Title

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Journal

Journal of Behavioral Addictions, 13(4)

ISSN

2062-5871

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Publication Date

2024-12-30

DOI

10.1556/2006.2024.00068

Peer reviewed

AKADÉMIAI KIADÓ

Journal of Behavioral Addictions

13 (2024) 4, 1051–1063

DOI:
10.1556/2006.2024.00068

FULL-LENGTH REPORT

The longitudinal association between reward processing and symptoms of video game addiction in the Adolescent Brain Cognitive Development Study

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Received: April 15, 2024 • Revised manuscript received: August 16, 2024 • Accepted: November 19, 2024
Published online: December 9, 2024

ABSTRACT

Background and aims: Video games are a common form of entertainment in adolescents, which may result in gaming habits characterized by impairment to reward-related decision-making. The aim of the current study was to investigate the relationship between reward processing and symptoms of gaming addiction in adolescents. *Methods:* Data from three consecutive follow-up years (years 2, 3 and 4) of the Adolescent Brain Cognitive Development (ABCD) Study were analyzed (n = 6,143, total observations = 12,745, mean age at year-2 = 12 years). Participants completed the Video Game Addiction Questionnaire (VGAQ) at each visit. Discrete stages of reward processing were measured at the year-2 visit using the Monetary Incentive Delay task while the participant completed a functional magnetic resonance imaging (fMRI) scan. Bayesian hierarchical linear models were employed to examine the longitudinal association between reward processing in regions of interest at year-2 and VGAQ scores over time. *Results:* Lower activation in the bilateral caudate during the anticipation of a large reward (β = −0.87, 95% CI: −1.68, −0.07) was associated with greater VGAQ scores over time. This implies that for each one-unit increase in brain activity in the caudate, there was an associated 0.87-point decrease in symptoms of gaming addiction as measured by the VGAQ. No association was found between reward feedback and VGAQ scores. *Discussion and Conclusions:* The findings suggest that abnormal reward processing in the caudate nucleus is associated with symptoms of gaming addiction in adolescents. These results provide a clearer understanding of the brain mechanisms involved in gaming addiction, which could inform future preventive and therapeutic strategies.

KEYWORDS

gaming addiction, video games, reward processing, adolescent, longitudinal, imaging

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INTRODUCTION

Background

Video game use is a common form of entertainment that can sometimes develop into a problematic condition. According to recent surveys, an estimated 71% of Americans under

18 play video games, typically about 13 h per week (Entertainment Software Association, 2022). While video games can offer small cognitive performance benefits in adolescents (Bader Chaarani et al., 2022), for some individuals, gaming can become problematic.

Problematic gaming behaviors are characterized by adverse effects on social and functional well-being, often referred to as gaming addiction (Petry & O'Brien, 2013). These negative consequences are particularly pronounced in children and adolescents, and include social isolation, poor academic outcomes, and emotional and behavioral issues (Gentile et al., 2011; Jeong & Kim, 2011; Lemmens, Valkenburg, & Peter, 2011). Notably, studies have found significant correlations between gaming and higher levels of depression and ADHD symptomatology (Bader Chaarani et al., 2022). The condition has garnered increasing attention in recent years. In 2013, the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) included Internet Gaming Disorder as a condition requiring further research (American Psychiatric Association & American Psychiatric Association, 2013). Subsequently, in 2018, the International Classification of Diseases (ICD-11) included Gaming Disorder as a recognized disorder characterized by impaired control over gaming, prioritization of gaming over other activities, and continuation or escalation of gaming despite negative consequences (World Health Organization, 2019/2021). Recent studies estimate that around 3% of the global population has gaming disorder, with higher prevalence rates in males and adolescents (Stevens, Dorstyn, Delfabbro, & King, 2020).

To date, neural research into gaming addiction has focused almost entirely on adult populations (Weinstein & Lejoyeux, 2020). However, adolescents may be particularly vulnerable to addiction due to greater reward-seeking and risk-taking behaviors, which can persist into adulthood (Bava & Tapert, 2010; Nora D Volkow & Wargo, 2022). Whether abnormal reward processing is associated with gaming problems in adolescents is less clear.

Neuroimaging studies implicate several brain regions involved in gaming addiction and different aspects of reward processing. The striatum is at the center of the brain network involved in reward evaluation, and is comprised of the nucleus accumbens (NAcc), the caudate nucleus, and the putamen (Cai et al., 2016; Haber, 2011). The NAcc is essential for the processing of rewards and influences the emotional and motivational aspects of reward processing (Haber & Knutson, 2010). The caudate nucleus is heavily involved in higher cognitive functions related to decision-making, reward-related learning, and neural activity related to reward anticipation (Grahn, Parkinson, & Owen, 2008; Haber & Knutson, 2010; Watanabe & Hikosaka, 2005). The pallidum is involved in reward encoding, motivational signaling, and proper valuation of reward outcomes (Haber, 2011; Ottenheimer, Richard, & Janak, 2018; Richard, Ambroggi, Janak, & Fields, 2016; Smith, Tindell, Aldridge, & Berridge, 2009).

Functional magnetic resonance imaging (fMRI) studies report abnormal brain activity in the striatum of adolescents and young adults with gaming addiction. For example, a study examining the correlates of gaming frequency and brain activity in adolescents reported significant neural differences between frequent and infrequent gamers (Kühn et al., 2011). Frequent gamers showed enhanced striatal activity during loss feedback in the Monetary Incentive Delay (MID) task, paralleling dopamine increases seen in pathological gamblers during losses (Kühn et al., 2011). Another study found that frequent online gamers had significantly less activation in the ventral striatum during the anticipation of large rewards when compared to non-gamers, suggesting a deficiency in the reward network (Hahn et al., 2014).

