at *P* < .05.

### Structural Equation Modeling

To investigate the potential mediating role that time spent watching videos, behavioral problems, or psychiatric disorders have in the association between video gaming with BOLD signal activation during SST and n-back tasks, we used structural equation modeling to model the association between video gaming (independent variable) and activation in the SST and n-back task (dependent variable), with video watching, behavioral problems, and psychiatric disorders scores included as covariates (**Figure 1**).  $\beta$  Coefficients from the fMRI general linear model (model described in the eMethods in [Supplement 1](#)) were extracted using MATLAB (MathWorks) for each task and contrast

from vertexes showing significant differences between NVGs and VGs in the vertexwise analyses. Mean  $\beta$  coefficients were computed for each contrast and included as the BOLD signal variable in the model. Total behavioral problems and psychiatric disorder scores were calculated from the CBCL<sup>21</sup> as the sum of the scores of all of the problem and psychiatric items, respectively. The direct effect of video gaming on BOLD signal (parameter  $b_1$ ) served to check whether any initial association remained significant after controlling for the covariates included in the model. This determination was accomplished by letting each covariate predict both video gaming and BOLD signal such that each covariate could have direct effects (represented as  $b_2$  and  $b_3$ ) as well as an indirect effect on BOLD signal via video gaming ( $b_1 \times b_2$ ) (Figure 1). In this regard, video gaming could be interpreted as a mediator of the covariates' effects. The total effect of covariates on the BOLD signal equals  $b_1 \times b_2 + b_3$ , whereas the covariate-corrected effect of video gaming on the BOLD signal equals  $b_1$ . The root mean square error of approximation, comparative fit and Tucker-Lewis indices, defined as measures of the goodness-of-fit of statistical models, were also calculated for each model. The model was specified in R software, version 4.0.4 (R Foundation for Statistical Computing) using the structural equation modeling package lavaan,<sup>28</sup> version 0.6-7.

## Results

### Demographic Characteristics

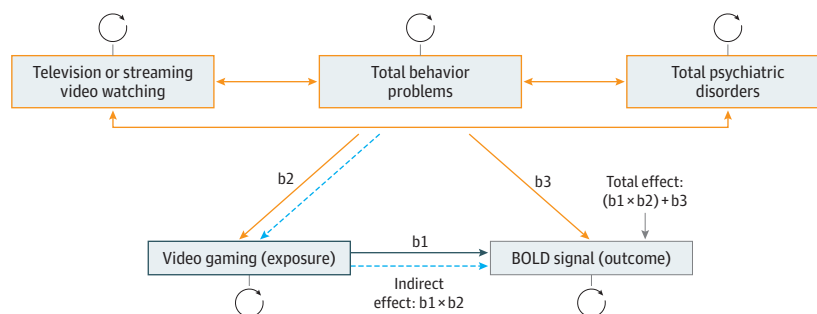
A total of 2217 children (mean [SD] age, 119 [7.6] months; 9.91 [0.62] years; 1399 [63.1%] females) participated in this study (Table 1). The final sample used in the SST analyses consisted of 1128 NVGs who had never played video games (0 gaming hours per week) and 679 VGs who played 21 hours per week or more. The final sample used in the n-back analyses consisted of 1278 NVGs who had never played video games (0 hours per week of gaming) and 800 gamers who played 21 hours per week or more.

The NVG vs VG between-group comparisons showed that groups did not differ on age, but did differ on sex, race and ethnicity, combined parental income, and raw BMI and IQ measures (Table 1). Comparison of NVGs and VGs using linear mixed models showed the adjusted means of BMI and IQ did not differ between the 2 groups (Table 2). Although mental health and behavioral scores from the CBCL were consistently higher in VGs, these differences reached statistical significance for attention problems, depression, and ADHD scores (FDR  $P < .05$ ) (Figure 2). The  $t$  scores from the CBCL were less than 56 in both groups and thus, none of the measures in either group was high enough to reach clinical significance (Figure 2).

