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An fMRI study of cognitive control in problem gamers

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ABSTRACT

A small proportion of video game players develop uncontrolled gaming behavior. A dysfunctional cognitive control circuit may explain this excessive behavior. Therefore, the current study investigated whether problem gamers are characterized by deficits in various aspects of cognitive control (inhibitory control, error processing, attentional control) by measuring brain activation using functional magnetic resonance imaging during Go–NoGo and Stroop task performance. In addition, both impulsivity and attentional control were measured using self-reports. Participants comprised 18 problem gamers who were compared with 16 matched casual gaming controls. Results indicate significantly increased self-reported impulsivity levels and decreased inhibitory control accompanied by reduced brain activation in the left inferior frontal gyrus (IFG) and right inferior parietal lobe (IPL) in problem gamers relative to controls. Significant hypoactivation in the left IFG in problem gamers was also observed during Stroop task performance, but groups did not differ on behavioral and self-reported measures of attentional control. No evidence was found for reduced error processing in problem gamers. In conclusion, the current study provides evidence for reduced inhibitory control in problem gamers, while attentional control and error processing were mostly intact. These findings implicate that reduced inhibitory control and elevated impulsivity may constitute a neurocognitive weakness in problem gamers.

1. Introduction

Video gaming has become very popular since the enormous increase in the use of computers and the internet. While people can gain various benefits from playing online video games (Granic et al., 2014), an estimated three to eight percent of gamers in Western countries develop uncontrolled gaming behavior (Gentile, 2009; Grant et al., 2010; Van Rooij et al., 2011). Consequently, in the past few years an increasing number of problems associated with uncontrolled online video game playing have been reported by health-care institutions (Wisselink et al., 2013). Similar to substance-dependent individuals, this subset of online game players displays excessive and compulsive online gaming behavior resulting in psychological, social, and occupational or academic problems (Van Rooij et al., 2011; Kuss and Griffiths, 2012). In this group, game-playing behavior is continued despite adverse consequences, a major reason for the inclusion of internet gaming disorder in an annex of the Diagnostic Statistical Manual – Fifth edition (DSM-5) as a potential new disorder, awaiting further evidence. This clearly indicates that more research is needed to resolve the conceptual confusion concerning the definition and core elements of this proposed disorder to stimulate the development of adequate prevention and treatment.

Cognitive control is one of the key processes involved in the regulation of potentially harmful behavior (Ridderinkhof et al., 2004), and it has been described as a multifactorial construct in which cognitive operations are posited to allow individuals to select appropriate behavior, optimize goal-directed behavior, and adapt behavior accordingly (Botvinick et al., 2001; Ridderinkhof et al., 2004). Inhibitory control, error processing and attentional control are three widely investigated aspects of cognitive control measured by Go–NoGo and classic Stroop tasks (Carter et al., 2000; Hester et al., 2004; Chambers et al., 2007; van Noordt and Segalowitz, 2012). Inhibitory control is mostly involved in the inhibition of automatic and inappropriate behavior, while error processing is involved in the monitoring of performance errors and ongoing behavior in order to prevent future mistakes. Additionally, attentional control facilitates the processing of relevant

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stimuli and inhibits the processing of less relevant stimuli to increase the likelihood that the most appropriate stimuli will guide behavior (Franken, 2003). A dysfunctional cognitive control circuit may explain the excessive and compulsive gaming behavior of problem gamers such as the inability to control the amount of game playing, particularly when excessive gamers are confronted with gaming-related cues (Brand et al., 2014). In addition, adequate cognitive control is of key importance when habitual and rigid behavioral patterns need to be changed. A substantial literature suggests that both substance dependence and behavioral addictions, such as pathological gambling, are characterized by reduced cognitive control (Lubman et al., 2004; Verdejo-Garcia et al., 2008; Van Holst et al., 2010; Luijten et al., 2014). Regarding problematic gaming, previous studies found elevated self-reported impulsivity levels (Cao et al., 2007; Park et al., 2010; Littel et al., 2012; Ding et al., 2014) and reduced inhibitory control during affectively neutral conditions (Cao et al., 2007; Littel et al., 2012; Zhou et al., 2012) or when confronted with gaming-related cues (Decker and Ga, y2011; van Holst et al., 2012; Liu et al., 2014). Some studies, however, did not find impairments in behavioral inhibitory control in problem gamers (Dong et al., 2010; Ding et al., 2014). Studies investigating attentional control are also inconclusive as yet, with some studies showing an association between reduced attentional control and problematic gaming or internet addiction (Kronenberger et al., 2005; Dong et al., 2013), and other studies failing to find reduced attentional control as indicated by Stroop interference scores in problem gamers (Mathews et al., 2005; Bailey et al., 2010; Dong et al., 2012). With regard to brain activation related to inhibitory and attentional control in problem gamers, most neuroimaging studies suggest less efficient recruitment of prefrontal and parietal brain regions as compared with findings in controls (Mathews et al., 2005; Bailey et al., 2010; Dong et al., 2012; Littel et al., 2012; Brand et al., 2014; Ding et al., 2014; Liu et al., 2014).

Studies investigating error processing in problem gamers are very scarce. To the best of our knowledge, one previous study investigated error processing in problem gamers. That electroencephalographic (EEG) study used event-related potentials (ERPs) to show reduced error processing in problem gamers (Littel et al., 2012).

