AKADÉMIAI KIADÓ

Journal of Behavioral Addictions

11 (2022) 1, 40–48

DOI:
10.1556/2006.2021.00090

FULL-LENGTH REPORT

Functional connectivity between the parahippocampal gyrus and the middle temporal gyrus moderates the relationship between problematic mobile phone use and depressive symptoms: Evidence from a longitudinal study

LIWEI ZOU[1,3,5†], XIAOYAN WU[2,3,4,5†], SHUMAN TAO[6], YAJUAN YANG[7], QINGJUN ZHANG[8], XUEDONG HONG[8], YANG XIE[2,3,5], TINGTING LI[2,3,5], SUISHENG ZHENG[8*] and FANGBIAO TAO[2,3,4,5*]

[1] Department of Radiology, the Second Hospital of Anhui Medical University, No 678 Furong Road, Hefei, 230601, Anhui, China

[2] Department of Maternal, Child and Adolescent Health, School of Public Health, Anhui Medical University, No 81 Meishan Road, Hefei, 230032, Anhui, China

[3] MOE Key Laboratory of Population Health Across Life Cycle, No 81 Meishan Road, Hefei, 230032, Anhui, China

[4] NHC Key Laboratory of Study on Abnormal Gametes and Reproductive Tract, No 81 Meishan Road, Hefei, 230032, Anhui, PR China

[5] Anhui Provincial Key Laboratory of Population Health and Aristogenics, No 81 Meishan Road, Hefei, 230032, Anhui, China

[6] Department of Nephrology, the Second Hospital of Anhui Medical University, No 678 Furong Road, Hefei, 230601, Anhui, China

[7] School of Nursing, Anhui Medical University, No 15 Feicui Road, Hefei, 230601, Anhui, China

[8] Ping An Healthcare Diagnostics Center, Hefei, 230000, Anhui, China

Received: July 20, 2020 • Revised manuscript received: November 11, 2021; December 19, 2021 • Accepted: December 28, 2021
Published online: January 19, 2022

ABSTRACT

Background and aim: Problematic mobile phone use (PMPU) is prevalent and increases the risk for a variety of health problems. However, few studies have explored the neural mechanisms that might render adolescents more or less vulnerable. Here, we aimed to identify whether PMPU is associated with depressive symptoms and whether this relationship is moderated by intrinsic functional connectivity (iFC) which is associated with PMPU. *Methods:* In this longitudinal study, we included 238 students (mean age = 19.05, SD = 0.81) that came from a university in Hefei, China. They all finished MRI scans at baseline and completed questionnaires both at baseline and 1 year later. A self-rating questionnaire for adolescent problematic mobile phone use and depression anxiety stress scale-21 were used to assess PMPU and depressive symptoms. We first assessed the relationship between PMPU and depressive symptoms using an autoregressive cross-lagged model. Then, we detected the brain regions that were associated with PMPU. Moreover, the neuroimaging results were extracted to explore whether the iFC of these brain regions moderated the relationship between PMPU and depression. *Results:* Consistent with our hypotheses, PMPU was positively associated with depressive symptoms, and the relationship between PMPU and depressive symptoms was moderated by iFC of the left parahippocampal gyrus-right middle temporal gyrus both at baseline and after 1 year ($\beta = 0.554$, $P = 0.003$; $\beta = 0.463$, $P = 0.016$, respectively). *Conclusions:* These results advance the understanding of PMPU and suggest that iFC of the left parahippocampal gyrus-right middle temporal gyrus may be a neurobiological contributor to its relationship with depressive symptoms.

†First authors: Liwei Zou and Xiaoyan Wu.

*Corresponding authors.
E-mail: taofangbiao@126.com, zhengss0509@sina.com

KEYWORDS

smartphone addiction, depression, moderate effect, resting-state, MRI

INTRODUCTION

Depression is a common mental disorder at all ages (Boers, Afzali, Newton, & Conrod, 2019). Adolescence is a developmental stage that is defined as the transition period from childhood to adulthood (Crone & Konijn, 2018). Adolescents are currently growing up in a digital time and hence are called "digital natives" (Haluza, Naszay, Stockinger, & Jungwirth, 2017). However, the rate of depression has increased among adolescents in recent decades. Researchers have identified the amount of time spent in digital device use as possible reason for this increase (Augner & Hacker, 2012; Brailovskaia & Margraf, 2020).

