Structural Brain Differences Associated with Extensive Massively-Multiplayer Video Gaming

Qinghua He[1, 2,3,4,5*,**], Ofir Turel[6,7*,**], Lei Wei[1], Antoine Bechara[7]

[1] Faculty of Psychology, Southwest University, Chongqing, China
[2] Key Laboratory of Cognition and Personality, Ministry of Education, Southwest University, Chongqing, China
[3] Chongqing Collaborative Innovation Center for Brain Science, Chongqing, China
[4] Southwest University Branch, Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University, Chongqing, China
[5] Institute of Psychology, Key Laboratory of Mental Health, Chinese Academy of Sciences, Beijing, China
[6] Information Systems and Decision Sciences, California State University, Fullerton, CA, United States
[7] Brain and Creativity Institute, University of Southern California, Los Angeles, USA
* These authors have made equal contributions.
** Corresponding authors:
(1) Prof. Ofir Turel
800 N. State College Blvd., Fullerton CA, USA 92834,
Email: oturel@fullerton.edu
Phone: +1 (657) 278-5613
(2) Prof. Qinghua He
Faculty of Psychology
Southwest University
Chongqing, 400715, China
Email: heqinghua@swu.edu.cn

Abstract

Video gaming can be associated with inter-individual differences in brain morphology. Much of this literature has focused on non-professional/occasional gamers who barely play, on the one extreme; or Internet Gaming Disorder (IGD) cases who typically play more than 5 h/day, on the other extreme. We sought to extend this literature and focus on extensive gamers, who play about 3 h/day, which is typically more than non-professional gamers, but less than IGD cases. Findings regarding this sector of gamers can inform research on risk factors or markers for IGD development, even before addiction symptoms emerge. We predicted that extensive gamers have smaller prefrontal regions that presumably reflect weaker inhibition abilities, and larger visuomotor regions that presumably reflect stronger motor skills in response to visual stimuli. We tested these assertions with a between-subject brain morphology comparison of 26 extensive League of Legends (LOL) and matched 26 non-gamers, using voxel based morphometry, deformation based morphometry, and cortical thickness and sulcus depth analyses. Findings largely supported our predictions by pointing to morphological alterations in extensive gamers in the bilateral ventromedial prefrontal cortex and left dorsolateral prefrontal cortex, as well is in the left superior parietal lobule. These findings suggest that extensive gamers, at least of Massive-Multiplayer battle arena games, present brain alterations that are consistent with presumed loss of control (as mediated by the prefrontal cortex), but also improved attention and visoumotor skills (as mediated by superior parietal lobule). Implications for research and practice are discussed.

Keywords: video games, prefrontal cortex, superior parietal lobule, brain morphology, extensive video gaming

Introduction

Videogames are a popular form of entertainment; in 2019 there are about 2.5 Billion gamers worldwide (Statista.com, 2019a). While low-moderate levels of video gaming can improve various psychological and physiological facets, including motor skills, visual selective attention, cognitive abilities, and hand-eye coordination (Bavelier et al., 2011; Pujol et al., 2016), extensive video gaming can be associated with attention problems, impulsivity, depression, anxiety, social phobia, reduced school performance (Gentile et al., 2011), substance use (Turel & Bechara, 2019), school misconduct (Pujol et al., 2016), and increased intake of unhealthy foods (Pentz, Spruijt-Metz, Chou, & Riggs, 2011)

Because all of these associations can be rooted in relevant brain faculties (Pujol et al., 2016), there is a need to better understand possible brain alterations that are linked to extensive video game play (defined in this study as about 3 h/day). Like any other repeated behavior, video gaming can be associated with (be driven by and/or drive) structural brain differences (Weinstein, Livny, & Weizman, 2017). The direction of the association is not clear yet, as both possibilities (1. video gaming leads to brain adaptations through neural recruitment, growth, death or pruning; or 2. underlying inter-individual structural differences explain video

gaming behaviors) are viable and can co-occur (Kanai & Rees, 2011). While experimental studies using video gaming as an intervention have produced changes in select brain regions (e.g., hippocampus , dorsalteral prefrontal cortex, inferior frontal gyrus; see Gleich, Lorenz, Gallinat, & Kuhn, 2017; Kuhn, Gleich, Lorenz, Lindenberger, & Gallinat, 2014), the possibility that underlying differences in brain structures drives gaming behavior cannot be ruled out, because most studies on such associations have been correlational (see review in Palaus, Marron, Viejo-Sobera, & Redolar-Ripoll, 2017).