### Individual Behavioral Performance Measures

Performance on the SST was in the anticipated range (mean [SE] SSRT, 293.7 [9.7] milliseconds; mean [SE] go RT, 538 [1.82] milliseconds), with a mean (SE) rate of correct inhibitions of 51.5%

Figure 1. Model Used to Study the Association Between Video Gaming and BOLD Signal Activation in the n-Back Task and Stop Signal Task



BOLD indicates blood oxygen level dependent.  $b_1$  indicates the direct effect of videogaming on BOLD signal.  $b_2$  and  $b_3$  represent for each covariate the direct effects on videogaming and BOLD signal, respectively. The dashed blue arrow and the black arrow represent the indirect and total effects of each covariate on BOLD signal, respectively. Circled arrows represent the variance of each variable in the model.

(0.001%). The distributions for D' were as expected, with children performing better on the 0-back task (mean [SE] D' = 2.25 [0.03] milliseconds) than the 2-back task (mean [SE] D' = 1.8 [0.03] milliseconds;  $P < .001$ ). Linear mixed models compared task performance measures between NVGs and VGs with age, sex, puberty, race and ethnicity, household income, and scanner site included as covariates. Analyses showed that videogaming was associated with small improvements in performance in the SST and n-back tasks (Figure 2). In the SST, compared with NVGs, VGs had statistically significantly faster reaction times. The adjusted means (SE) times for SSRT were 287.3 (9.8) vs 300.1 (9.6) milliseconds (SMD 0.04 milliseconds;  $P = .02$ ), and the adjusted means (SE)

Table 1. Screen Time and Demographic Characteristics in NVGs and VGs in the SST and n-Back Samples

| Variable                                                       | SST sample              |                         |                    | n-Back sample           |                         |                    |
|----------------------------------------------------------------|-------------------------|-------------------------|--------------------|-------------------------|-------------------------|--------------------|
|                                                                | NVGs (n = 1128)         | VGs (n = 679)           | P value            | NVGs (n = 1278)         | VGs (n = 800)           | P value            |
| Video gaming, mean (SD), h/wk                                  | 0                       | 25.57 (3.4)             | NA                 | 0                       | 25.54 (2.85)            | NA                 |
| Age, mean (SD), mo                                             | 119.0 (7.7)             | 119.6 (7.3)             | .07 <sup>a</sup>   | 118.9 (7.1)             | 119.5 (8.5)             | .04 <sup>a</sup>   |
| Sex, No. (%)                                                   |                         |                         |                    |                         |                         |                    |
| Male                                                           | 245 (21.7)              | 519 (76.5)              | <.001 <sup>b</sup> | 282 (22)                | 612 (76.5)              | <.001 <sup>b</sup> |
| Female                                                         | 883 (78.3)              | 160 (23.5)              |                    | 996 (77.9)              | 188 (23.5)              |                    |
| Watching television or online video streaming, mean (SD), h/wk | 11.34 (0.33)            | 28.54 (1.1)             | <.001 <sup>a</sup> | 11.7 (0.3)              | 29.0 (0.5)              | <.001 <sup>a</sup> |
| Combined parental income, mean (SD) <sup>c</sup>               | 7.62 (2.3) <sup>c</sup> | 6.51 (2.5) <sup>c</sup> | <.001 <sup>a</sup> | 7.50 (2.3) <sup>c</sup> | 6.31 (2.6) <sup>c</sup> | <.001 <sup>a</sup> |
| Scanner manufacturer, No. (%)                                  |                         |                         |                    |                         |                         |                    |
| GE                                                             | 243 (21.5)              | 127 (18.7)              | .004 <sup>b</sup>  | 280 (21.9)              | 145 (18.1)              | <.001 <sup>b</sup> |
| Phillips                                                       | 173 (15.4)              | 72 (10.6)               |                    | 200 (15.6)              | 84 (10.5)               |                    |
| Siemens                                                        | 712 (63.1)              | 480 (70.7)              |                    | 797 (62.4)              | 571 (71.4)              |                    |
| Handedness, % left-handed                                      | 6.82                    | 6.92                    | .97 <sup>b</sup>   | 6.65                    | 7.5                     | .42 <sup>b</sup>   |
| Race and Ethnicity, No. (%)                                    |                         |                         |                    |                         |                         |                    |
| Asian                                                          | 34 (3)                  | 4 (0.5)                 | <.001 <sup>b</sup> | 37 (3)                  | 7 (0.9)                 | <.001 <sup>b</sup> |
| Black                                                          | 112 (10)                | 163 (24)                |                    | 145 (11)                | 206 (25.75)             |                    |
| Hispanic                                                       | 240 (21)                | 133 (20)                |                    | 281 (22)                | 160 (20)                |                    |
| White                                                          | 634 (56)                | 303 (44.5)              |                    | 699 (55)                | 333 (41.6)              |                    |
| Other <sup>d</sup>                                             | 108 (10)                | 77 (11)                 |                    | 116 (9)                 | 94 (11.75)              |                    |
| BMI, mean (SD)                                                 | 18.53 (4)               | 19.3 (4.6)              | <.001 <sup>a</sup> | 18.7 (4.1)              | 19.2 (4.5)              | .008               |
| IQ, mean (SD)                                                  | 102.42 (17.8)           | 96.4 (17.3)             | <.001 <sup>a</sup> | 101.2 (17.9)            | 95.2 (17.2)             | <.001 <sup>a</sup> |