Information from the NAcc and pallidum travels to the dorsal anterior cingulate cortex (dACC) and parts of the prefrontal cortex like the orbitofrontal cortex (OFC), which are associated with evaluating reward value and outcomes (Haber, 2011). The dACC plays a role in reward monitoring and assessment of gains and losses (Heilbronner & Hayden, 2016). The OFC is important for valuing real and imaginary future rewards, with the medial OFC responding to reward outcomes and the lateral OFC coding for negative reinforcement (Bray, Shimojo, & O'Doherty, 2010; Noonan, Mars, & Rushworth, 2011; Peters & Büchel, 2010). Abnormal prefrontal cortex activity has been linked to gaming addiction risk, indicating greater risk-taking tendencies and reduced loss aversion in adolescents with gaming addiction (Qi et al., 2016).

The amygdala is closely linked to emotional processing and reward evaluation, and recent studies have found that the amygdala is reliably activated by both primary (e.g., food) and secondary (e.g., money) rewards irrespective of loss (Sescousse, Caldú, Segura, & Dreher, 2013; Yacubian et al., 2006). Likewise, the insula appears to be involved in the subjective affective experience of rewards, and may also be strongly activated when an individual is faced with a potential loss (Sescousse et al., 2013). A systematic review of the neurobiology of impulsivity found that abnormalities in the amygdala and insula in individuals with Internet Gaming Disorder may indicate a problematic regulation of negative emotions (Li, Turel, & He, 2023). In addition, a study of young adults reported significantly higher functional connectivity with the left amygdala over the right insula and the right amygdala with the left insula in those with Internet Gaming Disorder (Ko et al., 2015).

Overall, the brain regions involved in the reward network are interrelated and perform overlapping functions, making it crucial to examine multiple brain regions associated with reward processing to identify specific contributions to gaming addiction. By identifying the distinct roles that different brain regions play in reward processing, future studies can better target these areas to develop more precise neurobiological models of gaming addiction and lead to more accurate identification of individuals at risk for developing a gaming problem. Moreover, this understanding might also contribute to public health initiatives aimed at promoting healthy gaming behaviors.

Study aims

The generalizability of current research into gaming addiction is limited by small sample sizes and a relative lack of longitudinal studies, limiting our understanding of how this may manifest into later life addictive behaviors. Most neuroimaging studies on gaming addiction focus on the reaction to gains rather than losses, making it difficult to fully characterize reward processing at different stages of decision-making (Y. W. Yao, Zhang, Fang, Liu, & Potenza, 2022). Furthermore, to comprehensively understand gaming addiction, it is essential to consider various factors that may influence gaming behaviors, such as age, sex, socioeconomic status, and environmental influences. These factors can impact the development and severity of gaming addiction and must be accounted for in research to accurately assess their relationships with gaming behaviors.

Here, we examined the relationship between neural activity during the anticipation and feedback of monetary rewards and monetary losses and longitudinal symptoms of gaming addiction. We used task-fMRI data from the Monetary Incentive Delay (MID) task at the year-2 visit of the Adolescent Brain Cognitive Development[SM] (ABCD) Study. Outcome measures included gaming addiction scores collected using the Video Game Addiction Questionnaire (VGAQ) at the year-2 (mean age = 12 years), year-3 (mean age = 12.9 years), and year-4 (mean age = 14 years) study visit. We hypothesize that decreased brain activity in key reward processing regions during the anticipation phase of the MID task will be strongly associated with greater VGAQ scores over time. We further hypothesize that an increase in brain activity in reward processing regions during the feedback phase of the MID task will be strongly associated with greater VGAQ scores. The current study was completed using data from the ABCD Study© 5.1 data release (http://dx.doi.org/10.15154/z563-zd24).

METHODS

Participants

The ABCD Study is a prospective cohort study that enrolled 11,878 children aged 9–10 at 21 currently active research sites in the United States (Nora D. Volkow et al., 2018). This ongoing study will follow participants until they are approximately 19–20 years old (Garavan et al., 2018). The study aims to characterize the psychological and neurobiological development of pre-adolescents into young adulthood (Garavan et al., 2018). The ABCD Study protocol includes a biennial magnetic resonance imaging (MRI) scan (Casey et al., 2018; Garavan et al., 2018). Adolescents, along with a participating caregiver, also completed a series of sociodemographic and other questionnaires at each study visit (Barch et al., 2018).

The current longitudinal analysis included adolescents that attended the year-2, year-3, or year-4 visit. Data used in the analysis was collected between approximately July 2018 and January 2022 (age range 10–15). Previous study visits were excluded due to absence of measures related to video game addiction (i.e., the VGAQ was not collected prior to the year-2 visit). Children that failed the task-fMRI quality control or were missing the VGAQ measure were also excluded from these analyses. The final analytic sample included 12,745 observations from 6,143 children.

Measures

The Video Game Addiction Questionnaire. The VGAQ is a 6-item questionnaire on a 6-point Likert scale (0 = Never, 1 = Very Rarely, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Very Often) (Fig. S1 in Supplementary Materials) (Bagot et al., 2022). Psychometric findings support the validity of the VGAQ in the measurement of video game addiction in adolescents (Bagot et al., 2022). The VGAQ was completed by participants that reported playing video games (i.e., the VGAQ was skipped if a child reported not playing any single-player or online multiplayer video games during a typical week). There are no current recommendations on what constitutes a cut-off for problematic gaming using the VGAQ. For the current analyses, the VGAQ scores were calculated for participants using the sum of all responses. Creation of a summary score from Likert-type items is recommended when there are five or more categorical levels and there is strong internal consistency reliability (VGAQ McDonald's ω at year-2 = 0.86, year-3 = 0.87, year-4 = 0.87) (Bagot et al., 2022; Johnson & Creech, 1983; Rickards, Magee, & Artino Jr, 2012; Sullivan & Artino, 2013). VGAQ scores ranged from 0 to 30, with higher scores indicating greater symptoms of gaming addiction.