Regardless of the direction of the relationship, findings regarding structural brain differences that are associated with extensive video gaming can serve as a basis for better understanding possible benefits and drawbacks of extensive video gaming, or alternatively, possible risk factors for extensive gamming. These can inform intervention studies aimed at improving the wellbeing of gamers. Moreover, while there is much research on low/occasional video gaming (often <3 h/week) on the one extreme, and on the other, on gamers who meet Internet Gaming Disorder (IGD) criteria (see review in Palaus et al., 2017), little attention has been given to extensive gamers –in this study, about 3 h/day, who may differ from those who meet IGD criteria (IGD subjects often play > 45 hours/week, see van Rooij, Schoenmakers, Vermulst, van den Eijnden, & van de Mheen, 2011). As such, findings from this study can provide insights regarding this unique, and growing gamer segment (Przybylski, 2019; Siervo, Gan, Fewtrell, Cortina-Borja, & Wells, 2018). Here, we seek to make first strides toward this objective through addressing the research question: what structural brain differences are associated with extensive gaming.

We note that prior research has found differences across the brain that relate to IGD and/or light gaming (including many prefrontal, parietal and limbic regions; see tables in Palaus et al., 2017). However, there remains a gap in knowledge regarding brain differences associated with extensive gaming. We hypothesize that extensive gaming can reflect some loss of control, and hence be associated with deficient self-regulation and poor integration of visceral stimuli into decision making (Dong & Potenza, 2014, 2016). Since these are typically manifested in reduced gray matter volume and cortical thickness of prefrontal brain regions, such as the dorsolateral prefrontal cortex (dlPFC), ventromedial prefrontal cortex (vmPFC) and orbital frontal cortex (OFC) (e.g., Boes et al., 2008; Cho et al., 2013; Kühn, Schubert, & Gallinat, 2010; Qiu et al., 2013), we hypothesize that the gray matter volume and cortical thickness of prefrontal regions will be reduced in extensive gamers compared to non-gamers.

Moreover, given the increased arm movement in response to visual cues imposed by extensive gaming (Pujol et al., 2016), we expect extensive gaming to be associated with differences in regions that govern visuomotor control (Mutha, Sainburg, & Haaland, 2011; Wu et al., 2016), such that the differences reflect faster, more efficient reactions to visual stimuli. Specifically, the superior parietal lobule (SPL) mediates tasks that are highly repetitive in video gaming, including reaching, grasping, eye movement, action perception, object and shape orientation and storing knowledge on how tools are employed (Culham & Valyear, 2006). The direction of gray matter differences in this region (reduction or enhancement), though, is not clear. Given the multitude of relevant functions the SPL serves, findings focusing on different tasks have been inconsistent. For example, while Koscik,

O'Leary, Moser, Andreasen, and Nopoulos (2009) found lower SPL gray matter volume associations with improved mental rotation performance, Sripada et al. (2015) found that thicker SPL is associated with increased visual–motor performance. As such, we put forth a general hypothesis that gray matter volume and cortical thickness of SPL will differ between extensive gamers and non-gamers.

Methods

Participants

Participants were recruited from university campus through flyers posted on bulletin boards; half of the flyers recruited extensive League of Legends (LOL) players (explained as playing LOL for more than 1.5 years, and spending about three hours per day in the past 6 months on LOL), and the other half recruited people who do have not played LOL and who have not played videogames in the last six months. LOL is a massively-multiplayer battle arena game. We focused on LOL given its high popularity; in 2016 it had 100 million monthly active players (Statista.com, 2019b), as well as the feasibility of finding extensive players (about 3h/day). A total of 52 volunteers were recruited. Specifically, 26 extensive LOL players (6 females; mean age = 20.46 ± 2.10 years) were recruited, and were matched in terms of age and gender (selected from 50 responses) to 26 people who have not ever played LOL and have not played videogames in the last six months; i.e., controls (6 females; mean age = 20.69 ± 2.21 years). All participants were asked to read and sign the informed consent, which was approved by the Institutional Review Board of Southwest University.

Procedures

Upon arrival, people in both groups were interviewed regarding their LOL play patterns. To meet extensive player criteria, LOL players were required to have 1.5 years of LOL experience and to spend about 3 hours per day playing LOL. All reported that LOL is the primary game they played. To be in the control group pool, people were required to have no experience with LOL, and to have not played videogames in the last six months. No exclusions were made (these criteria were described in the flyers). Both groups were also interviewed regarding current or past neurological disorders that may affect result interpretation (Psychoses, current major depression episode, a history of major depression episodes or major depressive disorder, heavy drinking, substance abuse, schizophrenia, current and history of anxiety disorders, and bipolar disorder) and abnormal uncorrected vision. No exclusions based on these criteria were made. Next, the LOL group completed an online survey that included several control and descriptive variables (see details below). Immediately afterwards, all participants were subjected to a high-resolution structural MRI scan with Siemens 3 Tesla scanner.