Abbreviations: NA, not applicable; NVGs, non-video gamers; SST, stop signal task; VGs, video gamers.

<sup>a</sup> Two-tailed *t* test.

<sup>b</sup>  $\chi^2$  Test.

<sup>c</sup> Income brackets are as follows: 1, less than \$5000; 2, \$5000 to less than \$12 000; 3, \$12 000 to less than \$16 000; 4, \$16 000 to less than \$25 000; 5, \$25 000 to less

than \$35 000; 6, \$35 000 to less than \$50 000; 7, \$50 000 to less than \$75 000; 8, \$75 000 to less than \$100 000; 9, \$100 000 to less than \$200 000; and 10, \$200 000 or more.

<sup>d</sup> Includes American Indian, Alaska Native, Native Hawaiian, Pacific Islander, and multiple racial and ethnic categories.

Table 2. Differences in IQ, BMI, and Task Performance Measures in NVGs and VGs, Accounting for Sociodemographic Factors<sup>a</sup>

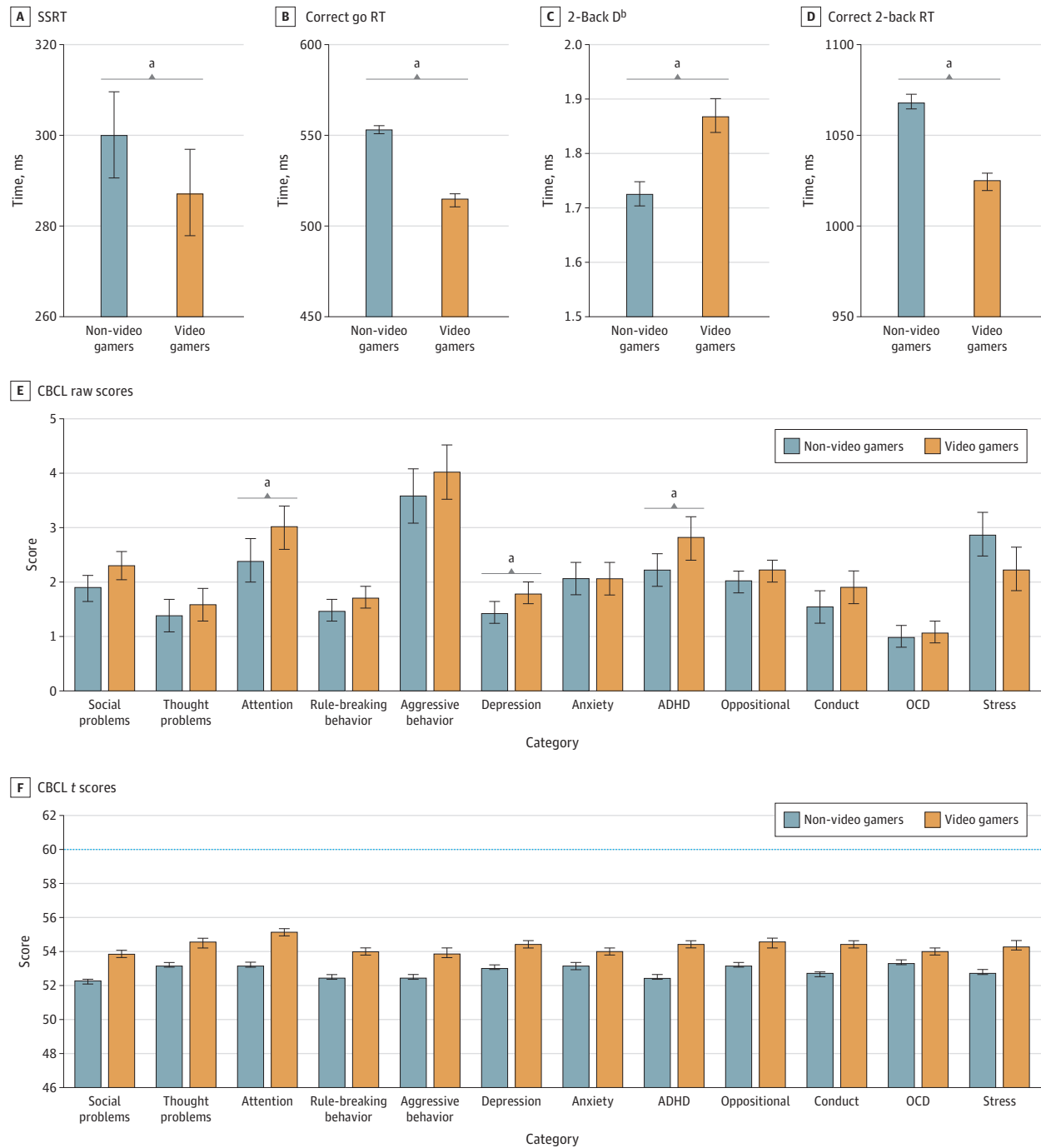
| Variable                            | SST sample      |               |      |         | n-Back sample   |               |       |         |
|-------------------------------------|-----------------|---------------|------|---------|-----------------|---------------|-------|---------|
|                                     | NVGs (n = 1128) | VGs (n = 679) | SMD  | P value | NVGs (n = 1278) | VGs (n = 800) | SMD   | P value |
| IQ scores, AM (SE)                  | 97.5 (1.2)      | 96.3 (1.4)    | 0.03 | .15     | 98.7 (1.4)      | 97.06 (1.5)   | 0.03  | .073    |
| BMI, AM (SE)                        | 19.9 (0.4)      | 20.4 (0.4)    | 0.04 | .057    | 20.1 (0.4)      | 20.5 (0.5)    | 0.028 | .15     |
| SSRT, AM (SE), ms                   | 300.1 (9.6)     | 287.3 (9.8)   | 0.04 | .018    | NA              | NA            | NA    | NA      |