Imaging measures. The Monetary Incentive Delay (MID) task measures neural activity related to the anticipation and receipt (i.e., feedback) of rewards and losses (Casey et al., 2018; Knutson, Westdorp, Kaiser, & Hommer, 2000). The ABCD version of the MID task included 10 possible contrasts (Fig. S2 in Supplementary Materials) intended to characterize general reward processing. As part of the task, participants were presented with an incentive cue consisting of five trial types: win money ($0.20 or $5), lose money (−$0.20 or −$5), or no incentive ($0) (Fig. 1) (Knutson et al., 2000). Task-related activity was localized by subtracting the neutral condition from a positive or negative condition (e.g., winning $5). Participants were shown a cue (pink circle, yellow square, or blue triangle) at the beginning of each trial that indicated the trial type (win, loss, no incentive) and amount at stake (Casey et al., 2018). Participants then had to press a button as soon as the target was shown on screen. The trial was lost if the participant did not press the button within a certain time limit. A feedback message informed the participant of the trial outcome. Importantly, the task motivated participants by providing real monetary incentives related to performance (Casey et al., 2018). Participants were paid an average of $21 for their performance on the MID task (Casey et al., 2018). The MID task was designed to ensure a success rate near 60% for

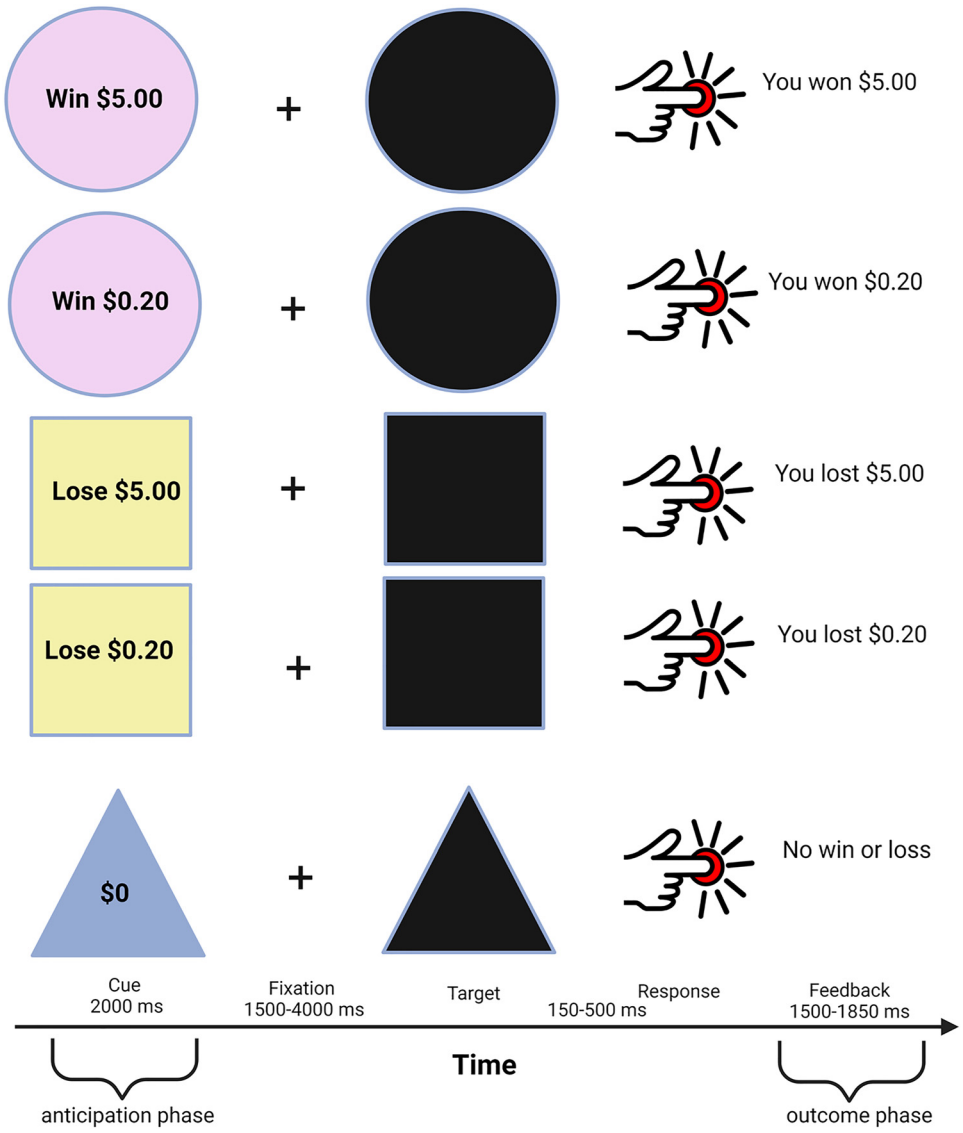

Fig. 1. Each trial of the MID task begins with an incentive cue (2,000 ms) of five possible trial types (Win $.20, Win $5, lose $.20, Lose $5, $0). The incentive cue represents the anticipation phase. This is followed by a jitter anticipation event (1,500–4,000 ms). Next, a variable target (150–500 ms) appears prompting the participant to respond as quickly as possible to either win money or avoid losing money. The target event is followed by a feedback message informing the participant of the trial outcome. Figure recreated from Casey, 2018; Casey et al., 2018). Figure created using Biorender

all win money trials (Casey et al., 2018). A total of 2 runs with 50 trials each (10 per trial type) were completed by participants (B Chaarani et al., 2021). In total, there were 40 reward and loss trials and 20 neutral trials included in the anticipation phase. The feedback phase included approximately 24 positive feedback and 16 negative feedback trials per run (Casey et al., 2018). The MID task duration was 5 min and 42 s per run (Casey et al., 2018).