Analytical Plan

We compared whole brain neuroimaging data of extensive gamers with this on non-gamers after controlling for covariates. In order to provide a more complete picture regarding the hypothesized differences multiple neuroimaging techniques and analyses were employed. These include Voxel Based Morphometry (VBM), Deformation based morphometry (DBM), which can be more sensitive and precise compared to VBM (Schwarz & Kašpárek, 2011), and

cortical thickness and sulcus depth analyses, which are also informative regarding the possible efficiency of the regions of interest (Hilgetag & Barbas, 2005). Details about each technique are provided in separate sub-sections.

Survey

The survey captured the following control and descriptive variables using open ended and Likert-type questions: age, sex, the daily frequency of playing LOL, and years of experience with videogames (not just LOL).

MRI Protocol and Image Preprocessing

The MRI scans were performed in a 3T Siemens MAGNETOM Tim/Trio scanner at the Brain Imaging Center at the Southwest University. The T1-weighted 3D-Magnetization Prepared RApid Gradient Echo (MPRAGE) sequence was used for covering the whole brain for about 12 minutes (TR (repetition time)/TE (echo time) = 2530/3.39 ms, flip angel = 7^{o}, matrix = 256 × 256, 196 sagittal slices, 1 mm isotropic resolution). Image analyses were carried out using CAT12 toolbox [The Computational Anatomy Toolbox, http://www.neuro.uni-jena.de/cat/, version 12.3 (r1318)], which integrates with the SPM12 software [Statistical Parametric Mapping, https://www.fil.ion.ucl.ac.uk/spm/software/spm12/, version 12 (7219)] in the MATLAB [The Mathworks Inc., version R2014b (8.3.0.532)] environment. T1 images for all subjects were first automatically segmented into gray matter (GM), white matter (WM) and CSF after a scrupulous quality check of the initial images for avoiding artefacts. They were then affine registered to a MNI template space and subsequently modulated by a nonlinear deformation. Diffeomorphic Anatomical Registration using Exponential Lie algebra (DARTEL) tools were used for these registrations (Ashburner, 2007).

VBM Analysis

The output modulated normalized gray matter volume (voxel size = 1.5 mm × 1.5 mm × 1.5 mm) from preprocessing step were smoothed with an 8 mm isotropic Gaussian kernel. Two sample t-test models were built to examine group differences in gray matter volume (GMV). Intracranial volume for each participant was extracted to serve as a covariate of no interest along with age and sex in the GLM model. Whole brain differences were corrected for multiple comparisons using family-wise error correction at the cluster level ($p < 0.05$ FWE) and with cluster size larger than 100 voxels.

DBM Analysis

Deformation based morphometry (DBM) compares the position of each voxel in each brain to a standardized brain; It is therefore a robust, valid and useful tool for detecting between-individuals and between-groups morphological differences (Cardenas, Studholme, Gazdzinski, Durazzo, & Meyerhoff, 2007; Gaser, Nenadic, Buchsbaum, Hazlett, & Buchsbaum, 2001). Deformations provide information about the type and localization of the structural differences between the brains. DBM is analyzed using CAT which calculates the Jacobian determinant during preprocessing. Two sample t-test models were built to account for group differences in the Jacobian determinant. Intracranial volume for each participant was not used as a control (no need in DBM), but age and sex served as covariates of no interest in the GLM model. Whole brain differences were corrected for multiple comparisons using family-wise error correction at the cluster level ($p < 0.05$ FWE) and with cluster size larger than 100 voxels.

Cortical Thickness and Sulcus Depth Analyses

After preprocessing, CAT uses a projection scheme, which considers 92 blurred sulci to create a more accurate cortical thickness map. Cortical thickness is measured by estimating the gray matter distance between the inner surface and the outer surface (Dahnke, Yotter, & Gaser, 2013). Sulcus depths was also estimated using common approaches (Yotter, Nenadic, Ziegler, Thompson, & Gaser, 2011). Topology correction and visual quality control was also performed (Yotter, Dahnke, Thompson, & Gaser, 2011). Newly created images (split into left and right hemispheres) were smoothed with 15 mm FWHM Gaussian kernel. Two sample t-test models were estimated in order to examine group differences in cortical thickness; this was done for each hemisphere independently. Intracranial volume for each participant was not used as a covariate, but age and se were included in the GLM model. Whole brain difference was corrected for multiple comparisons using family-wise error correction at the cluster level ($p < 0.025$ FWE, because of the two hemispheres) and with cluster size larger than 100 voxels.