In line with these summarized findings, a recent review concluded that while some similarities in cognitive control functions were identified between problematic gaming and substance-dependent individuals, research in this field is yet in an early, inconclusive stage (Luijten et al., 2014). Therefore, the aim of the current study was to investigate various aspects of cognitive control and associated brain functions in a group of problem gamers. More specifically, inhibitory control, error processing and attentional control were investigated using a Go–NoGo and a Stroop task while brain activation was measured with functional magnetic resonance imaging (fMRI). Additionally, self-report measures to investigate related personality traits were obtained. The current study further aimed to address the specificity of reduced cognitive control for problematic gaming by including as controls participants that regularly plays games without losing control over their game playing, and by carefully matching these non-problematic gamers with the problematic gamers on other potentially addictive behaviors such as smoking and alcohol use. The inclusion of a well-matched non-problematic gamers as a control group is important for the field as it ensures that potentially observed problems in cognitive control are specifically related to problematic gaming behavior.

Based on previous literature, it was hypothesized that problem gamers would show increased self-reported impulsivity levels and reduced self-reported attentional control compared with non-problematic gamers. Furthermore, impairments in inhibitory control, error processing and attentional control were expected for behavioral measures of the Go–NoGo and the Stroop task. Finally, problematic gamers, as compared with non-problematic gamers, were expected to show reduced brain activation associated with cognitive control in the anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), and inferior frontal gyrus (IFG) as well as parietal and subcortical regions.

2. Methods

2.1. Participants

Based on classroom/internet screening 22 male problem gamers and 23 male controls were invited to participate in the current study. During the screening procedure, potential participants completed the Videogame Addiction Test (VAT, van Rooij et al., 2012). In line with a previous study investigating cognitive performance in problem gamers (Littel et al., 2012), a VAT score of 2.5 or higher/1.5 or lower was required for problem gamers and controls, respectively. Age between 18 and 30 years old was an inclusion criterion for both groups. Exclusion criteria were a) current or past substance dependence (other than cigarettes), b) current or past serious physical or mental illness, c) current use of psychoactive medication, or medication that may affect blood circulation and/or respiration, and d) fMRI contraindications. To assess these criteria, the following questions were posed to participants: Do you use medication? Do you have mental problems, or did you have any mental problems in the past? Did your parents, caregivers, friends or any health care professional ever express any concerns about your mental well-being? Have you been diagnosed with attention deficit hyperactivity disorder? Do you use any drugs other than alcohol and nicotine? Following this questioning, participants were also excluded in case of any doubts about their mental well-being.

In line with the aim of the current study to compare problem gamers with casual gamers, controls were required to game between 2 and 15 h per week. Immediately after scanning, participants completed the VAT again (average number of days in between screening and scanning was 31 days (range 4–91). To be included in the analyses, participants were required to have again a VAT score of 2.5 or higher/1.5 or lower. Six controls and four problem gamers no longer met this requirement and were therefore excluded from the analyses. By applying this strict inclusion criterion, we ensured that the included participants were stable problematic gamers and that the controls consisted of game players who did not lose control over their gaming behavior. One more control participant was excluded because of a severe brain abnormality. The final group consisted of 18 problem gamers and 16 controls. Detailed participant characteristics are displayed in Table 1, and details on types of games played are presented in Table 2. The study was conducted in accordance with the Declaration of Helsinki, and all participants provided written informed consent after explanation of study procedures. The ethics committee of Erasmus MC-University Medical Centre Rotterdam approved the study.

2.2. Procedures

Smoking participants were instructed to abstain from smoking for 1 h before the experiment to reduce the acute effects of nicotine on cognitive performance without introducing significant withdrawal effects on cognitive performance. Smoking status was objectively confirmed using a calibrated Micro+Smokerlyzer (Bedfont Scientific Ltd., Rochester, UK). After scanning, participants completed a list of several questionnaires and received a financial compensation of €25.

2.3. Questionnaires

For the assessment of problem gaming, the 14-item VAT questionnaire was used (van Rooij et al., 2012). An example of a VAT item is ‘How often did you try to reduce your gaming time without success?’ Optional answers ranged from one to five (i.e., ‘never’ to ‘very often’). All items were averaged across the scale, resulting in single score representing an index of problematic gaming behavior. The Barratt 30-item Impulsiveness Scale 11 (BIS-11) was used to measure self-reported impulsivity (Patton et al., 1995). Furthermore, the 20-item Attentional Control Scale (ACS) was used to measure self-reported attentional control, including attentional shifting, focusing, and controlling thought (Koster et al., 2009; Fajkowska and Derryberry, 2010). Alcohol consumption was measured using the Quantity-Frequency-Variability Index (Lemmens et al., 1992). This three-item questionnaire measures quantity, frequency, and variability (binge drinking) of alcohol use.

2.4. Task paradigms

2.4.1. Go–NoGo task

Participants completed the Go/NoGo task in which letters were presented at 1 Hz (Nestor et al., 2011; Luijten et al., 2013). Letters were presented for 700 ms followed by a 300-ms blank screen. Participants were required to make a button press response as fast as possible to each letter (Go trials) and to withhold this response whenever the letter was the same as the previous one (NoGo trials). NoGo

Table 1
Participant characteristics.