Image processing. Image processing and estimation of activity in regions-of-interest (ROIs) was done by the ABCD Data Analysis, Informatics & Resource Center (DAIRC). Details of the processing and curation of imaging data have been previously published (Hagler et al., 2019). Briefly, cortical and subcortical surface-based values for ROIs were generated using the FreeSurfer brain imaging software package (Hagler et al., 2019). Individual subject level brain activity related to the MID task (e.g., contrast of brain activity in a ROI during a large reward anticipation trial versus a no incentive trial) was calculated using a general linear model (Hagler et al., 2019). The resulting output included contrast beta weights that represent the weighted average across two runs for each participant. In our analyses, consistent with previous ABCD analyses of behavioral outcomes, the contrast beta weights were the exposure of interest used to examine reward processing (Hawes et al., 2021). The current study focused on four separate contrasts: anticipation of a large reward versus anticipation of no loss or reward, anticipation of a large loss versus anticipation of no loss or reward, large and small reward with positive

feedback versus large and small reward with negative feedback, and large and small loss with positive feedback versus large and small loss with negative feedback (Fig. S3 in Supplementary Materials).

Neuroimaging data exclusion. The DAIRC excluded imaging data that failed the quality control (QC) process at the year 2 visit (Fig. S4 in Supplementary Materials) (Hagler et al., 2019). In addition, we excluded participant imaging data if they were not recommended for inclusion due to task-specific quality control issues (imgincl_mid_include = 0) (Hagler et al., 2019). The task-specific exclusion criteria included the following recommendations: 1) fewer than 1 MID series that passed QC (iqc_mid_ok_ser = 0), 2) unacceptable performance for feedback analyses (tfmri_mid_beh_performflag = 0), and 3) fewer than 200 degrees of freedom (tfmri_mid_all_b_dof < 200). More information on the variables can be obtained on the ABCD Wiki (https://wiki.abcdstudy.org/) and ABCD Data Dictionary (https://data-dict.abcdstudy.org/).

Covariates. The main effects of the following variables were considered as covariates: age of the child, sex at birth, parent-reported race/ethnicity of the child, household income, youth-reported neighborhood safety, youth-reported parental monitoring scores, parent-reported ADHD Kiddie Schedule for Affective Disorders and Schizophrenia for DSM-5 (KSADS-COMP) diagnosis, and symptoms of anxiety or depression. Sex at birth was included due to the increased risk of problematic gaming habits in males (Chen, Oliffe, & Kelly, 2018). Parent-reported race/ethnicity of the child was included due to greater frequency of media use in minority children (Carson, B, Chen, & Alegria, 2012). Household demographics (e.g., household income, parent educational attainment) were considered potential confounders due to their strong correlation with problematic gaming habits in the gaming literature (Nagata, Singh, et al., 2022). Household income was coded as a categorical variable with the following levels: <$50,000, $50,000 to <$100,000, ≥$100,000, Do Not Know, Refuse to Answer. ADHD diagnosis was considered for adjustment due to the link with excessive and problematic gaming (Weiss, Baer, Allan, Saran, & Schibuk, 2011). Presence of ADHD (1 = Yes, 0 = No) was measured using the parent-report on the KSADS-COMP (Townsend et al., 2020). Parental monitoring and neighborhood safety were included as potential confounders due to their strong correlation with gaming problems (i.e., greater parental monitoring and neighborhood safety is associated with decreased problematic gaming habits) (Ding, Li, Zhou, Dong, & Luo, 2017; Nagata, Singh, et al., 2022). Symptoms of anxiety or depression were not included in the final model due to possibly being on the causal pathway between ROIs and gaming outcomes (Männikkö, Ruotsalainen, Miettunen, Pontes, & Kääriäinen, 2017). Covariates that were plausible confounders and improved the model fit were considered for adjustment. Models were compared using leave-one-out (LOO) cross-validation information criterion. Model comparison using LOO values is considered a robust Bayesian alternative to comparable fit criterion (e.g., Akaike information criterion) (Vehtari, Gelman, & Gabry, 2017).

Statistical analysis

Bayesian hierarchical linear models were used to examine the association between beta-weights extracted from ROIs during the MID task at the year-2 visit and VGAQ scores over time. The primary outcome measure was the child's total VGAQ score at the year-2, year-3, and year-4 visits (i.e., a time-variant measure). The bilateral ROIs included the caudate nucleus, dorsal anterior cingulate cortex (DACC), insula, lateral orbitofrontal cortex (LOFC), medial orbitofrontal cortex (MOFC), nucleus accumbens (NAcc), pallidum, putamen, and amygdala. Results of the Bayesian hierarchical linear models were expressed as beta coefficients and 95% Bayesian posterior credible intervals (CI). Evidence of an association was defined as any CI that did not include the null value (i.e., excluded a beta coefficient = 0). The models included a nested random effects structure that accounted for clustering of participants within family units (Dick et al., 2020). A centered time variable (interview age) was included as a fixed and random slope term to account for correlated and heteroscedastic residuals over time within person (Singer & Willett, 2003). We utilized four separate hierarchical linear models to investigate the relationship between brain activity and symptoms of gaming addiction. Each model represented a different experimental condition: anticipation of a large reward ($5) versus neutral ($0), anticipation of a large loss ($5) versus neutral ($0), reward positive versus negative feedback, and loss positive versus negative feedback. Each model included only the beta weights representing the average ROI activity during that specific condition (e.g., all beta weights related to ROI activity during large reward anticipation). This approach allowed us to isolate the effects of brain activity during each condition on the trajectory of gaming addiction symptoms over time.