| Correct go RT, AM (SE), ms          | 552 (2.2)       | 514 (2.9)     | 0.5  | .002    | NA              | NA            | NA    | NA      |
| 0-back D', AM (SE), ms <sup>b</sup> | NA              | NA            | NA   | NA      | 2.18 (0.03)     | 2.33 (0.03)   | 0.15  | <.001   |
| 2-back D', AM (SE), ms <sup>b</sup> | NA              | NA            | NA   | NA      | 1.72 (0.03)     | 1.87 (0.03)   | 0.15  | .002    |

Abbreviations: AM, adjusted mean; BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); NA, not applicable; NVGs, non-video gamers; SMD, standardized mean difference; SSRT, stop signal reaction time; SST, stop signal task; VGs, video gamers.

<sup>a</sup> Adjusted means and standard errors from linear mixed models accounting for sociodemographic factors are reported.

<sup>b</sup> D' was calculated as the z-transformed hit rate minus the z-transformed false alarm rate.

Figure 2. Differences of Cognitive Task Performance and Child Behavior Checklist (CBCL) Measures Between Video Gamers and Non-Video Gamers



A-D, Adjusted means and standard errors from linear mixed models accounting for sociodemographic factors are visualized. F, A t score of 59 or less indicates nonclinical symptoms, a t score between 60 and 64 indicates that the child is at risk for problem behaviors, and a t score of 65 or greater indicates clinical symptoms. The t score of 60 is visually represented with a dashed blue line on the graph. Whiskers represent SEs. ADHD indicates attention-deficit/hyperactivity disorder; OCD, obsessive-compulsive disorder; RT, reaction time; and SSRT, stop signal reaction time.