	Problem gamers $N=18$	Controls $N=16$	t/χ^2 (p)[a]
VAT[b]	3.34 (0.45)	1.26 (0.19)	17.91 (< 0.001)
Gaming days per week (#)	6.68 (0.55)	3.31 (1.89)	7.08 (< 0.001)
Gaming hours per week (#)	35.00 (15.37)	7.44 (7.32)	6.79 (< 0.001)
Age	20.83 (3.05)	21.38 (3.03)	0.52 (0.61)
Education			0.43 (0.81)
Low	61%	50%	
Medium	33%	44%	
High	6%	6%	
Handedness (right handed)	72%	75%	0.34 (0.86)
Smoking, smokers (%)	19%	33%	0.93 (0.34)
Smoking, cigarettes per week within smokers (#)	60.83 (56.51)	64.67 (22.48)	0.11 (0.92)
Alcohol use, drinking days per month (#)	7.56 (2.12)	7.88 (1.36)	0.52 (0.61)
Alcohol use, drinks per drinking day (#)	5.06 (1.92)	4.38 (1.67)	1.01 (0.28)
Alcohol use, binging episodes[c] (# in last 6 months)	6.44 (1.62)	6.19 (1.52)	0.48 (0.64)
Barratt Impulsiveness Scale	67.83 (10.15)	60.13 (11.45)	2.08 (< 0.05)
Attention Control Scale	52.56 (6.86)	55.75 (6.33)	1.14 (0.17)

Mean (S.D.), p Value in parentheses.

[a] t for continuous variables and χ^2 for categorical variables for the between group effects.
[b] VAT scores obtained on day of scanning.
[c] Defined as 6 or more alcoholic drinks at one occasion.

Table 2
Types of games primarily played by participants.

Type of game	% Problem gamers [a] $N=18$	% Control gamers [a] $N=15$, 1 missing
MMO action games/shooters (single player; first person/third person/tank)	83.3 ($n=15$)	80 ($n=12$)
Sandbox/open adventure game incl. action RPG (mainly offline)	61.1 ($n=11$)	40 ($n=6$)
Sport/racing	44.4 ($n=8$)	46.7 ($n=7$)
Massive multiplayer role playing game (MMORPG)	38.9 ($n=7$)	0
Multiplayer online battle arena (MOBA)	38.9 ($n=7$)	6.7 ($n=1$)
Music games	5.6 ($n=1$)	0
Casual tablet/phone games	5.6 ($n=1$)	13.3 ($n=2$)

[a] Question: which game or games do you play primarily?

trials were presented semi-randomly by introducing jitter in the number of intervening Go trials (mean = 7.25, range = 3–16). Twelve percent of the trials were NoGo trials. The number of Go versus NoGo trials was 817 versus 110, respectively. Four 15-s rest periods were included in the task. Behavioral outcome measures for this task representing inhibitory control are Go and NoGo accuracy and reaction times. The major behavioral outcome measures for this task representing error processing are reaction times following correct inhibition versus reaction times following incorrect inhibition (i.e., post-error slowing).

2.4.2. *Stroop task*

The classic Stroop task was used to measure attentional control. The task consisted of blocks of incongruent words (e.g., 'red' in blue ink), congruent words (e.g., 'red' in red ink) and letter strings (e.g., 'MMMM' in red ink). Letter string blocks were included to increase the number of conditions, which, in combination with a semi-random block order, reduced multicollinearity between parameter estimates for incongruent and congruent words. Every block type was presented six times, resulting in a total of 18 blocks. After each six blocks there was a 38-s resting period. Each block consisted of 10 words or letter strings. Each trial within a block began with a 250-ms fixation cross, followed by 1750 ms of word presentation. Participants were asked to indicate the color that the word was presented in by giving a button response as rapidly and accurately as possible.

2.5. *Data analyses questionnaires and task performance*

Between-group comparisons for participant characteristics (including questionnaires) were analyzed using independent samples t-tests for continuous and Chi-Square tests for categorical variables. Repeated Measures Analyses of Variance (RM-ANOVAs) were applied to analyze behavioral performance outcomes for both tasks. Group (problem gamers, controls) was included as a two-level between-subject factor in all RM-ANOVAs. For analyses concerning Go–NoGo task performance, Inhibition was included as a two-level within-subject factor (Go, NoGo), both for accuracy rates and reaction times. Correctness (Post-Correct, Post-Error) was included as a two-level within-subject factor in the reaction time analyses investigating post-error slowing. For the Stroop task, Congruency (Congruent, Incongruent) was included as a two-level within-subject factor.

2.6. *Image acquisition and analyses*

Imaging data were collected on a 3T GE Healthcare (The Discovery® MRI 750 3.0T, Milwaukee, WI, USA) scanner. Blood oxygen level-dependent (BOLD) sensitive functional T2*-weighted images were acquired in 44 axial slices covering the entire supratentorial brain, repetition time (TR) = 2500 ms, echo time (TE) = 30 ms, field of view (FOV) = 240 mm, and isotropic voxel size of 2.5 mm^3. A structural 3D inversion recovery fast spoiled gradient echo T1-weighted image was acquired in 164 contiguous axial slices, TR = 7.9 ms, TE = 3.1 ms, FOV = 240 mm, and isotropic voxel size of 1 mm^3. Imaging processing using Statistical Parametric Mapping (SPM8, Wellcome Trust Centre for Neuroimaging, London, UK) included realignment of all functional images. Participant movement did not exceed 3 mm in any direction. The anatomical scan was co-registered to the mean T2*-weighted image. Segmentation and normalization were performed using the unified segment and normalize framework implemented in SPM8 (Ashburner and Friston, 2005) with the SPM T1-weighted Montreal Neurological Institue (MNI) template. Voxel size was resampled to $2 \times 2 \times 2$ mm^3 during normalization. Functional scans were spatially smoothed using a 3D 8-mm full-width at half-maximum Gaussian kernel. For the Go–NoGo task, the four conditions (NoGo correct, NoGo incorrect, Go correct and Go incorrect) were modeled in the context of the general linear model using delta functions convolved with a canonical hemodynamic response function. Two contrasts, i.e., NoGo correct minus Go correct and NoGo incorrect minus Go correct, were defined to represent brain activation associated with inhibitory control and error processing, respectively. For the Stroop task, the three task conditions (Congruent, Incongruent, Letters) were modeled. The contrast Incongruent minus Congruent was defined to represent brain activation associated with attentional control. The three contrasts were subsequently used for between-group comparisons using independent samples t-tests. Between-group differences are reported at $p < 0.05$ corrected for multiple comparisons. Monte Carlo Simulations (1000 simulations, individual voxel threshold $p < 0.001$) were performed to determine the minimal required cluster size within pre-defined regions of interest to achieve the family-wise error corrected p Value of $p < 0.05$). Given their important role in inhibitory control, error processing and attentional control (Cabeza and Nyberg, 2000; Hester et al., 2004; Garavan et al., 2006; Chambers et al., 2009), the bilateral ACC, DLPFC, IFG, inferior and superior parietal gyrus (IPG/SPG), insula, putamen and caudate were selected as regions of interest (ROIs). ROIs were defined using the automatic anatomical labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002). To investigate brain-behavioral associations, activation estimates (β weights) within brain regions showing group differences were extracted using Marsbar (Brett et al., 2002) and correlated with the main behavioral indices, i.e., NoGo task accuracy for inhibitory control, post-error slowing for error processing, and Stroop task accuracy and reaction time difference scores (Incongruent minus Congruent) for attentional control. Extracted brain-activation estimates were also correlated with VAT scores and hours of gaming per week at day of testing within the problem gaming group to assess whether the observed deviant brain activation was associated with characteristics of their excessive gaming behavior.