In China, it has been reported that there were 985.8 million mobile phone users, 21.0% of whom were students, by December 31, 2020 (CNNIC, 2021). Currently, mobile phones, the main digital device, have saturated college life. Excessive digital device use may have potential negative consequences, and high frequencies of mobile phone use have drawn the attention of researchers toward the detrimental impact on adolescents' mental health, especially regarding depression (Ng et al., 2020; Zhang, Yang, Tu, Ding, & Lau, 2020; Zou et al., 2019).

Problematic mobile phone use (PMPU) is defined as the inability to regulate one's mobile phone use, with features of craving, tolerance, and dependence, which would eventually lead to adverse health and functional consequence (Billieux et al., 2015; Zou et al., 2021). PMPU has also been known as problematic smartphone use, smartphone addiction, mobile phone addiction and mobile phone dependence (Derevensky, Hayman, & Lynette, 2019; Li, Li, Liu, & Wu, 2020).

Several studies have shown a positive relationship between PMPU and depression in adolescents (Demirci, Akgonul, & Akpinar, 2015; Lapierre, Zhao, & Custer, 2019; Liu et al., 2019; Park, Yang, Shin, Jang, & Park, 2019). Another study found no association (Casiano, Kinley, Katz, Chartier, & Sareen, 2012), whereas a systematic review by Elhai et al. (Elhai, Dvorak, Levine, & Hall, 2017) reported a significant association between problematic or general smartphone use and the severity of depression among different adolescents and adults. However, most studies were cross-sectional in design and the evidence was limited.

A growing number of studies are focusing on brain structure and function in addictive behaviours to define neural mechanisms based on advancements in neuroimaging techniques. Emerging evidence suggests that gray matter volume (GMV), cortical thickness and intrinsic functional connectivity (iFC) are altered in addictive behaviours, such as internet gaming disorder (IGD) (Weinstein, Livny, & Weizman, 2017; Yao et al., 2017). The iFC between brain regions reflects the correlation of activities and has been an important tool to understand altered brain function in studies. Brain function may pay a key role among the relationship between addictive behaviours and mental health. We hypothesized that iFC between brain regions were correlated with PMPU, which could moderate the association between PMPU and depressive symptoms.

Here, we conducted a longitudinal follow-up study to detect the relationship between PMPU and depressive symptoms among college students. Second, we aimed to detect the difference of brain function between PMPU group and Non-PMPU group by comparing iFC between two groups applying a ROI-based approach. At last, we used moderating analysis to assess the underlying mechanisms of the association between PMPU and depressive symptoms.

METHODS

Participants

The study initially recruited 574 college freshmen from five different majors in Anhui Medical University at baseline, and progressively assess behaviours and mental health 1 year later. The present study was a subset of participants who took part in the brain imaging study, based on a voluntary basis. Moreover, we also described the aim of study and the questionnaires to the students. At last, we send a QR code to class teacher for collecting information by the electronic questionnaires. A total of 268 students completed the MRI scan in the baseline, combined the questionnaire data (baseline and 1 year later) and the image preprocessing criteria, we eventually included the 238 college students (Fig. 1).