<sup>a</sup> Significant differences with false discovery rate-corrected  $P < .05$ .  
<sup>b</sup> D' was calculated as the z-transformed hit rate minus the z-transformed false alarm rate.

times for correct go RT were 514 (2.9) vs 552 (2.2) milliseconds (SMD, 0.5 milliseconds;  $P = .002$ ). Following a similar pattern, the O-back D' score was significantly higher in VGs relative to NVGs (adjusted means [SE], 2.33 [0.03] vs 2.18 [0.03];  $P < .001$ ) (Table 2). Similarly, 2-back D' was significantly higher in VGs relative to NVGs (adjusted means [SE], 1.87 [0.03] vs 1.72 [0.02];  $P < .002$ ). Reaction time for correct responses during the 2-back condition were significantly faster in VGs relative to NVGs (adjusted means [SE], 1025 [4.8] vs 1069 [3.7];  $P < .002$ ) (Table 2 and Figure 2). Compared with NVGs, VGs, scored lower on the list sorting working memory task, and there were no differences between groups on the Rey Auditory Verbal Learning Test (see eMethods and eResults in Supplement 1).

### Vertexwise Task fMRI Analyses

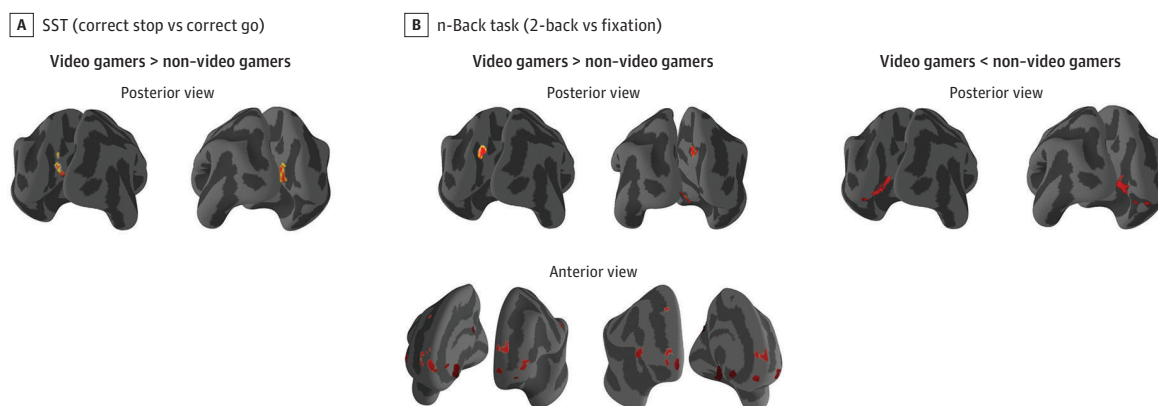
Families with 2 siblings consisted of less than 5% and families with 3 siblings of less than 0.1% in both fMRI samples. In the correct stop vs correct go condition of the SST, vertexwise analyses showed significantly greater BOLD signal in VGs compared with NVGs in the bilateral precuneus (Figure 3). No significant differences were observed in the incorrect stop vs correct go condition of the SST.

In the 2-back vs fixation condition of the n-back task, a significantly greater BOLD signal was observed in VGs compared with NVGs in bilateral parts of the dorsal posterior cingulate gyrus, subparietal cortex, middle and superior frontal gyri, and precuneus (Figure 3). Meanwhile, a smaller BOLD signal was observed in VGs in the 2-back vs fixation condition in bilateral parts of the occipital cortex and the calcarine sulcus (Figure 3). The direction, anatomical label, cluster size, and peak vertex number for each cortical region showed significant changes between VGs and NVGs (Table 3). Cortical clusters showing these differences in the n-back sample also survive a Bonferroni familywise error correction at  $P < .05$ . Similar patterns of BOLD differences between VGs and NVGs were observed in male and female groups examined separately. No significant differences were observed in the O-back vs fixation condition of the n-back task.

### Structural Equation Modeling

The two structural equation models (for the SST and n-back task) showed good fits with root mean square error of approximation less than 0.04, a comparative fit index greater than 0.9, and Tucker-Lewis Index greater than 0.9. Video watching was positively associated with video gaming for both models (estimates, 0.12 for SST and 0.14 for n-back tasks;  $P \leq .001$ ). However, video watching and total behavioral and psychiatric problems did not have significant direct ( $b_3$ ), indirect ( $b_1 \times b_2$ ), or total ( $[b_2 \times b_1] + b_3$ ) effects on the BOLD signal in either model. Of importance, the direct effect of video gaming on the BOLD signal remained significant in both models.