3. Results

3.1. Self-reported data

See Table 1 for mean scores and standard deviations for questionnaire data per group. Problem gamers scored significantly higher $t(32)=2.08$, $p<0.05$ on self-reported impulsivity. No significant group differences were found for self-reported attentional control.

3.2. Task performance

Behavioral data of one problem gamer were not recorded properly for the Go–NoGo task; therefore, this participant could not be included in task performance and imaging analyses results resulting from the Go–NoGo task. Means and standard deviations for all behavioral task performance measures are summarized per group in Table 3.

3.2.1. Inhibitory control

The RM-ANOVA for task accuracy showed a robust main effect of Inhibition, $F(1,31)=325.99$, $p<0.001$, showing that participants were less accurate on NoGo trials compared with Go trials. In addition, both the Group main effect, showing reduced accuracy in problem gamers, $F(1,31)=4{,}91$, $p<0.05$, and the Group × Inhibition interaction, $F(1,31)=4{,}27$, $p<0.05$, were significant. Post-hoc tests revealed that problem gamers were less accurate for NoGo trials, $p<0.05$, compared with non-problematic gamers, while no Group effect was found for Go trials. The RM-ANOVA of reaction times showed a main effect of Inhibition $F(1,31)=66.92$, $p<0.001$. Go reaction times were longer than incorrect NoGo reaction times. For reaction times, no main or interaction effects were found for Group.

3.2.2. Error processing

The RM-ANOVA for post-NoGo correct and post-NoGo error reaction times showed a main effect of Correctness, $F(1,31)=49.64$, $p<0.001$, and Group, $F(1,31)=5.03$, $p<0.05$. The Group × Correctness interaction was not significant. The main effect of Correctness involved longer response times for trials following erroneous responses compared with trials following a correct response, suggesting that across groups participants showed post-error slowing. The main effect of Group showed that problem gamers have overall shorter response times, both for trials following correct and incorrect NoGo trials.

3.2.3. Attentional control

Both reaction times and accuracy scores related to Stroop task performance showed a main effect for Congruency, $F(1,32)=74.47$, $p<0.001$ and $F(1,32)=19.36$, $p<0.001$, respectively. Mean reaction times indicated that reaction times for incongruent trails were longer than for congruent trials, while mean accuracy scores were lower for incongruent than for congruent trials. No main or interaction effect of Group was found for Stroop task performance.

3.3. Imaging results

3.3.1. Inhibitory control

Between-group comparisons showed reduced brain activation in problem gamers compared with non-problematic gamers in the left IFG and in the right inferior parietal lobe (IPL) (see Fig. 1 and Table 4 for x, y, z coordinates, Z-values and cluster sizes). Brain activation in the right IPL ($x=46$, $y=-58$, $z=34$) was positively associated with NoGo accuracy, $\rho=0.40$, $p<0.05$, suggesting that reduced brain activation in this region in may be associated with the observed reduced NoGo accuracy in problem gamers. Activation estimates in the regions showing group differences were not associated with VAT scores or hours of gaming per week in the problematic gaming group.

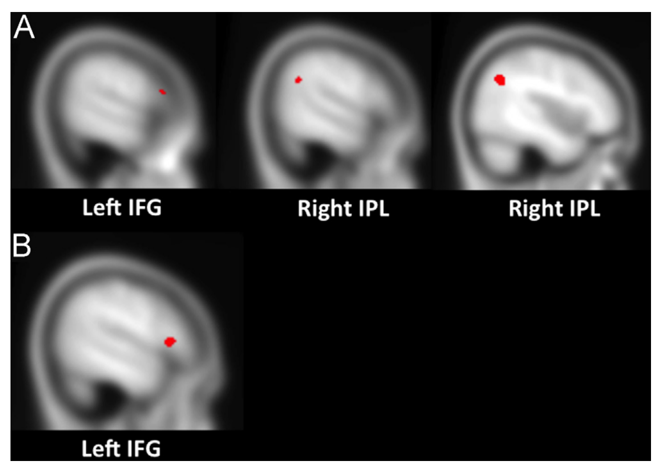

Fig. 1. Reduced brain activation in problem gamers relative to non-problematic gamers. Top part A shows reduced brain activation in problem gamers relative to non-problematic gamers for inhibitory control on the Go–NoGo task. The lower part B shows reduced brain activation in problem gamers relative non-problematic gamers for attentional control in the Stroop task.