Bayesian hierarchical modeling reduces the risk of a false "statistically significant" finding by incorporating partial pooling of information across groups (e.g., family units) and conditions (e.g., large reward anticipation) (Gelman, Hill, & Yajima, 2012). The partial pooling, along with the inclusion of random effects in the model, results in estimates that are more regularized compared to traditional frequentist approaches (Gelman et al., 2012). Additionally, Bayesian hierarchical modeling accounts for multiplicity by integrating prior information and uncertainty into the analysis, providing a robust framework for inference. Weakly informative priors were specified for the fixed and random effects to allow the results to be primarily driven by the data, while still benefiting from the regularizing influence of the priors. All analyses were conducted using Bayesian inference methods with the brms package in R (Bürkner, 2017; R. Team, 2019; R. C. Team, 2013). Tables were created using the *tableone* package in R (Yoshida, Bohn, & Yoshida, 2020). Data wrangling was conducted using the tidyverse package

in R (Wickham et al., 2019). Statistical analyses were performed using R version 4.2.2 and R Studio version 2023.06.1 (R. Team, 2019; R. C. Team, 2013). Code for the replication of current study results can be obtained on GitHub: https://github.com/Daniel-Adan-Lopez/ABCD_Gaming.

Ethics

This work has been conducted in accordance with the tenets of the Declaration of Helsinki and with approval from the ethics review board at the University of Rochester School of Medicine and Dentistry. Parental consent and child assent were obtained at each ABCD Study visit (Garavan et al., 2018). Caregiver consent and child assent were approved by the Institutional Review Board at each ABCD study site.

RESULTS

Demographic characteristics of the sample

The analytic sample included 6,143 adolescents (12,745 observations) that attended the year-2, year-3, or year-4 visit and did not have missing data (Table 1). Missing data was minimal for non-imaging predictor variables (64 observations or 0.5% of the sample). The mean age of children included in the sample ranged from 12 to 14 across the three timepoints. Most children were male, White, and had a parent with a college degree. Around 5–6% of children had a present diagnosis of ADHD at each study visit.

Participants excluded due to poor data quality during the MID task at the year-2 visit were more likely to be older, from a minority group, and from a household with less than some college educational attainment (Table S1 in Supplementary Materials). There was no significant difference in the year-2 VGAQ score of included and excluded participants ($p = 0.07$). Participants excluded due to missing VGAQ data (i.e., reported not playing any video games) were more likely to be female, White, from households with a postgraduate degree, and from households with incomes ≥ $100,000 (Table S2 in Supplementary Materials).

Table 1. Analytic sample demographics at each ABCD study visit

	Year-2 (n = 4,818)	Year-3 (n = 5,245)	Year-4 (n = 2,682)
Age of child (months(SD))	143.6 (7.9)	154.5 (7.7)	168.4 (8.1)
Child sex at birth			
Male	2,959 (61.4)	3,213 (61.3)	1,664 (62.0)
Female	1,859 (38.6)	2,032 (38.7)	1,018 (38.0)
Race/ethnicity of child			
Asian	78 (1.6)	88 (1.7)	49 (1.8)
Black	657 (13.6)	626 (11.9)	296 (11.0)
Hispanic	916 (19.0)	990 (18.9)	570 (21.3)
White	2,671 (55.4)	2,999 (57.2)	1,510 (56.3)
Other	496 (10.3)	542 (10.3)	257 (9.6)
Household Income ($)			
<50,000	1,254 (26.0)	1,283 (24.5)	694 (25.9)
50,000 to <100,000	1,364 (28.3)	1,483 (28.3)	773 (28.8)
≥100,000	1,831 (38.0)	2,102 (40.1)	1,016 (37.9)
Do not know	190 (3.9)	189 (3.6)	102 (3.8)
Refuse to answer	179 (3.7)	188 (3.6)	97 (3.6)
Household Educational Attainment			
< HS Diploma	294 (6.1)	291 (5.5)	152 (5.7)
HS Diploma/GED	470 (9.8)	456 (8.7)	242 (9.0)
Some College	1,467 (30.4)	1,562 (29.8)	816 (30.4)
Bachelor	1,405 (29.2)	1,568 (29.9)	799 (29.8)
Post Graduate Degree	1,176 (24.4)	1,360 (25.9)	668 (24.9)
Neighborhood Safety			
Strongly Disagree	115 (2.4)	118 (2.2)	58 (2.2)
Disagree	239 (5.0)	249 (4.7)	117 (4.4)
Neutral	915 (19.0)	967 (18.4)	513 (19.1)
Agree	1,581 (32.8)	1,707 (32.5)	875 (32.6)
Strongly Agree	1,968 (40.8)	2,204 (42.0)	1,119 (41.7)
KSADS ADHD Diagnosis (Present)			
Yes	284 (5.9)	289 (5.5)	142 (5.3)
No	4,534 (94.1)	4,956 (94.5)	2,540 (94.7)
Parental Monitoring (mean(SD))	4.46 (0.47)	4.36 (0.50)	4.39 (0.48)
VGAQ score	6.33 (6.19)	7.02 (6.39)	6.77 (6.24)

Note: Distributions are presented as n (%), except where noted.
SD = Standard Deviation.
KSADS = Kiddie Schedule for Affective Disorders and Schizophrenia.
VGAQ = Video Game Addiction Questionnaire.