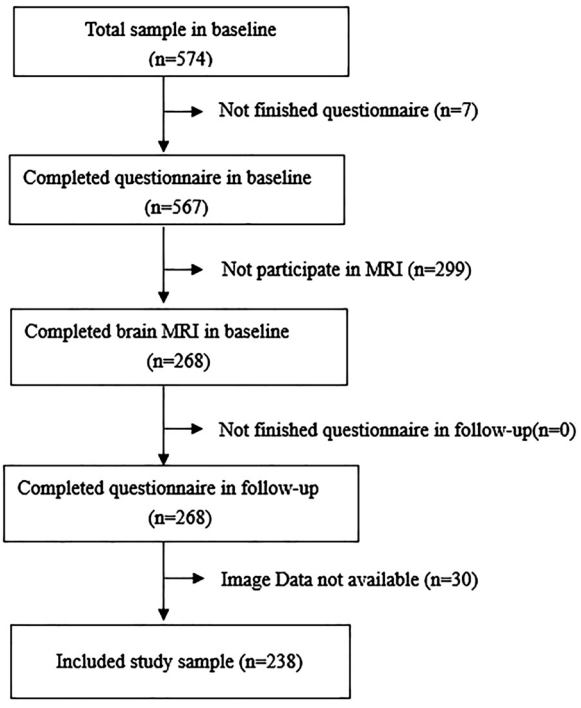

Fig. 1. The flow diagram of sample selection in this study

This study included 238 college students aged between 17 and 22 years old (mean ± SD: 19.05 ± 0.81) after imaging preprocessing and obtained questionnaire data at both baseline and 1 year later. The information collected from all subjects contained sociodemographic data, such as gender, age, residential area, family income, parents' education level, and two measures regarding problematic mobile phone use and depressive symptoms: the Self-rating Questionnaire for Adolescent Problematic Mobile Phone Use (SQAPMPU) (Tao, Fu, Wang, Hao, & Tao, 2013) and the Depression Anxiety Stress Scale-21 (DASS-21) (K. Wang, Zou, et al., 2016).

Measures

Self-rating Questionnaire for Adolescent Problematic Mobile Phone Use (SQAPMPU): The SQAPMPU consists of 13 items (e.g. "I always feel I do not have enough time to use my mobile phone," "I do not have enough time for sleeping due to the time I spend on my mobile phone," and "I feel lost without my mobile phone") and a 5-point Likert scale ranging from 1 (not at all) to 5 (extremely true), which is used to assess PMPU in college students. This scale covers 3 dimensions: withdrawal symptoms, craving, and physical and mental health status. The total score ranged from 13 to 65. We defined SQAPMPU ≥28 as the PMPU group and SQAPMPU <28 as the non-PMPU group, with the 75th percentile as the cutoff point. Cronbach's alpha coefficient was 0.90.

Depression Anxiety Stress Scale-21 (DASS-21): The subscale depression of the DASS-21 consists of 7 items (e.g. "I couldn't seem to experience any positive feeling at all," "I felt that I had nothing to look forward to," and "I felt that life was meaningless"). Each item on the measure contains 4 options to describe how often each feeling is experienced. The scores assign 0 for not at all, 1 for several days, 2 for more than half the days and 3 for nearly every day. The total scores range from 0 to 21, with higher scores indicating more severe depressive symptoms. Cronbach's alpha coefficient was 0.85.

MRI acquisition

MRI scans were obtained on a 3.0 T Philips Ingenia CX scanner (Philips, Best, Netherlands) with a 32-channel head coil at the Ping An Healthcare Diagnostics Center (Hefei, Anhui, China). Foam pads and earplugs were used for each participant to reduce head motion and scanner noise. The resting data of functional images were acquired by echo planar imaging (EPI) sequence with echo time (TE) = 25 ms, repetition time = 2,000 ms, 90° flip angle, 35 slices, field of view (FOV) = 240 × 240, and slice thickness = 4 mm. For each subject, a total of 240 vol were acquired. The acquisition time was 8 min and 8 s.

fMRI data preprocessing

Functional image preprocessing was performed with DPABI v4.5 (http://rfmri.org/dpabi) and SPM12 toolkits. The first 10 vol were dropped duo to instability of the initial MRI signal and to allow participants to adapt to the MRI acquisition circumstances. The subsequent steps were slice time correction and head motion correction. We excluded 30 participants (5 in the PMPU group and 25 in the non-PMPU group) due to head motion correction for a criterion of 2 mm in translation and 2° in rotation. We also used the criteria of calculating the framewise displacement (FD) to express instantaneous head motions, with a threshold of 0.5 mm. No one was excluded under the head motion criterion. Next, the corrected images were normalized to Montreal Neurological Institute (MNI) spaces by EPI templates in SPM 12, resampled to 3-mm isotropic voxels, and further spatially smoothed with a 4-mm full width-half maximum (FWHM) Gaussian kernel. After linear detrending and temporal bandpass filtering (0.01–0.1 HZ), several nuisance variables, including Friston 24 head motion parameters, white matter, cerebrospinal fluid signal and global mean signal were regressed from the BOLD time series for all voxels.

fMRI data analysis

Regions of interest (ROIs) were defined by the Human Brainnetome Atlas and consist of 210 cortical and 36 subcortical subregions that contain information on both anatomical and functional connections (Fan et al., 2016). For each subject, the representative time series of each ROI was estimated by averaging the fMRI time series throughout all voxels in each ROI (Salvador et al., 2005). We computed the Pearson correlation coefficient between each pair of 246 ROIs to assess the iFC for all participants. Finally, to improve the normality of the correlation coefficients, Fisher's r-to-z transformation was performed for subsequent analysis. We used the false discovery rate (FDR) corrected for multiple comparisons ($P < 0.05$). We also extracted iFC from the difference between college students with and without PMPU in these brain regions to perform moderating analysis.