Results

Sample Characteristics

The two groups were matched on age and gender. No between-group difference in total intracranial volume (TIV) was observed. **Table 1** summarizes the characteristics of the groups and outlines tests of relevant between-group differences.

Table 1: Demographic and descriptive information of the samples

	Controls	LOL	Statistics
n (females)	26(6)	26(6)	-
Age	20.69 ± 2.21 years	20.46 ± 2.10 years	$t(50) = 0.39$, $p = 0.70$
Years of video-gaming	-	8.11 ± 2.75	-
TIV	1503.53 ± 90.47 ml	1498.03 ± 149.97	$t(50) = 0.16$, $p = 0.87$

TIV: Total intracranial volume.

VBM Results

VBM results showed significantly increased GMV in several regions in the control group compared to the extensive LOL group. These included the bilateral VMPFC, left lateral frontal pole, left dorsolateral prefrontal cortex, and right VMPFC (**Table 2** and **Figure 1**). The opposite comparison produced no significant differences.

Table 2: VBM results showed higher GMV in control group than in LOL group

L/R	Brain Region	No. of voxels	MNI x	MNI y	MNI z	*t* value	*z* value
L/R	VMPFC	3558	-12	60	-8	8.66	6.66
L	LFP	304	-39	42	-8	6.74	5.61

L	DLPFC	113	-38	41	17	6.11	5.21
R	VMPFC	258	8	17	-23	5.98	5.13

L: left; R: right; MNI, Montreal Neurological Institute; VMPFC: ventromedial prefrontal cortex; LFP: lateral frontal pole; DLPFC: dorsolateral prefrontal cortex.

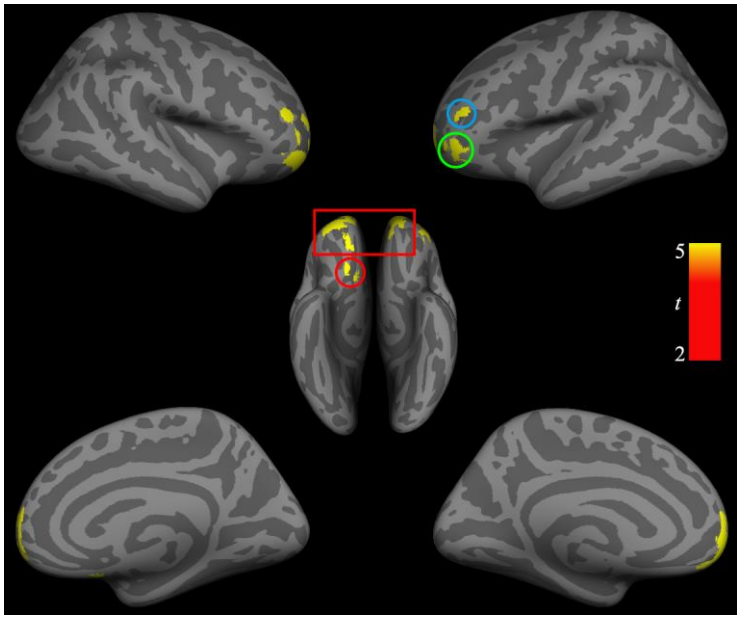

Figure 1: Increased GMV in control group compared to extensive LOL group as suggested by the VBM analysis. The figure highlights significant differences as projected to a standard brain surface using Freesurfer. Dark represents sulci and white represents gyri; right hemisphere is illustrated on the left and left hemisphere is on the right. The red circle and red rectangle cover the VMPFC, the blue circle covers the DLPFC, and the green circle covers the LFP. See **Table 2** for abbreviation of brain regions.

DBM Results

DBM results showed that one specific region, namely the right ventral striatum extending to VMPFC (**Table 3** and **Figure 2**) had a significantly higher Jacobian determinant value in the control group compared with the extensive LOL group. The opposite comparison showed no significant differences.

Table 3: DBM results showed higher Jacobian determinant value in control group than in LOL group

L/R	Brain Region	No. of voxels	MNI x	MNI y	MNI z	*t* value	*z* value
R	VMPFC	102	14	32	-15	4.98	4.45

L: left; R: right; MNI, Montreal Neurological Institute; VMPFC: ventromedial prefrontal cortex.