Video Game Addiction Questionnaire

The mean VGAQ score at the three timepoints was 6.3, 7.0, and 6.8, respectively (range = 0–30). Approximately 19.3% of the analytic sample had a VGAQ score of 0. A histogram of the distribution at each study visit is included in the supplementary materials (Fig. S5 in Supplementary Materials). The distribution of responses for individual items found that a substantial portion of participants reported low-frequency gaming behaviors (Table S3 in Supplementary Materials). The most endorsed items were ‘ I spend a lot of time thinking about playing video games’ and ‘I play video games so I can forget about my problems,’ but even these items had a considerable number of ‘never,’ ‘very rarely,’ and ‘rarely’ responses. VGAQ scores were greater in males, non-White children, and children from lower income households (Table 2). Children with and without a present diagnosis of ADHD had a mean VGAQ score of 8.5 and 6.3 at the year-2 visit, respectively. Children that strongly disagreed or disagreed that their neighborhood was safe from crime had a mean VGAQ score of 9.6 and 8.5 at the year-2 visit.

Associations between large reward anticipation and VGAQ scores

The fully adjusted models found an inverse association between large reward anticipation and VGAQ score in the bilateral caudate (Table 3). Holding other variables constant, a one-unit increase in the anticipation of a large reward versus neutral condition in the bilateral caudate was associated with a 0.87-point decrease in VGAQ score

Table 2. Distribution of covariates and VGAQ score in the ABCD Study

	Video Game Addiction Score at year-2 (n = 4,818)	Video Game Addiction Score at year-3 (n = 5,245)	Video Game Addiction Score at year-4 (n = 2,682)
Child sex at birth			
Male	8.2 (6.5)	8.8 (6.4)	8.2 (6.2)
Female	3.8 (5.1)	4.6 (5.6)	4.8 (5.8)
Race/ethnicity of child			
Asian	6.4 (6.1)	7.4 (6.1)	8.1 (6.0)
Black	8.0 (7.4)	8.3 (7.5)	7.1 (7.1)
Hispanic	7.1 (6.6)	8.1 (6.8)	7.6 (6.7)
White	5.7 (5.7)	6.4 (5.9)	6.4 (5.8)
Other	6.8 (6.6)	7.2 (6.5)	7.4 (6.7)
Household Income ($)			
<50,000	7.8 (7.2)	8.3 (7.2)	7.8 (6.9)
50,000 to <100,000	6.4 (6.2)	7.1 (6.3)	6.7 (6.2)
≥100,000	5.4 (5.5)	6.3 (5.8)	6.3 (5.8)
Do not know	7.4 (6.8)	8.2 (7.0)	7.3 (6.1)
Refuse to answer	6.9 (6.6)	7.2 (6.4)	7.2 (6.4)
Household Educational Attainment			
< HS Diploma	7.8 (7.1)	7.9 (7.3)	6.8 (6.3)
HS Diploma/GED	7.8 (7.0)	8.2 (7.2)	7.8 (6.8)
Some College	7.1 (6.8)	7.8 (6.8)	7.3 (6.5)
Bachelor	5.8 (5.9)	6.5 (6.0)	6.6 (6.1)
Post Graduate Degree	5.5 (5.6)	6.4 (5.8)	6.3 (5.8)
Neighborhood Safety			
Strongly Disagree	9.6 (8.0)	9.3 (7.5)	8.8 (7.4)
Disagree	8.5 (7.6)	8.1 (7.2)	7.4 (6.4)
Neutral	7.4 (6.6)	7.9 (6.7)	7.6 (6.4)
Agree	6.3 (6.0)	7.2 (6.3)	6.9 (6.4)
Strongly Agree	5.8 (6.0)	6.4 (6.3)	6.3 (5.8)
KSADS ADHD Diagnosis (Present)			
Yes	8.5 (6.9)	9.0 (6.7)	9.7 (6.9)
No	6.2 (6.1)	6.9 (6.4)	6.6 (6.2)

Note: Distributions are represented as mean (SD) unless otherwise noted.

Table 3. Association between reward anticipation and VGAQ score

	Anticipation of Large Reward vs. Neutral VGAQ Score (n = 6,143) β (95% CI)	Anticipation of Large Loss vs. Neutral VGAQ Score (n = 6,143) β (95% CI)
Bilateral		
Amygdala	−0.5 (−1.05, 0.6)	−0.49 (−1.08, 0.1)
Caudate	**−0.87 (−1.68, −0.07)**	−0.64 (−1.47, 0.21)
Dorsal ACC	−0.12 (−1.03, 0.81)	0.34 (−0.6, 1.29)
Insula	0.13 (−0.94, 1.19)	−0.0 (−1.13, 1.11)
LOFC	0.34 (−0.25, 0.94)	0.48 (−0.13, 1.09)
MOFC	0.03 (−0.32, 0.39)	−0.03 (−0.38, 0.32)
NACC	0.42 (−0.01, 0.86)	0.04 (−0.43, 0.5)
Pallidum	0.1 (−0.69, 0.9)	0.06 (−0.77, 0.9)
Putamen	0.09 (−0.98, 1.12)	−0.3 (−1.35, 0.73)

Note: ACC = Anterior Cingulate Cortex, LOFC = Lateral Orbitofrontal Cortex, NACC = Nucleus Accumbens, MOFC = Medial Orbitofrontal Cortex, VGAQ = Video Game Addiction Questionnaire.
Note: All models are adjusted for age, sex, race/ethnicity, household education, household income, neighborhood safety, parental monitoring, KSAD ADHD diagnosis, and study site.
Bold = Credible interval excludes the null value of 0.

(β = −0.87, 95% CI: −1.68, −0.07). There were no other ROIs associated with VGAQ scores in the large reward anticipation condition.

Associations between large loss anticipation and VGAQ scores

The fully adjusted models did not find an association between ROIs during the large loss anticipation condition and VGAQ scores over time.