Statistical analysis

Moderation analysis used by PROCESS (model 1) that is a macro of SPSS, which was developed by Hayes (Hayes & Rockwood, 2017). The statistical significance was set at two-tailed $P < 0.05$ and was performed using SPSS version 23.0 (SPSS, Chicago, IL, USA) and Mplus 8.3.

An autoregressive cross-lagged model was used to test the relationship between PMPU and depressive symptoms.

Differences in iFC were conducted at the group level to identify the significant iFC related to PMPU. Then, we performed moderating analysis to assess whether iFC moderates the association between PMPU and depressive symptoms. A moderating analysis was conducted with PMPU as an independent variable, iFC between brain regions that were strongly ($P < 0.05$, FDR corrected) associated with PMPU as a moderator, and depressive symptoms at baseline and 1 year later as a dependent variable by PROCESS in SPSS.

Ethics

The study was approved by the Ethics Committee of Anhui Medical University and written informed consent was obtained before the survey.

RESULTS

Demographic data

The demographics of the study participants are summarized in Table 1. We included 238 participants aged between 17 and 22 years old and the mean age (SD) was 19.05 (0.81). Of the sample, 55 were male (23.1%), 142 (59.7%) participants came from rural areas, and 31.9% (n = 76) of participants were classified as PMPU. We did not find any differences in gender, residential area, number of siblings, perceived family income or parents' educational level between PMPU and non-PMPU students, except for the depression scores at baseline.

Cross-lagged model

The model showed that the PMPU at baseline was positively associated with depressive symptoms 1 year later but did not find depressive symptoms at baseline associated with PMPU 1 year later. There was a significant relationship between PMPU and depressive symptoms both at baseline and 1 year later (Fig. 2, Table 2).

Association between PMPU and functional connectivity: whole brain analysis

For iFC analysis, we found that iFC of the left inferior frontal gyrus (IFG)-left occipital gyrus (OcG), right orbital gyrus

Table 1. Demographic characteristics of adolescents with and without problem mobile phone use

	Total (n = 238)	PMPU group (n = 76)	Non-PMPU group (n = 162)	Test value ($t/\chi^2/Z$)	P value
Age (years), Mean ± SD	19.05 ± 0.81	19.12 ± 0.65	19.02 ± 0.87	−0.89	0.376
Gender					
Male (n, %)	55 (23.1%)	14 (18.4%)	41 (25.3%)	1.38	0.240
Female (n, %)	183 (76.9%)	62 (81.6%)	121 (74.7%)		
Residential Area					
Rural (n, %)	142 (59.7%)	48 (63.2%)	94 (58.0%)	0.57	0.452
Urban (n, %)	96 (40.3%)	28 (36.8%)	68 (42.0%)		
Any siblings					
Yes (n, %)	53 (22.3%)	14 (18.4%)	39 (24.1%)	0.96	0.328
No (n, %)	185 (77.7%)	62 (81.6%)	123 (75.9%)		
Perceived family income					
Low (n, %)	49 (20.6%)	18 (23.7%)	31 (19.1%)	1.67	0.422
Medium (n, %)	177 (74.4%)	56 (73.7%)	121 (74.7%)		
High (n, %)	12 (5.0%)	2 (2.6%)	10 (6.2%)		
Father's educational level					
Primary school or lower (n, %)	50 (21.0%)	22 (28.9%)	28 (17.3%)	5.36	0.068
Middle school (n, %)	121 (50.8%)	38 (50.0%)	83 (51.2%)		
College or above (n, %)	77 (28.2%)	16 (21.1%)	51 (31.5%)		
Mother's educational level					
Primary school or lower (n, %)	109 (45.8%)	38 (50%)	71 (43.8%)	2.04	0.360
Middle school (n, %)	81 (34.0%)	21 (27.6%)	60 (37.1%)		
College or above (n, %)	48 (20.2%)	17 (23.4%)	31 (19.1%)		
SQAPMPU scores (Median)	23.50	34.00	21.00	–	–
DASS-depression scores (Baseline, Median)	2	6	0	−5.45	<0.001
DASS-depression scores (1 year later, Median)	0	2	0	−1.93	0.054

Note: PMPU, problematic mobile phone use; SD, standard deviation; SQAPMPU, Self-rating Questionnaire for Adolescent Problematic Mobile Phone Use scale; DASS, Depression Anxiety Stress Scale.