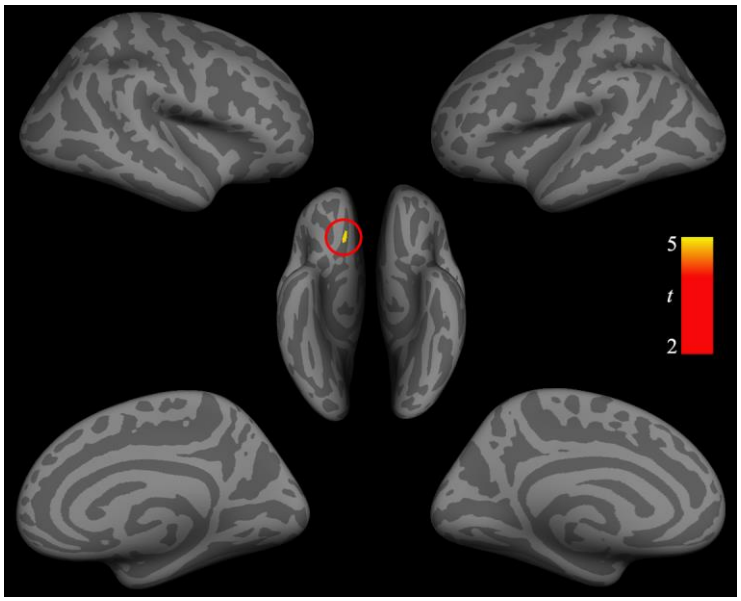

Figure 2: Higher Jacobian determinant value in control group compared to extensive LOL group as suggested by the DBM analysis. The figure highlights significant differences as projected to a standard brain surface using Freesurfer. Dark represents sulci and white represents gyri; right hemisphere is illustrated on the left and left hemisphere is on the right. The red circle covers the right VMPFC. See **Table 3** for abbreviation of brain regions.

Cortical Thickness Results

Results of cortical thickness analysis showed that several regions had a significantly higher cortical thickness in the control group compared with thickness in the extensive LOL group. These included the left superior parietal lobe, left VMPFC, left DMPFC, left superior parietal lobe, left DLPFC, left SFG, right VMPFC, and right SFG (**Table 4** and **Figure 3**). The opposite comparison showed no significant differences.

Table 4: Cortical thickness results showed thicker cortex in control group than in LOL group

L/R	Brain Region	No. of voxels	MNI x	MNI y	MNI z	*t* value	*z* value
L	SPL	318	-53	-45	47	5.92	5.08
L	VMPFC	462	-4	55	-23	5.90	5.06
L	DMPFC	381	-19	63	10	5.67	4.91
L	SPL	179	-63	-33	33	5.56	4.84
L	DLPFC	175	-40	30	33	5.31	4.67

L	SFG	133	-17	40	47	5.28	4.65
R	DMPFC	2618	5	57	-18	7.07	5.79
R	SFG	284	41	14	53	6.26	5.30

L: left; R: right; MNI, Montreal Neurological Institute; SPL, superior parietal lobe; VMPFC: ventromedial prefrontal cortex; DMPFC, dorsomedial prefrontal cortex; DLPFC, dorsolateral prefrontal cortex; SFG, superior frontal cortex.