Figure 3. Vertexwise Between-Group Comparisons in Video Gamers vs Non-Video Gamers



SST indicates stop signal task.

Data were missing or partially missing on the screen time questionnaire for 11 NVG participants (0.5% of the sample). We reran our analyses on both SST and n-back task-fMRI data, as well as behavioral and mental health measures with and without those participants, and there were no differences in the adjusted means or statistical significance of our findings.

Discussion

To date and to our knowledge, this is the largest study to assess the association among video gaming, cognitive performance, and brain function. The behavioral performance findings showed that VGs performed better on both the SST and n-back task compared with NVGs; however, the differences were very small and measured in fractions of milliseconds. The fMRI findings demonstrated that VGs show a greater BOLD signal in bilateral parts of the precuneus, using an SST probing inhibitory control. Moreover, results showed a smaller BOLD signal in VGs in parts of the occipital cortex and calcarine sulcus and more activation in cingulate, subparietal, middle, and frontal gyri, and the precuneus during the n-back working memory task. In line with psychological and behavioral studies<sup>2</sup> that suggest detrimental associations of video gaming with mental health in children, we observed significantly higher attention problems, depression, and ADHD scores in VGs compared with NVGs. The marginally higher scores in VGs in the other CBCL categories leave open the possibility that VGs may be on a trajectory to show more mental health symptoms with time and more exposure to video gaming.

The behavioral performance findings in the SST sample are in line with the behavioral findings of the studies by Chisholm et al<sup>29</sup> and Bavelier et al,<sup>30</sup> showing that VGs are less susceptible to attentional distraction and outperform NVGs on both selection-based and response-based processes, suggesting that enhanced attentional performance in VGs may be underpinned by a greater capacity to suppress or disregard irrelevant stimuli. However, these results contradict those obtained in previous studies<sup>31,32</sup> that used go/no-go tasks and those showing higher impulsivity levels to be associated with video gaming. These studies<sup>31,32</sup> adopted a different design and outcome

Table 3. Anatomical Label, Cluster Size, and Peak Vertex Number of Cortical Regions Where Significant Changes Were Detected in the SST and n-Back Tasks Between VGs and NVGs

| BOLD signal and cortical region | Cluster size (No. of vertexes) | Peak vertex No. (mean space) |
|---------------------------------|--------------------------------|------------------------------|
| SST/correct stop vs correct go  |                                |                              |
| Greater BOLD signal in VGs      |                                |                              |
| Left precuneus                  | 126                            | 8                            |
| Right precuneus                 | 134                            | 30                           |
| n-Back/2-back vs fixation       |                                |                              |
| Greater BOLD signal in VGs      |                                |                              |
| Left posterior cingulate gyrus  | 48                             | 90                           |
| Right posterior cingulate gyrus | 64                             | 114                          |
| Left precuneus                  | 145                            | 21                           |
| Right precuneus                 | 124                            | 6                            |
| Left inferior parietal gyrus    | 98                             | 2304                         |
| Right inferior parietal gyrus   | 73                             | 2284                         |
| Left middle frontal gyrus       | 81                             | 1173                         |
| Right middle frontal gyrus      | 67                             | 1125                         |
| Left superior frontal gyrus     | 168                            | 6563                         |
| Right superior frontal gyrus    | 182                            | 6488                         |
| Smaller BOLD signal in VGs      |                                |                              |
| Left lateral occipital          | 102                            | 9669                         |
| Right lateral occipital         | 119                            | 9357                         |
| Left calcarine sulcus           | 56                             | 7982                         |
| Right calcarine sulcus          | 68                             | 6992                         |

Abbreviations: BOLD, blood oxygen level dependent; NVGs, non-video gamers; SST, stop signal task; VGs, video gamers.