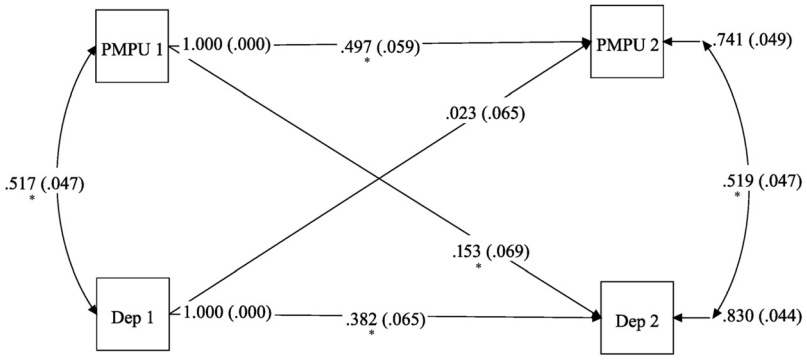

Fig. 2. Cross-lagged model of PMPU associated with depressive symptoms in this study. PMPU, problematic mobile phone use

Table 2. Standardized coefficient of PMPU and depressive symptom on cross-lagged model

Parameter	β	SE	P
Stability paths			
PMPU 1→PMPU 2	0.497	0.059	<0.001
Dep 1→Dep 2	0.382	0.065	<0.001
Cross-lagged effects			
PMPU 1→Dep 2	0.153	0.069	0.008
Dep 1→PMPU 2	0.023	0.065	0.729

Note: PMPU, problematic mobile phone use; Dep, depressive symptom; SE, standard error.

(OrG)-left OcG and left parahippocampal gyrus (PhG)-right middle temporal gyrus (MTG) increased in the PMPU group compared with college students without PMPU (P < 0.05, FDR corrected) and did not find significantly decreased iFC in PMPU (Fig. 3).

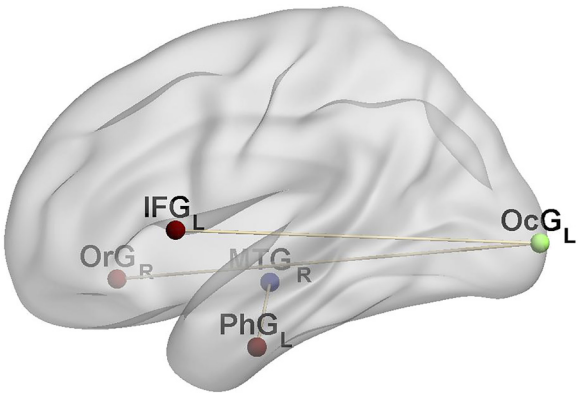

Fig. 3. Intrinsic functional connectivity (iFC) of whole brain analysis between college students with PMPU and without PMPU. PMPU students showed increased iFC of left inferior frontal gyrus (IFG) to left occipital gyrus (OcG), right orbital gyrus (OrG) to left OcG and left parahippocampal gyrus (PhG) to right middle temporal gyrus (MTG) than college students without PMPU (P_{FDR} < 0.05). PMPU, problematic mobile phone use

Moderation analysis

For moderation analysis, we tested whether the association between PMPU and depressive symptoms was reduced or increased by introducing iFC, which was significantly associated with PMPU, from the above group-level results. We found that iFC of the left PhG-the right MTG had a significant moderating effect on the association between PMPU and depressive symptoms both at baseline and 1 year later ($\beta = 0.351$, $\Delta R^2 = 0.028$, $P = 0.003$, $\beta = 0.149$, $\Delta R^2 = 0.023$, $P = 0.016$, respectively) (Table 3, Fig. 4). The results indicated that lower iFC of the left PhG-the right MTG could reduce the association between PMPU and depressive symptoms.