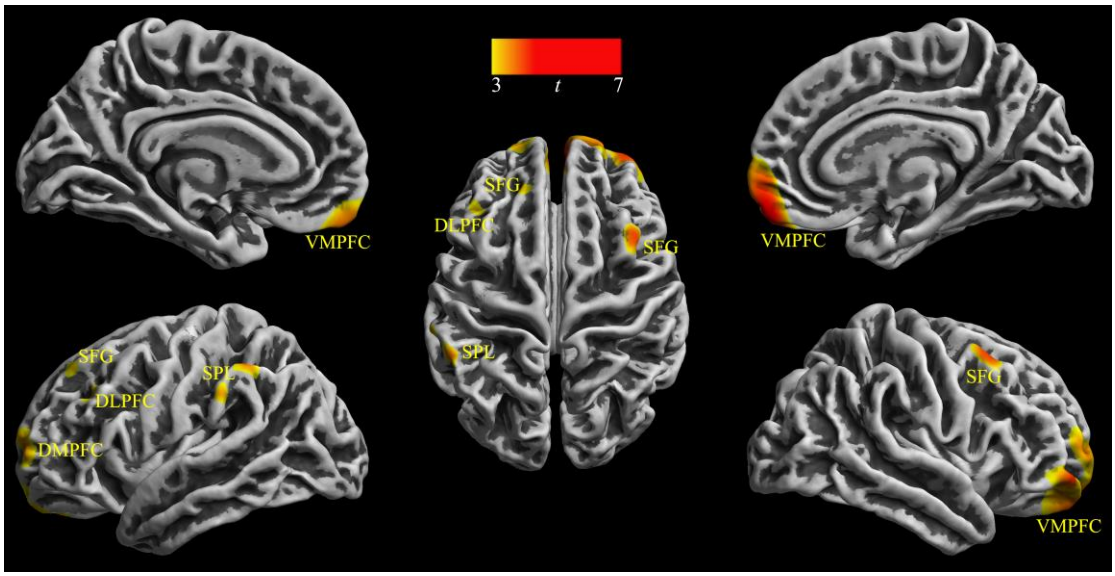

Figure 3: Increased cortical thickness in control group compared to extensive LOL group. Significant regions were projected to a standard brain surface using CAT12. Right hemisphere is illustrated on the left and left hemisphere is on the right. Brain region names were labeled with yellow color. See **Table 5** for abbreviations.

Sulcus Depth Results

Results of sulcus depth comparison pointed to significantly increased sulcus depth in the right VMPFC of the control group, compared with the extensive LOL group (**Table 5** and **Figure 4**). The opposite comparison showed no significant difference.

Table 5: Sulcus depth comparison results showed deeper sulcus in control group compared to LOL group

L/R	Brain Region	No. of voxels	MNI x	MNI y	MNI z	*t* value	*z* value
R	VMPFC	170	12	43	-26	5.12	4.53

L: left; R: right; MNI, Montreal Neurological Institute; VMPFC: ventromedial prefrontal cortex.

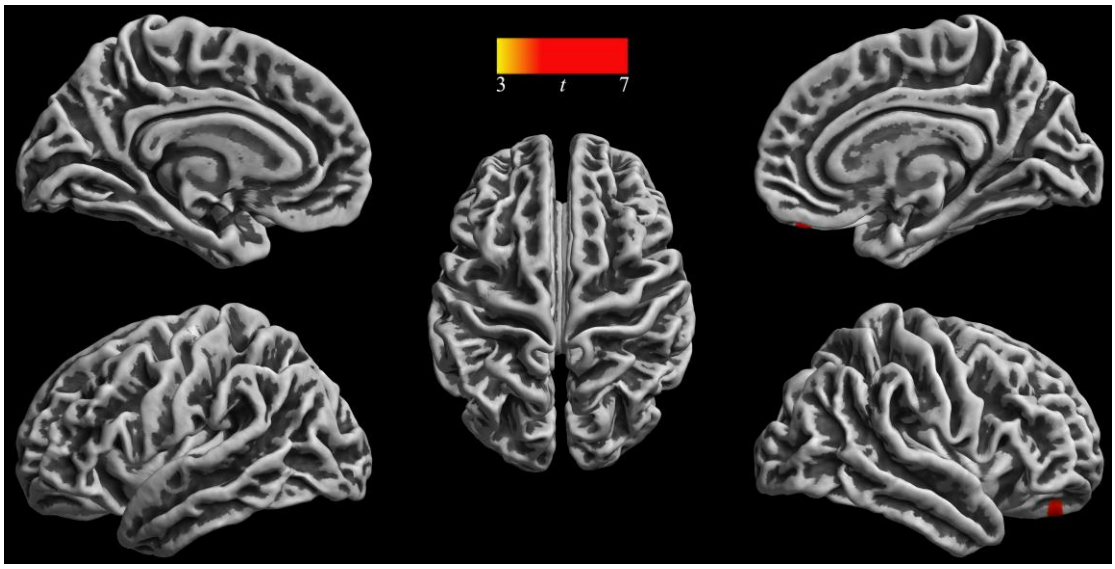

Figure 4: Increased sulcus depth in right VMPFC in control group compared to extensive LOL group. It was projected to a standard brain surface using CAT12. Right hemisphere is illustrated on the left and left hemisphere is on the right. See **Table 5** for abbreviation of brain regions.

Discussion

Playing video games, especially massively-multiplayer online games for several hours per day is not unusual for many young adults. About 10.6 % of young adults (18-25 years of age) play over 2.9 hours/day, and another 8.1% play between 1.7 to 2.9 hours a day (Limelight Networks, 2019). Such extensive gamers received less attention compared to light and addicted gamers (Palaus et al., 2017), even though their brain anatomy may be associated with their gaming pattern. This association can be through predisposing gaming behavior and/or through adaptations in response to repetitive gaming. The current study, hence, sought to test hypotheses about potential brain differences associated with gaming behavior in this sector of the population considered as extensive gamers. We predicted the existence of differences in extensive gamers compared to non-gamers in prefrontal regions that presumably reflect weaker inhibition abilities, and differences in visuomotor regions that presumably reflect stronger motor skills in response to visual stimuli.