Table 3
Behavioral indices of task performance on the Go–NoGo and Stroop tasks.

Inhibitory control	Problem gamers	Controls	Error processing	Problem gamers	Controls	Attentional control	Problem gamers	Controls
NoGo accuracy *	45.67 (14.95)	56.87 (15.00)	Post-error reaction time	373.66 (70,24)	417.57 (70,23)	Incongruent accuracy	79.41 (23.00)	89.17 (7.43)
Go accuracy	98.65 (1.61)	99.97 (0.66)	Post-correct reaction time	284.64 (63.05)	318.48 (43.24)	Congruent accuracy	89.90 (20.37)	94.27 (5.64)
NoGo reaction time	354.25 (49.56)	377.36 (50,95)				Incongruent reaction time	925.52 (143.76)	915.78 (89.87)
Go reaction time	378.14 (50.14)	409.39 (42.48)				Congruent reaction time	796.73 (136.87)	785.51 (73.69)

Mean (S.D.), accuracy rates are displayed in percentages and reaction times in milliseconds.

* Group difference, $p<0.05$.

Table 4
Group differences for brain activation associated with inhibitor control.

	MNI coordinates			Z-value*	mm^3
	x	y	z		
Gamers < controls					
Left IFG	−58	24	18	3.47	40
Right IPL	46	−58	34	3.70	680
Right IPL	56	−50	28	3.32	88
Gamers > controls	–				

MNI: Montreal Neurological Institute.
IFG: inferior frontal gyrus, IPL: inferior parietal lobe.
* $p<0.05$ corrected for multiple comparisons within predefined regions of interest.

3.3.2. Error processing
No differences between problem and non-problematic gamers were identified for brain activation associated with error processing.

3.3.3. Attentional control
Problem gamers showed decreased brain activation associated with attentional control on the Stroop task in the left IFG (see Fig. 1 and Table 5 for x, y, z coordinates, Z-values and cluster size). The association between brain activation in the IFG and reaction times and accuracy scores reflecting attentional control was not significant. Activation in the left IFG was not associated with VAT scores, but it showed a negative association with hours of gaming per week in the problematic gaming group, $\rho=-0.55$, $p<0.05$.

4. Discussion

The current study investigated whether problem gamers are characterized by deficits in various aspects of cognitive control by measuring self-reported personality traits and brain activation during Go–NoGo and Stroop task performance. Increased self-reported impulsivity levels and decreased inhibitory control accompanied by reduced brain activation in the left IFG and right IPL were found in problem gamers relative to non-problematic gamers. Hypoactivation in the left IFG in problem gamers was also observed during Stroop task performance, but neither behavioral nor self-reported indices of attentional control were found to be impaired in problem gamers. No evidence was found for reduced error processing in problem gamers.

Our findings of increased self-reported impulsivity and reduced inhibitory control (i.e., lower NoGo accuracy) support findings of previous studies showing elevated impulsivity (Park et al., 2010; Ding et al., 2014) and reduced inhibitory control in problem gamers (Cao et al., 2007; Littel et al., 2012). Interestingly, some previous studies only found reduced inhibitory control when gaming cues were presented and not during neutral conditions (Decker and Ga, y2011; van Holst et al., 2012; Liu et al., 2014). These findings, together with the observation that overall NoGo accuracy rates in our study and in that of Littel et al. are lower compared with other studies, suggests that inhibitory control in problem gamers may only be compromised in cognitively challenging situations. Finally, the strict inclusion criteria and the large number of gaming hours per week (35 on average) suggest that the problem gamers in the current study represent a quite severe group, which in itself may be associated with more severe inhibition problems. The observed reduced inhibitory control in problem gamers in the current study may be due to hypoactivation in the left IFG and right IPL, a conjecture that is supported by a positive correlation between NoGo accuracy and brain activation in the right IPL. In line with the current findings, reduced cortical thickness has been found in problem gamers in both the IFG and right IPL (Yuan et al., 2013; Lin et al., 2014). The IFG is a region critically involved in implementing the inhibitory brake (Chambers et al., 2006), and it has previously been found to be hypoactive in problem gamers when inhibitory control is required (Ding et al., 2014). Interestingly, left IFG activation was also reduced in problem gamers during Stroop task performance, suggesting that reduced left IFG activation may be a characteristic of problem gamers across multiple facets of cognitive control. However, Stroop task performance and self-reported attentional control were not impaired in problem gamers. It may be that reduced left IFG activation associated with attentional control represents subtle inhibition problems during Stroop task performance, not strong enough to hamper the behavioral expression of attentional control. Previous studies investigating attentional control in problem gamers by means of the Stroop task also report mixed findings. While some studies showed an association between excessive gaming or internet addiction and Stroop interference scores (Kronenberger et al., 2005; Dong et al., 2013), three other studies did not identify behavioral deficits during Stroop performance (Mathews et al., 2005; Bailey et al., 2010; Dong et al., 2012). Additionally, differences in brain activation between problem gamers and controls were previously found both in the direction of reduced (Mathews et al., 2005; Bailey et al., 2010) and increased (Dong et al., 2012) prefrontal activation. Altogether, findings regarding attentional control in problem gamers seem inconclusive. These very mixed results might suggest that attentional control capacities in problem gamers are intact. However, the mixed results might also be the result of relatively low sample sizes in most studies involving problem gamers, including the present study. These results should be interpreted cautiously until future studies with larger sample sizes can be carried out.