measures, included young adult age ranges, and had small sample sizes ( $n < 56$ ). The behavioral performance findings in the n-back task are also in accordance with previous studies showing enhanced visuospatial working memory performance in VGs compared with NVGs<sup>5,33</sup> and in experimental vs control groups after video game training sessions.<sup>5-7,34</sup> In both tasks, the significantly faster millisecond RTs in VGs compared with NVGs while simultaneously performing more accurately may reflect improved cognitive skills acquired through video gaming and not caused by impulsive responding. According to a previous EEG study,<sup>35</sup> earlier latencies in the visual pathways are another feature found in VGs, which may contribute to faster RTs in visual tasks after years of practice. The faster millisecond performance times on both the SST and n-back task is supported by previous studies showing that VGs outperform NVGs on a range of cognitive tasks<sup>36</sup> (a flanker task, an enumeration task, and 2 attentional blink tasks) and on crystallized and fluid intelligence measures assessed via the Youth National Institutes of Health Toolbox.<sup>37</sup> In addition, supporting our findings, research on video game training in groups of NVGs using action video games (mainly enhancing one's attentional control) demonstrated that video game training consistently led to transferrable improvements in cognitive performance.<sup>38</sup>

The imaging findings showing a greater BOLD signal associated with video gaming during the SST in the precuneus—a brain region involved in a variety of complex functions including attention, cue reactivity, memory, and integration of information—are consistent with previous fMRI studies<sup>3</sup> in children and young adolescents using response inhibition tasks showing more activation in VGs in parietal areas of the cortex, including the precuneus. More broadly, the findings agree with the evidence that VGs display enhanced overall neural recruitment in a range of attentional control areas during response inhibition tasks.<sup>3</sup> Of interest, in a previous study<sup>39</sup> investigating changes in resting state functional connectivity after video game practice in young participants using a test-retest design, the key finding was increased correlated activity during rest in the precuneus, suggesting that this area exhibits a practice effect associated with the cognitively demanding video games.<sup>39</sup> Advantages for VGs in various attention-demanding tasks have also been reported by Cardoso-Leite et al.<sup>40</sup> Moreover, in line with our findings, an electroencephalography study<sup>41</sup> showed that heavy-use VGs had larger event-related potential amplitudes relative to NVGs in response to numerical targets under high load conditions, suggesting that heavy-use VGs may show greater sensitivity than NVGs to task-relevant stimuli under increased load, which in turn may underpin greater BOLD changes and improved behavioral performance compared with mild-use VGs and NVGs.

Our finding of less activation in VGs in occipital areas while performing better on the n-back task is consistent with a previous fMRI study<sup>33</sup> that used a visuomotor task and showed less activation in occipitoparietal regions in VGs and improved visuomotor task performance; these findings suggest a reduction in visuomotor cognitive performance measures as a consequence of the video gaming practice. In addition, in line with our results, Granek et al,<sup>4</sup> using an increasingly complex visuomotor fMRI task, observed greater prefrontal activation in 13 VGs who played a mean (SD) of 12.8 (8.6) hours per week during the preceding 3 years compared with 13 NVGs, which the authors related to the increased online control and spatial attention required by VGs for processing complex, visually guided reaching. Similarly, Gorbet and Sergio<sup>42</sup> found that VGs showed less motor-related activity in the cuneus, middle occipital gyrus, and cerebellum, which they explained as an indicator that VGs have greater neural efficiency when conducting visually guided responses. In addition, previous fMRI research has found significantly greater activation related to video gaming in regions associated with working memory, including the subparietal sulcus and the precuneus.<sup>43,44</sup> In a more recent study,<sup>45</sup> changes in BOLD signal in the subparietal lobe, precentral gyrus, and precuneus from before to after training using a video game with a working memory component predicted changes in performance in an untrained working memory task, suggesting a practice-induced plasticity in these regions.

Although video watching is highly confounded with video gaming in our fMRI samples, our models indicate that the response inhibition and working memory effects remained significant when controlling for video watching (in addition to behavioral and psychiatric problems), suggesting that

the observed BOLD alterations in the SST and n-back task are more specific to video gaming than video watching. This finding is important because it suggests that children must actively engage with a video's content, as opposed to passively watching a video, to exhibit altered brain activation in key areas of the brain involved in cognition.