The VBM results showed that extensive gamers have reduced gray matter volume in the VMPFC bilaterally, and especially the right VMPFC, as well as in left DLPFC extended to the LFP. The DBM results also point to reduced GMV in right VMPFC in extensive gamers compared to non-gamers. The cortical thickness analysis demonstrated that extensive gamers had several thinner cortices compared to non-gamers. Importantly, these included the L SPL and several prefrontal regions, including the L VMPFC, bilateral DMPFC and L DLPFC. Lastly, the sulcus depth analysis demonstrated shallower sulci in the R VMPFC in extensive gamers compared to non-gamers. These results largely support our first hypothesis by

showing structural indicators of less efficient prefrontal regions in terms of inhibition in extensive gamers, as reflected in lower volumes of, and thinner VMPFC and DLPFC, and shallower sulcus depth in the VMPFC. The results also provide some support for our second hypothesis by showing thinning of L SPL in extensive gamers, which can manifest in improved visuomotor skills.

The results regarding the prefrontal cortex are in line with studies on excessive gaming behaviors. Such behaviors are often seen as stemming from impairments in decision making and impulse control that involve modulations in the VMPFC and DLPFC (Hare, Camerer, & Rangel, 2009; Sokol-Hessner, Hutcherson, Hare, & Rangel, 2012; Steinbeis, Haushofer, Fehr, & Singer, 2016). These regions are involved in integrating somatic markers, or value signals related to reward and punishment experiences, into decision making and exerting self-control over tempting behaviors (Bechara, 2005; Bechara & Damasio, 2005). Abnormalities in these regions, as reflected in reduced gray matter volume (Matsuo et al., 2009), thinning of these cortices (Drobetz et al., 2014), and reduced cortical surface (i.e., shallower sulci) (Mackey & Petrides, 2014; Medic et al., 2016), are linked to reduced ability of individuals to adjust expectations, assess future consequences, and ultimately increase impulsivity and problematic behaviors (Dalwani et al., 2011). Given that videogames are highly rewarding (Han et al., 2011), we show that extensive gaming is associated with prefrontal brain differences that resemble those observed in other repeated tempting behaviors, such as substance use (He et al., 2018) and eating (Schmidt et al., 2018).

Interestingly, prior findings regarding prefrontal regions differed, based on the extent of gaming. In healthy non-expert (i.e., "light") gamers, video gaming was associated with increased volumes in prefrontal regions (Basak, Voss, Erickson, Boot, & Kramer, 2011; Kühn, Gleich, Lorenz, Lindenberger, & Gallinat, 2013; Kuhn, Lorenz, et al., 2014), presumably given the training and skill acquisition video gaming provides. However, consistent with the notion that such benefits accrue only at low-levels of gaming (up to one hour/week, see Pujol et al., 2016), reverse associations (i.e., reduced prefrontal volumes) were often observed in the case of excessive/addicted gamers (e.g., Jin et al., 2016). We show here that playing about 3 h/day (about 21 hours/week), which is much below typical playing time of addicted users (van Rooij et al., 2011), but higher than this of non-expert gamers, is more consistent with the addiction model of brain differences in that differences in prefrontal morphology that manifest in low self-control (reduced volume) overpower differences that may accrue due to light gaming and consequent skill improvement (increase volume). Hence, playing extensively can be a risk factor or a marker for weak decision-making and impulse control, even before addiction symptoms in relation to video gaming emerge. Future research should examine the possibility of identifying IGD risks at early stages, when people play about 3 h/day. Similarly, gaming of 3 h/day can signal to therapists, educators, and gamers, the need to more closely monitor the situation and preventing full loss of control.

It is worth noting that we did not observe differences in sub-cortical regions that mediate reward processing (the amygdala-striatal system). Prior research has shown reduced gray matter volumes in these regions in social media addiction cases (He, Turel, & Bechara, 2017; He, Turel, Brevers, & Bechara, 2017) and increased volumes in IGD cases (Yuan et al.,

2017). These regions are connected to frontal-cortical regions; the connectivity between these groups of regions has been shown to be impaired in IGD cases (Bi et al., 2017; Yuan et al., 2010; Yuan et al., 2011; Yuan et al., 2016; Yuan et al., 2017). While we did not examine connectivity in this study, our findings point to at least possible differences between IGD cases and extensive gamers in terms of the sources of cognitive control deficits. While the former group presents impaired cognitive control that manifests in differences in the reward and inhibition brain systems, as well as in the connectivity between then, extensive gamers seem to have presumed impaired self-control that manifest primarily in prefrontal-cortical regions. Future research should more directly examine such structural and connectivity differences between extensive gamers and IGD cases.