Associations between reward feedback and VGAQ scores

The models did not find evidence of an association between reward positive feedback or loss positive feedback and VGAQ scores over time (Table 4).

DISCUSSION AND CONCLUSIONS

The current study examined the longitudinal association between anticipatory-feedback phase contrasts and symptoms of gaming addiction in a large sample of adolescents. We found that an increased response in the bilateral caudate during the anticipation of a large reward was associated with decreased VGAQ scores over time. The feedback phase of reward processing did not predict VGAQ scores in the analytic sample. These findings highlight the role of the caudate nucleus in gaming addiction.

The caudate and symptoms of gaming addiction

Our results indicate that blunted activity in the caudate nucleus is associated with greater symptoms of gaming addiction over time. This finding is consistent with literature suggesting that abnormal striatal functioning during the anticipation of rewards is linked to addiction risk (Balodis & Potenza, 2015; Y.-W. Yao et al., 2020). For example, a study measuring dopamine receptors in young adults with (n = 5) and without (n = 7) Internet addiction found an inverse association between Internet addiction severity and dopamine receptors in the left dorsal caudate, and significantly fewer dopamine receptors in the bilateral caudate of participants with Internet addiction (Kim et al., 2011). Another study found that the volume of the right caudate and right nucleus accumbens was significantly greater in 27 persons (mean age = 17.9) with Internet Gaming Disorder compared to 30 healthy controls (mean age = 18.3) (Cai et al., 2016). These results support our observation that reduced caudate activation correlates with higher gaming addiction symptoms, suggesting that a blunted reward response in this region may contribute to problematic gaming behaviors.

Conversely, some studies have reported increased caudate activation in addicted gamers during reward processing. For instance, a study with young adults found exaggerated brain activity in the caudate during reward anticipation in individuals with gaming addiction (Wang et al., 2021). Another study found increased activity in the caudate when young adult participants with a gaming addiction viewed gaming-related pictures (Ko et al., 2009). Differences from our findings may be attributed to the specific tasks used in these studies, which could highlight the diminished sensitivity to non-gaming related rewards in participants with symptoms of gaming addiction.

Protective role of caudate activation

Higher activation in the caudate nucleus during the anticipation of a large reward may serve as a protective factor against gaming addiction. The caudate is a fundamental contributor to successful goal-directed action due to its connectivity with higher level cognitive areas, such as the dorsolateral prefrontal cortex (Grahn et al., 2008). Lower activation may indicate that the brain's reward system has become less responsive to standard rewards in certain gamers.

Table 4. Association between reward feedback and VGAQ score

	Reward Positive vs. Negative Feedback VGAQ Score (n = 6,143) β (95% CI)	Loss Positive vs. Negative Feedback VGAQ Score (n = 6,143) β (95% CI)
Bilateral		
Amygdala	0.26 (−0.3, 0.8)	−0.03 (−0.53, 0.46)
Caudate	−0.04 (−0.85, 0.77)	−0.42 (−1.2, 0.39)
Dorsal ACC	0.23 (−0.67, 1.1)	−0.03 (−0.91, 0.85)
Insula	0.71 (−0.34, 1.78)	−0.01 (−1.03, 1.01)
LOFC	0.02 (−0.54, 0.56)	0.2 (−0.35, 0.76)
MOFC	0.06 (−0.28, 0.4)	0.24 (−0.09, 0.58)
NACC	0.12 (−0.28, 0.53)	0.11 (−0.3, 0.52)
Pallidum	0.26 (−0.5, 1.0)	0.33 (−0.45, 1.12)
Putamen	−0.87 (−1.85, 0.14)	−0.17 (−1.12, 0.78)

Note: ACC = Anterior Cingulate Cortex, LOFC = Lateral Orbitofrontal Cortex, NACC = Nucleus Accumbens, MOFC = Medial Orbitofrontal Cortex, VGAQ = Video Game Addiction Questionnaire.
Note: All models are adjusted for age, sex, race/ethnicity, household education, household income, neighborhood safety, parental monitoring, KSAD ADHD diagnosis, and study site.
Bold = Credible interval excludes the null value of 0.

A study using the MID task to examine neural responses in addicted (n = 22, mean age = 22.3) and non-addicted gamers (n = 27, mean age = 22) reported blunted caudate activity in the former (Y.-W. Yao et al., 2020). Interestingly, the group differences in reward processing were only noted during the feedback stages of a loss condition, not during the anticipation of a reward. A study comparing World of Warcraft gamers with non-gamers observed blunted striatal activity in response to large monetary rewards in the former group (Hahn et al., 2014). Additionally, a study with a community sample of 1,510 adolescents (mean age = 14.5) reported positive activation of the bilateral caudate during the reward anticipation phase of the MID Task, indicating that greater activation in response to rewards reflects typical functioning in healthy adolescents (Cao et al., 2019). A meta-analysis of neuroimaging studies using adolescent samples similarly found positive activation of the caudate nucleus during reward anticipation (Silverman, Jedd, & Luciana, 2015). Collectively, the inverse relationship between reward anticipation and symptoms of gaming addiction may signal a blunted reward response and a reduced sensitivity to everyday rewards in certain gamers.

Strengths

The strengths of this study include a large, diverse sample of adolescents with measurement of gaming addiction symptoms across multiple timepoints. Multivariable methods reduced the influence of potential confounders (e.g., ADHD diagnosis, parental monitoring) and strengthens the validity of the associations observed. The use of Bayesian hierarchical models further improved the precision of our measures of association by accounting for the shared variance within families in the ABCD Study. Instead of using arbitrary cut points, we opted for a total score for the VGAQ. This approach minimized the risk of misclassification and allowed for a more nuanced understanding of gaming addiction that captures the full spectrum of gaming behaviors, from non-problematic to potentially problematic use. Finally, the study included the feedback phase of the MID task rather than solely focusing on anticipatory processing. By doing so, we characterized the decision-making process in children that play video games and detected differences in discrete stages of reward processing.