DISCUSSION

To our knowledge, this is the first longitudinal study to detect the neural mechanism underlying the association between PMPU and depressive symptoms by iFC from MRI. In line with our hypothesis, PMPU increases college students' risk for depressive symptoms, and college students with PMPU have shown that they had increased iFCs of the left IFG-the left OcG, the right OrG-the left OcG and the left PhG-the right MTG. Furthermore, a moderate analysis found that iFC between the left PhG and right MTG played a key role in the association between PMPU and depressive symptoms. The results suggest a neural basis for understanding how PMPU is associated with depressive symptoms in college students.

For the association between PMPU and iFC, our results were not consistent with previous studies in internet addiction, which found increased iFC between the striatum and thalamus, amygdala and dorsolateral prefrontal cortex in internet gaming disorder compared with controls (Dong, Wang, Wang, Du, & Potenza, 2019; Liu et al., 2018). However, our results were consistent with previous brain structural studies, which reported abnormalities in gray matter volume in the IFG, lateral orbitofrontal cortex and left parahippocampal cortex in PMPU students compared to those in controls (Horvath et al., 2020; Lee, Namkoong, Lee, Lee, & Jung, 2019; Y. Wang, Zou, et al., 2016).

The IFG plays a key role in the frontoparietal network which involves inhibitory control, attention switching, and behaviour modulation (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010). Impairment of the function/structure of the IFG is associated with executive control and has served as behavioural disinhibition, which is related to the maintenance and exacerbation of addiction behaviours (Y. Wang, Zou, et al., 2016). The OrG is correlated with decision-making (Mohammadi et al., 2016; Wallis, 2007). Thus, it seems that interference with decision-making results due to abnormalities in the OrG and dysfunction of decision-making have been related to addiction behaviours (Lee et al., 2019). In particular, the iFC of the IFG and the OrG was identified in the present study while pursuing rewards in PMPU.

The PhG contributes to memory recall, which activity is related to the representation and retrieval of contextual information (Aminoff, Kveraga, & Bar, 2013). We found that iFC increased between the left PhG and the right MTG in the PMPU, which is consistent with previous results that suggested involuntary retrieval and processing of prior experiences in pathological gamblers (Clark, Boileau, & Zack, 2019; Crockford, Goodyear, Edwards, Quickfall, & el-Guebaly, 2005). Moreover, increased iFC of the PhG-MTG may be the underlying mechanism (at least partly) of the association between PMPU and depressive symptoms and may provide a new perspective for treating emotion problems in PMPU. Future studies are needed to determine the specificity mechanisms of negative emotion problems in the PMPU group.

The IFG, OrG and PhG are parts of reward-related brain regions that contribute to behavioural problems (Balodis & Potenza, 2015; Dong, Hu, & Lin, 2013). The reward circuit is

Table 3. Results from the moderated regression analysis predicting depressive symptoms in baseline and 1 year later

	Predictors	Model 1				Model 2			
		β	t	ΔR^2	F	β	t	ΔR^2	F
Cross-sectional effect									
1	PMPU	0.368	9.042**	<0.001	0.009	0.375	8.982**	0.001	0.238
	IFG-OcG	2.377	1.336			1.445	0.783		
	PMPU × IFG-OcG	0.020	0.096			0.103	0.488		
2	PMPU	0.368	9.064**	0.004	1.216	0.376	9.003**	0.007	2.316
	OrG-OcG	2.860	1.531			2.018	1.057		
	PMPU × OrG-OcG	0.260	1.103			0.365	1.523		
3	PMPU	0.352	8.756**	0.021	7.038*	0.351	8.527**	0.028	9.304**
	PhG-MTG	2.663	1.757			2.167	1.430		
	PMPU × PhG-MTG	0.477	2.653*			0.554	3.050**		
Longitudinal effect									
1	PMPU	0.172	4.104**	0.002	0.584	0.173	3.979**	0.002	0.531
	IFG-OcG	−2.014	−1.101			−1.663	−0.862		
	PMPU × IFG-OcG	0.164	0.764			0.161	0.729		
2	PMPU	0.168	4.006**	0.001	0.239	0.172	3.923**	0.001	0.219
	OrG-OcG	−0.588	−0.304			−0.713	−0.352		
	PMPU × OrG-OcG	0.119	0.489			0.118	0.468		
3	PMPU	0.147	3.526**	0.026	6.754*	0.149	3.412**	0.023	5.847*
	PhG-MTG	0.559	0.356			0.587	0.366		
	PMPU × PhG-MTG	0.484	2.600*			0.463	2.418*		

Note: *P < 0.05, **P < 0.01, model 1 was did not adjust any variables, model 2 was adjusted by age, gender, residential area, any siblings, perceived family income and parents' education level. PMPU, problematic mobile phone use; IFG, inferior frontal gyrus; OcG, occipital gyrus; OrG, orbital gyrus; PhG, parahippocampal gyrus; MTG, middle temporal gyrus.