Table 5
Group differences for brain activation associated with attentional control.

	MNI coordinates			Z-value*	mm^3
	x	y	z		
Gamers < controls					
Left IFG	−50	22	6	3.68	392
Gamers > controls	–				

IFG: inferior frontal gyrus; MNI: Montreal Neurological Institute.
* $p<0.05$ corrected for multiple comparisons within predefined regions of interest.

With regard to error processing, the current study did not find evidence for reduced error processing in problem gamers as was previously reported (Littel et al., 2012). This discrepancy may reflect difference in imaging techniques, as the study by Littel and colleagues used ERPs with a high temporal resolution, while brain activation in the current study was measured using fMRI. It is possible that the error-related negativity (ERN), which is an ERP component arising 25–100 ms after performance errors, is a more sensitive measure to investigate error-related brain activation compared with brain activation associated with incorrect NoGo responses measured with fMRI. An alternative explanation may be the difference in the control group between the two studies. The control group of the current study involves a group of regular gamers who on average play video games 3.3 days per week for 7.4 h per week, while the control group in the study by Littel et al. rarely played video games. It is therefore possible that the reduced error processing in problem gamers by Littel et al. is not specific for those who excessively play video games, but for video game players in general. Future studies should further investigate error processing in a population with various levels of gaming behavior to resolve these discrepant findings.

Although problems with cognitive control in problem gamers were only found for inhibitory control specifically, this reduced capacity to inhibit automatic, inappropriate responses may interact with several other neurocognitive processes that may contribute to problematic gaming behavior. A recent model (Brand et al., 2014) on the development and maintenance of generalized and specific (e.g., gaming related) internet addiction suggests that reduced cognitive control interacts with reactivity to gaming-related cues that may evoke craving in gamers (Ko et al., 2009, 2013). In addition, altered reward sensitivity (Dong et al., 2011) and decision-making problems (Yao et al., 2014) may interact with reduced inhibitory control, leading to loss of control over gaming related behaviors.

Besides the need for increased power in future studies, a few methodological issues deserve special attention. First, the results of the current, as well as previous studies, raise the important question as to whether any deficits in cognitive control in problem gamers are specific for problem gaming or merely represent trait impulsivity in general. Elevated impulsivity and reduced inhibitory control have been repeatedly found in various types of substance abuse as well as in pathological gamblers (van Holst et al., 2010). These similarities suggest that impaired inhibitory control may arise from shared personality characteristics such as impulsivity. Although the current cross-sectional design does not allow conclusions on causality, the fact that video gaming does not involve the ingestion of substances of abuse supports the idea that shared personality traits may explain problems with cognitive control in addiction. Nevertheless, the option that any prolonged excessive and compulsive behavior may change neural circuits cannot be excluded. Longitudinal studies including both substance-dependent individuals and individuals with problematic gaming behavior would be very valuable in resolving this issue.

Second, there is currently no standard diagnostic tool available to diagnose and identify problem gamers (Ferguson et al., 2011). We therefore adopted the strategy to only include participants in analyses who consistently scored within the pre-defined inclusion criteria (i.e., both during screening and testing). While this strategy increased the reliability of selecting stable problem gamers, it also revealed that a relatively large number of problem gamers (i.e., four out of 22) were no longer identified as problematic gamers during actual measurements, which raises questions about the stability of problem gaming behavior. The development of a standard diagnostic tool would be very valuable for the field so that study inclusion would no longer be based on self-report measures. Meanwhile studies should report various aspects of gaming behavior (gaming hours per week, types of games) to increase comparability of findings.

In conclusion, results of the current study suggest that problem gamers may be characterized by reduced inhibitory control, probably as a consequence of reduced brain activation in the left IFG and right IPL. Given that similar findings have been observed in substance-dependent individuals, these findings suggest that problematic video gaming shares some characteristics in its underlying mechanisms with substance dependence. Problem gamers also showed reduced IFG activation during Stroop task performance, although both behavioral and self-reported measures of attentional control did not differ between problem and non-problematic gamers. In addition, no evidence was found for impairments in error processing. Importantly, participants in the control group of this study consisted of well-matched non-problematic gamers so that the observation of elevated self-reported impulsivity, reduced inhibitory control and reduced brain activation in the left IFG and right IPL is likely to be specific for problematic gaming behavior.

Contributors

All authors were involved in study design. M.L., G.J.M. and T.M.S. supervised data collection. M.L. analyzed the data and drafted the manuscript. All authors were involved in data interpretation. G.J.M., I.H.A.F., B.J.W. and T.M.S. critically revised the manuscript. All authors reviewed the manuscript and approved the final version of the manuscript.