## Limitations

This study has some limitations, and the findings should be interpreted with caution. The 2 groups were different in terms of sex, race and ethnicity, parental income, and mental health and behavioral scores. While the results show statistically different SSRTs (287.3 [9.8] vs 300.1 [9.6] milliseconds), these are very small differences without clear implications. In addition, video games regroup a variety of gaming categories that include action-adventure, shooters, puzzle solving, real-time strategy, simulation, and sports. These specific genres of video games may have different effects for neurocognitive development<sup>46</sup> because they do not all equally involve interactive (ie, multisensory and motor systems) and executive function processes. In addition, single vs multiplayer games may also have differential impacts on the brain and cognition.<sup>46</sup> Not including the video-gaming genre in our analyses is a limitation of the current study because the screen time survey in the ABCD database does not include additional information on the genre of video games played. Future large studies investigating the association between video gaming and cognition would benefit from including game genre as a moderating variable in analyses. Another limitation of the current study is the use of only cross-sectional study designs, which cannot provide enough evidence to resolve causality or the directionality of the associations among video gaming and other variables. For example, we cannot resolve whether mental health issues or brain function changes precede and drive video gaming or whether video gaming results in mental health symptoms or altered neuroplasticity. Future works benefiting from the longitudinal design of the ABCD study will enable researchers to move beyond association toward causation using causal approaches, such as discordant twin analyses, bayesian causal networks, and machine learning.

## Conclusions

Overall, even with consideration of the correlational nature of these cross-sectional data, the current findings are consistent with video gaming being associated with faster performance on cognitive tests that involve response inhibition and working memory and altered BOLD signal on these tasks, although the differences in task performances were very small and measured in fractions of milliseconds. The results raise the possibility that video gaming may provide a cognitive training experience with measurable neurocognitive effects. However, the CBCL behavioral and mental health scores were higher in children who played video games for 3 or more hours a day, with attention problems, depression, and ADHD scores significantly higher in the VGs compared with the NVGs. Future ABCD data releases will allow researchers to test for longitudinal effects in which video gaming might improve response inhibition, working memory, and other cognitive functions, as previously suggested in a longitudinal intervention study<sup>34</sup> in which episodic and short-term memory gains were maintained during a 3-month follow-up period, as well as the association of mental health symptoms with exposure to video gaming. The longitudinal design of the ABCD study will enable within-participant testing for the correlates of accumulated video-gaming practice over the years. By using methods such as cross-lagged correlations or causal inference, researchers can assess whether video gaming is associated with subsequent mental health symptoms, behavioral issues, or neurocognitive development in adolescents.

## ARTICLE INFORMATION

**Accepted for Publication:** August 20, 2022.

**Published:** October 24, 2022. doi:10.1001/jamanetworkopen.2022.35721

**Retraction and Replacement:** This article was retracted on April 10, 2023, to fix errors in the analysis in the Key Points, Abstract, main text, Table 1, and Figure 2 (see [Supplement 2](#) for the retracted article with errors highlighted and [Supplement 3](#) for the replacement article with corrections highlighted).

**Correction:** This article was corrected on August 8, 2023, to add clarifications to the text and [Supplement 1](#), report the demographic variables in Table 1 and the adjusted outcomes in Table 2, and correct Figures 1 and 2.

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**Acquisition, analysis, or interpretation of data:** All authors.

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**Critical revision of the manuscript for important intellectual content:** Chaarani, Yuan, Loso, Potter, Garavan.

**Statistical analysis:** Chaarani, Ortigara, Yuan, Loso, Garavan.

**Obtained funding:** Chaarani, Potter, Garavan.

**Administrative, technical, or material support:** Chaarani, Ortigara, Potter.

**Supervision:** Chaarani, Garavan.

**Conflict of Interest Disclosures:** Dr Potter reported receiving grants from the National Institutes of Health during the conduct of the study. No other disclosures were reported.

**Additional Contributions:** We thank Shana Adise, PhD, and Nicholas D. Allgaier, PhD (Department of Psychiatry, University of Vermont, Burlington), for conducting independent statistical analyses for the corrected article.

**Additional Information:** Data used in the preparation of this article were obtained from the Adolescent Brain Cognitive Development (ABCD) Study (<https://abcdstudy.org>) held in the National Institute of Mental Health Data Archive. Computations were performed on the Vermont Advanced Computing Core supported in part by award OAC-1827314 from the National Science Foundation.

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#### SUPPLEMENT 1.

**eMethods.** Stop Signal Task (SST), n-back Task, and fMRI Acquisition and Preprocessing

**eMethods and eResults.** List Sorting and Rey Auditory Verbal Learning Test

#### SUPPLEMENT 2.

Retracted Article With Errors Highlighted

#### SUPPLEMENT 3.

Replacement Article With Corrections Highlighted