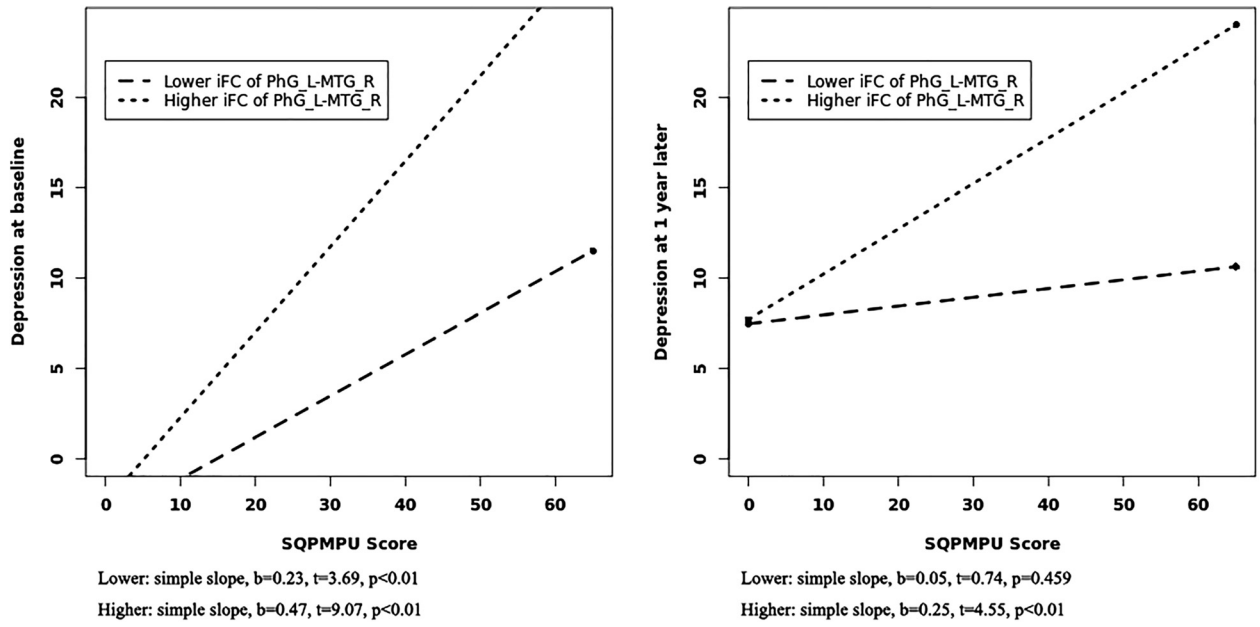

Fig. 4. Simple slope analyzes of moderation effect by iFC of left PhG to right MTG on PMPU and depressive symptom in baseline and 1 year later. For illustrative purposes, iFC of left PhG to right MTG were graphed at lower (-1 standard deviation) and higher (+1 standard deviation) connectivity from the mean level. PMPU, problematic mobile phone use; iFC, intrinsic functional connectivity; PhG, parahippocampal gyrus; MTG, middle temporal gyrus; L, left; R, right

a network of brain regions involved in reward processing, including reward anticipation and receipt of rewards. The results of this study were consistent with previous behavioural studies on disruption of reward-related function in major depressive disorder, which suggested insensitivity to reward contingencies (Admon & Pizzagalli, 2015; Pizzagalli, Iosifescu, Hallett, Ratner, & Fava, 2008), and that predicted a poor response to treatment (Downar et al., 2014). A dysfunctional reward system may have played a vital role in core features of depression based on converging evidence,

including anhedonia, decreased motivation and depressed mood (Keren et al., 2018; Luking, Pagliaccio, Luby, & Barch, 2016; Stringaris et al., 2015).