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References

Ashburner, J., Friston, K.J., 2005. Unified segmentation. NeuroImage 26, 839–851.
Bailey, K., West, R., Anderson, C.A., 2010. A negative association between video game experience and proactive cognitive control. Psychophysiology 47, 34–42.
Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. Psychological Review 108, 624–652.
Brand, M., Young, K.S., Laier, C., 2014. Prefrontal control and internet addiction: a theoretical model and review of neuropsychological and neuroimaging findings. Frontiers in Human Neuroscience 8, 375.
Brett, M., Anton, J.C., Valabregue, R., Poline, J.B., 2002. Region of interest analysis using an SPM toolbox. Meeting of the Organization for Human Brain Mapping, Sendai, Japan.
Cabeza, R., Nyberg, L., 2000. Imaging cognition: II. An empirical review of 275 PET and fMRI studies. Journal of Cognitive Neuroscience 12, 1–47.
Cao, F., Su, L., Liu, T., Gao, X., 2007. The relationship between impulsivity and Internet addiction in a sample of Chinese adolescents. European Psychiatry 22, 466–471.
Carter, C.S., Macdonald, A.M., Botvinick, M., Ross, L.L., Stenger, V.A., Noll, D., Cohen, J.D., 2000. Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. Proceedings of the National Academy of Sciences of the United States of America 97, 1944–1948.
Chambers, C.D., Bellgrove, M.A., Gould, I.C., English, T., Garavan, H., McNaught, E., Kamke, M., Mattingley, J.B., 2007. Dissociable mechanisms of cognitive control in prefrontal and premotor cortex. Journal of Neurophysiology 98, 3638–3647.
Chambers, C.D., Bellgrove, M.A., Stokes, M.G., Henderson, T.R., Garavan, H., Robertson, I.H., Morris, A.P., Mattingley, J.B., 2006. Executive "brake failure" following deactivation of human frontal lobe. Journal of Cognitive Neuroscience 18, 444–455.
Chambers, C.D., Garavan, H., Bellgrove, M.A., 2009. Insights into the neural basis of response inhibition from cognitive and clinical neuroscience. Neuroscience & Biobehavioral Reviews 33, 631–646.
Decker, S.A., Gay, J.N., 2011. Cognitive-bias toward gaming-related words and disinhibition in World of Warcraft gamers. Computers in Human Behavior 27, 798–810.
Ding, W.N., Sun, J.H., Sun, Y.W., Chen, X., Zhou, Y., Zhuang, Z.G., Li, L., Zhang, Y., Xu, J.R., Du, Y.S., 2014. Trait impulsivity and impaired prefrontal impulse inhibition function in adolescents with internet gaming addiction revealed by a Go/No-Go fMRI study. Behavioral and Brain Functions 10, 10–20 (20-9081-10-20).
Dong, G., Devito, E.E., Du, X., Cui, Z., 2012. Impaired inhibitory control in 'internet addiction disorder': a functional magnetic resonance imaging study. Psychiatry Research: Neuroimaging 203, 153–158.
Dong, G., Hu, Y., Lin, X., Lu, Q., 2013. What makes Internet addicts continue playing online even when faced by severe negative consequences? Possible explanations from an fMRI study. Biological Psychology 94, 282–289.
Dong, G., Huang, J., Du, X., 2011. Enhanced reward sensitivity and decreased loss sensitivity in Internet addicts: an fMRI study during a guessing task. Journal of Psychiatric Research 45, 1525–1529.
Dong, G., Lu, Q., Zhou, H., Zhao, X., 2010. Impulse inhibition in people with internet addiction disorder: electrophysiological evidence from a Go/NoGo study. Neuroscience Letters 485, 138–142.
Fajkowska, M., Derryberry, D., 2010. Psychometric properties of Attentional Control Scale: the preliminary study on a Polish sample. Polish Psychological Bulletin 41, 1–7.
Ferguson, C.J., Coulson, M., Barnett, J., 2011. A meta-analysis of pathological gaming prevalence and comorbidity with mental health, academic and social problems. Journal of Psychiatric Research 45, 1573–1578.
Franken, 2003. Drug craving and addiction: integrating psychological and neuropsychopharmacological approaches. Progress in Neuro-psychopharmacology & Biological Psychiatry 27, 563–579.
Garavan, H., Hester, R., Murphy, K., Fassbender, C., Kelly, C., 2006. Individual differences in the functional neuroanatomy of inhibitory control. Brain Research 1105, 130–142.
Gentile, D., 2009. Pathological video-game use among youth ages 8 to 18: a national study. Psychological Science 20, 594–602.
Granic, I., Lobel, A., Engels, R.C., 2014. The benefits of playing video games. American Psychologist 69, 66–78.
Grant, J.E., Potenza, M.N., Weinstein, A., Gorelick, D.A., 2010. Introduction to behavioral addictions. American Journal of Drug and Alcohol Abuse 36, 233–241.