While findings regarding the L SPL are not as consistent across imaging analyses, as our findings regarding prefrontal regions were, they are also informative. The L SPL is important for visuospatial attention (Corbetta, Miezin, Shulman, & Petersen, 1993), manipulating information in working memory (Ciaramelli, Grady, & Moscovitch, 2008; Filimon, Nelson, Hagler, & Serenoa, 2007), motor responses to visual stimuli (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005), perceptual switches (Kanai, Bahrami, & Rees, 2010), and storing information on how tools are employed (Culham & Valyear, 2006). The L SPL ultimately controls the movement of the right arm under visual guidance (Fabbri, Strnad, Caramazza, & Lingnau, 2014). All of these functionalities are tapped into during video gaming. This mix of functionalities, though, makes prediction regarding SPL morphological alteration difficult. Reduced GMV is associated with improved performance on some visuomotor tasks (e.g., mental rotation, see Koscik et al., 2009), but increased GMV is associated with others (e.g., Sripada et al., 2015).

Here, we found that extensive massively-multiplayer gaming is associated with thinner L SPL cortex. The thinning and/or reduction of GMV of cortices can indicate increased efficiency, as faster action can be afforded when fewer neurons need to communicate over a shorter distance (Kanai & Rees, 2011). For example, reduced amygdala-striatal volumes can afford more automatic and faster response to rewarding stimuli (He et al., 2018); and reduced rostrolaterl prefrontal cortex volume can afford better manipulation of self-generated thoughts (Dumontheil, Hassan, Gilbert, & Blakemore, 2010). Our findings are specifically in line with Kanai, Dong, Bahrami, and Rees (2011) who showed that reduced SPL volume is associated with reduced distractibility (higher concentration). It is therefore reasonable to assume that given that extensive video gaming requires concentration, among other things (knowledge of tool use, fast right hand movement, etc.), extensive video gamers have thinner L SPL compared to non-gamers. This proposition, though merits further research. From a practical standpoint, these preliminary findings suggest that there is a need to consider whether video gaming can be used for changing L SPL volume and induce increased concentration. This can be relevant for several pathologies that involve distractibility (e.g., ADHD).

Several limitations of this study should be acknowledged. First, our data were correlational. Hence, causality claims and direction of causality cannot be inferred. Second, we focused on one game (LOL), game type (massively-multiplayer battle arena), gamer age group (young-adults) and did not distinguish among different levels/divisions of gamers. Generalizability of

the findings to other games, game types, and gamer age groups should be established in the future via replication. This is especially true since the audience of this game is very wide, and we focused on one narrow age segment. In addition, more fine-grained conclusions can be made in future research by focusing on different levels/divisions of gamers. Moreover, although LOL is a type of video game, our findings do not have to generalize to other games or to the broad concept of video gaming. Third, the sample was relatively small, since a power analysis revealed that a sample of 27 per group was needed for a modest effect size. Thus, our findings should be treated as preliminary. Fourth, given that the LOL gamer population is male dominant, and that there are much fewer extensive female players, our sample was imbalanced in terms of gamer sex. This did not afford us to perform sex-difference analyses. Future research may examine the possibility that the sexes differ in brain morphology associated with extensive video gaming. Lastly, we focused on morphological attributes of key brain regions, but could not consider microstructures such as the specific neurons and glial cells in these regions. These limitations pave the way for future research.

Conclusion

This study showed that extensive massively-multiplayer video gamers (those who play about 3 h/day) are morphologically different from non-gamers in that they have reduced volumes, thinner cortices, and sometimes shallower sulci in regions that govern self-control (VMPFC and DLPFC). They also have a thinner SPL sulcus, presumably reflecting increased concentration and visuomotor abilities. We call for future research to further examine extensive video gamers and the potential for video games of all types to generate desired and unwanted brain changes.

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Author contributions

QH, OT, LW and AB contributed to the conception and design of the study, data acquisition, analysis and interpretation, and drafted the manuscript.

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Compliance with ethical standards

Conflict of Interest

The authors declare no conflict of interest in relation to this work.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was approved by the Ethics Committee at Southwest University.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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