Limitations

There were several limitations in this study. First, the analytic sample was substantially reduced by the exclusion of children with MID task data that did not meet QC standards. Previous research using the ABCD Study data has noted that certain groups (e.g., minority children, children from lower income households) were disproportionately excluded due to poor imaging quality (Cosgrove et al., 2022; Gard, Hyde, Heeringa, West, & Mitchell, 2023). The pattern of missing task-fMRI data likely harmed the generalizability of our findings, although we did not find a significant difference in the VGAQ scores of children with and without missing MRI data. Second, exclusion of children that did not complete the VGAQ measure meant that our sample included only children that play video games. Recent national surveys estimate that 71% of Americans under 18 play video games (Entertainment Software Association, 2022). Approximately 73% of children reported playing video games at the year-2 ABCD Study visit. Consequently, we expect that the study findings will have broad applicability to the general population despite exclusion criteria. The study period coincided with the COVID-19 pandemic, which may have influenced VGAQ scores. Although we did not observe a significant difference in mean VGAQ score across the three time points, there is evidence that screen time significantly increased among ABCD participants during the pandemic (Nagata, Cortez, et al., 2022). Additional time points will be necessary to fully understand the pandemic's impact and other factors (e.g., state policies) on trajectories of gaming addiction symptoms. Finally, we only had partial year-4 data, resulting in fewer than three timepoints for some children. Future ABCD Study data releases will provide critical information on the trajectories of gaming addiction and reward-processing.

Directions for future research

The findings of this study open several avenues for future research. First, additional time points will help elucidate the role of the caudate nucleus as adolescents transition into adulthood and provide insight into whether this relationship persists over time or changes with continued exposure to gaming. Second, research should explore modifiable factors that could help prevent the onset of gaming addiction symptoms, such as family dynamics or social support. Third, future studies could explore intervention strategies that target caudate nucleus activity to mitigate gaming addiction. For example, neurofeedback training, a noninvasive technique used to modulate brain activity in the dorsal striatum, could be explored as a potential treatment approach (Zhao et al., 2021).

Implications of the study findings

The findings from our study, conducted with a generally healthy population, provide valuable insights into the early neural markers of gaming addiction. By identifying the relationship between caudate activation and symptoms of gaming addiction in a population that largely falls within the range of typical gaming behavior, our study contributes to understanding the potential boundary between healthy and problematic gaming. This knowledge is critical for developing interventions aimed at promoting healthy gaming habits before gaming behavior escalates into addiction. Future work could build on these findings by exploring how neural activity in reward-related regions could serve as early indicators for potential targeted interventions.

CONCLUSIONS

Our findings suggest that the caudate nucleus plays a significant role in gaming addiction, with greater activation

potentially serving as a protective factor. These insights contribute to our understanding of the neural mechanisms underlying gaming addiction and highlight the importance of the caudate in reward processing.

Funding sources: Work on the ABCD study at the University of Rochester (UR) site is supported by a grant from the National Institute on Drug Abuse to EGF and JJF (NIDA – U01 DA050988). Neuroimaging at UR is supported by the Translational Neuroimaging and Neurophysiology (TNN) core of the UR Intellectual and Developmental Disabilities Research Center (UR-IDDRC), which is funded by a center grant from the Eunice Kennedy Shriver National Institute of Child Health and Human Development to JJF (NICHD P50 HD103536). Author EGF serves as Director of the TNN core. Adolescent Brain and Cognitive Development study is a service mark of the U.S. Department of Health and Human Services. The ABCD study is a registered trademark of the U.S. Department of Health and Human Services. DAL was funded by a National Institutes of Health (NIH)/National Institute of General Medical Sciences (NIGMS) grant (K12GM150451).

Data used in the preparation of this article were obtained from the Adolescent Brain Cognitive Development℠ (ABCD) Study (https://abcdstudy.org), held in the NIMH Data Archive (NDA). This is a multisite, longitudinal study designed to recruit more than 10,000 children age 9–10 and follow them over 10 years into early adulthood. The ABCD Study® is supported by the National Institutes of Health and additional federal partners under award numbers U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA 050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA 051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA 041089, U24DA041123, U24DA041147. A full list of supporters is available at https://abcdstudy.org/federal-partners.html. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/consortium_members/. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in the analysis or writing of this report. This manuscript reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators. The ABCD data repository grows and changes over time. The ABCD data used in this report came from https://doi.org/10.15154/1523041. DOIs can be found at https://doi.org/10.15154/1526509.

Authors' contribution: DL: Study concept and design, analysis and interpretation of data, statistical analysis, manuscript writing JF: Study concept and design, analysis and interpretation of data, study supervision EF: Study concept and design, analysis and interpretation of data, study supervision EVW: Study concept and design, analysis and interpretation of data, statistical analysis WT: Study concept and design, analysis and interpretation of data, statistical analysis.

All authors had full access to all data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Conflict of 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.

SUPPLEMENTARY MATERIAL

Supplementary data to this article can be found online at https://doi.org/10.1556/2006.2024.00068.

ABBREVIATIONS

ABCD	Adolescent Brain Cognitive Development
NAcc	Nucleus Accumbens
DACC	Dorsal Anterior Cingulate Cortex
mOFC	Medial Orbitofrontal Cortex
lOFC	Lateral Orbitofrontal Cortex
CI	Credible interval
ROI	Region of interest
CBCL	Child Behavior Checklist
MID	Monetary Incentive Delay
ADHD	Attention-deficit/hyperactivity disorder

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