Hester, R., Fassbender, C., Garavan, H., 2004. Individual differences in error processing: a review and reanalysis of three event-related fMRI studies using the Go/NoGo task. Cerebral Cortex 14, 986–994.
Ko, C.H., Liu, G.C., Hsiao, S., Yen, J.Y., Yang, M.J., Lin, W.C., Yen, C.F., Chen, C.S., 2009. Brain activities associated with gaming urge of online gaming addiction. Journal of Psychiatric Research 43, 739–747.
Ko, C.H., Liu, G.C., Yen, J.Y., Chen, C.Y., Yen, C.F., Chen, C.S., 2013. Brain correlates of craving for online gaming under cue exposure in subjects with Internet gaming addiction and in remitted subjects. Addiction Biology 18, 559–569.
Koster, E.H., De Raedt, R., Verschuere, B., Tibboel, H., De Jong, P.J., 2009. Negative information enhances the attentional blink in dysphoria. Depression and Anxiety 26, E16–E22.
Kronenberger, W.G., Mathews, V.P., Dunn, D.W., Wang, Y., Wood, E.A., Giauque, A.L., Larsen, J.J., Rembusch, M.E., Lowe, M.J., Li, T.Q., 2005. Media violence exposure and executive functioning in aggressive and control adolescents. Journal of Clinical Psychology 61, 725–737.
Kuss, D., Griffiths, M., 2012. Internet gaming addiction: a systematic review of empirical research. International Journal of Mental Health and Addiction 10, 278–296.
Lemmens, P., Tan, E.S., Knibbe, R.A., 1992. Measuring quantity and frequency of drinking in a general population survey: a comparison of five indices. Journal of Studies on Alcohol 53, 476–486.
Lin, X., Dong, G., Wang, Q., Du, X., 2014. Abnormal gray matter and white matter volume in 'Internet gaming addicts. Addictive Behaviors 40C, 137–143.
Littel, M., van den Berg, I., Luijten, M., van Rooij, A.J., Keemink, L., Franken, I.H.A., 2012. Error processing and response inhibition in excessive computer game players: an event-related potential study. Addiction Biology 17, 934–947.
Liu, G.C., Yen, J.Y., Chen, C.Y., Yen, C.F., Chen, C.S., Lin, W.C., Ko, C.H., 2014. Brain activation for response inhibition under gaming cue distraction in internet gaming disorder. The Kaohsiung Journal of Medical Sciences 30, 43–51.
Lubman, D.I., Yucel, M., Pantelis, C., 2004. Addiction, a condition of compulsive behaviour? Neuroimaging and neuropsychological evidence of inhibitory dysregulation. Addiction 99, 1491–1502.
Luijten, M., Machielsen, M.W.J., Veltman, D.J., Hester, R., de Haan, L., Franken, I.H.A., 2014. A systematic review of ERP and fMRI studies investigating inhibitory control and error-processing in substance dependence and behavioral addictions. Journal of Psychiatry and Neuroscience 39, 149–169.
Luijten, M., Veltman, D.J., Hester, R., Smits, M., Nijs, I.M., Pepplinkhuizen, L., Franken, I.H., 2013. The role of dopamine in inhibitory control in smokers and non-smokers: a pharmacological fMRI study. European Neuropsychopharmacology 23, 1247–1256.
Mathews, V.P., Kronenberger, W.G., Wang, Y., Lurito, J.T., Lowe, M.J., Dunn, D.W., 2005. Media violence exposure and frontal lobe activation measured by functional magnetic resonance imaging in aggressive and nonaggressive adolescents. Journal of Computer Assisted Tomography 29, 287–292.
Nestor, L., McCabe, E., Jones, J., Clancy, L., Garavan, H., 2011. Differences in "bottom-up" and "top-down" neural activity in current and former cigarette smokers: evidence for neural substrates which may promote nicotine abstinence through increased cognitive control. NeuroImage 56, 2258–2275.
Park, H.S., Kim, S.H., Bang, S.A., Yoon, E.J., Cho, S.S., Kim, S.E., 2010. Altered regional cerebral glucose metabolism in internet game overusers: a ^{18}F-fluorodeoxyglucose positron emission tomography study. CNS Spectrums 15, 159–166.
Patton, J.H., Stanford, M.S., Barratt, E.S., 1995. Factor structure of the Barratt Impulsiveness Scale. Journal of Clinical Psychology 51, 768–774.
Ridderinkhof, K.R., Ullsperger, M., Crone, E.A., Nieuwenhuis, S., 2004. The role of the medial frontal cortex in cognitive control. Science 306, 443–447.
Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., Joliot, M., 2002. Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. NeuroImage 15, 273–289.
van Holst, R.J., Lemmens, J.S., Valkenburg, P.M., Peter, J., Veltman, D.J., Goudriaan, A.E., 2012. Attentional bias and disinhibition toward gaming cues are related to problem gaming in male adolescents. The Journal of Adolescent Health 50, 541–546.
Van Holst, R.J., Van den Brink, W., Veltman, D.J., Goudriaan, A.E., 2010. Why gamblers fail to win: a review of cognitive and neuroimaging findings in pathological gambling. Neuroscience and Biobehavioral Reviews 34, 87–107.
van Noordt, S.J., Segalowitz, S.J., 2012. Performance monitoring and the medial prefrontal cortex: a review of individual differences and context effects as a window on self-regulation. Frontiers in Human Neuroscience 6, 197.
van Rooij, A.J., Schoenmakers, T.M., van den Eijnden, R.J., Vermulst, A.A., van de Mheen, D., 2012. Video game addiction test: validity and psychometric characteristics. Cyberpsychology, Behavior and Social Networking 15, 507–511.
Van Rooij, A.J., Schoenmakers, T.M., Vermulst, A.A., Van den Eijnden, R.J., van de Mheen, D., 2011. Online video game addiction: identification of addicted adolescent gamers. Addiction 106, 205–212.
Verdejo-Garcia, A., Lawrence, A.J., Clark, L., 2008. Impulsivity as a vulnerability marker for substance-use disorders: review of findings from high-risk research, problem gamblers and genetic association studies. Neuroscience and Biobehavioral Reviews 32, 777–810.
Wisselink, D.J., Kuijpers, W.G.T., Mol, A., 2013. Kerncijfers Verslavingszorg 2012 [Core statistics addiction care for the Netherlands in 2012]. Stichting Informatie Voorziening Zorg (IVZ).
Yao, Y.W., Chen, P.R., Chen, C., Wang, L.J., Zhang, J.T., Xue, G., Deng, L.Y., Liu, Q.X., Yip, S.W., Fang, X.Y., 2014. Failure to utilize feedback causes decision-making deficits among excessive Internet gamers. Psychiatry Research 219, 583–588.
Yuan, K., Cheng, P., Dong, T., Bi, Y., Xing, L., Yu, D., Zhao, L., Dong, M., von Deneen, K.M., Liu, Y., Qin, W., Tian, J., 2013. Cortical thickness abnormalities in late adolescence with online gaming addiction. PLoS One 8, e53055.
Zhou, Z., Yuan, G., Yao, J., 2012. Cognitive biases toward Internet game-related pictures and executive deficits in individuals with an Internet game addiction. PLoS One 7, e48961.