This study has several limitations and points that require further discussion. First, there are some limitations in our measures of PMPU through well-validated self-report questionnaires. Behavioural PMPU patterns obtained from mobile phone applications need to be detected further in future studies. Second, we used resting-state MRI studies and mainly focused on iFC from the whole-brain method rather than ROI-based iFC, such as reward-related brain regions.

CONCLUSIONS

The current study is the first to demonstrate that iFC between the left PhG and the right MTG has a moderating effect on the relationship between PMPU and depressive symptoms among college students. These results support that PMPU is a behavioural problem that correlated with abnormality of brain function, which reminder the importance to prevent and control PMPU, so as to reduce potentially risk of mental health problems among young adults.

Funding sources: This study was supported by National Natural Science Foundation of China (81773455, 81803257), Scientific Research of BSKY from Anhui Medical University (XJ201824), Open Project Program of Anhui Provincial Key Laboratory of Population Health & Aristogenics (JKYS20211).

Authors' contribution: T.F. designed the study. Z.L., W.X., T.S., X.Y., L.T and Y.Y. performed the survey research. Z.Q, H.X, and Z.S. conducted MRI and checked the MRI data. Z.L., W.X. and T.S. analyzed the data. Z.L. draft the manuscript. Finally, all authors read and approved the final manuscript.

Conflict of interest: The authors declare that they have no conflict of interest.

REFERENCES

Admon, R., & Pizzagalli, D. A. (2015). Dysfunctional reward processing in depression. *Current Opinion in Psychology*, *4*, 114–118. https://doi.org/10.1016/j.copsyc.2014.12.011.

Aminoff, E. M., Kveraga, K., & Bar, M. (2013). The role of the parahippocampal cortex in cognition. *Trends in Cognitive Sciences*, *17*(8), 379–390. https://doi.org/10.1016/j.tics.2013.06.009.

Augner, C., & Hacker, G. W. (2012). Associations between problematic mobile phone use and psychological parameters in young adults. *International Journal of Public Health*, *57*(2), 437–441. https://doi.org/10.1007/s00038-011-0234-z.

Balodis, I. M., & Potenza, M. N. (2015). Anticipatory reward processing in addicted populations: A focus on the monetary incentive delay task. *Biological Psychiatry*, *77*(5), 434–444. https://doi.org/10.1016/j.biopsych.2014.08.020.

Billieux, J., Philippot, P., Schmid, C., Maurage, P., De Mol, J., & Van der Linden, M. (2015). Is dysfunctional use of the mobile phone a behavioural addiction? Confronting symptom-based versus process-based approaches. *Clinical Psychology & Psychotherapy*, *22*(5), 460–468. https://doi.org/10.1002/cpp.1910.

Boers, E., Afzali, M. H., Newton, N., & Conrod, P. (2019). Association of screen time and depression in adolescence. *JAMA Pediatrics*, *173*(9), 853–859. https://doi.org/10.1001/jamapediatrics.2019.1759.

Brailovskaia, J., & Margraf, J. (2020). Decrease of well-being and increase of online media use: Cohort trends in German university freshmen between 2016 and 2019. *Psychiatry Research*, *290*, 113110. https://doi.org/10.1016/j.psychres.2020.113110.

Casiano, H., Kinley, D. J., Katz, L. Y., Chartier, M. J., & Sareen, J. (2012). Media use and health outcomes in adolescents: Findings from a nationally representative survey. *Journal of the Canadian Academy of Child and Adolescent Psychiatry = Journal de l'Academie canadienne de psychiatrie de l'enfant et de l'adolescent*, *21*(4), 296–301.

Clark, L., Boileau, I., & Zack, M. (2019). Neuroimaging of reward mechanisms in gambling disorder: An integrative review. *Molecular Psychiatry*, *24*(5), 674–693. https://doi.org/10.1038/s41380-018-0230-2.

CNNIC. (2021). The 47th China statistical report on internet development. http://www.cnnic.net.cn/hlwfzyj/hlwxzbg/.

Crockford, D. N., Goodyear, B., Edwards, J., Quickfall, J., & el-Guebaly, N. (2005). Cue-induced brain activity in pathological gamblers. *Biological Psychiatry*, *58*(10), 787–795. https://doi.org/10.1016/j.biopsych.2005.04.037.

Crone, E. A., & Konijn, E. A. (2018). Media use and brain development during adolescence. *Nature Communications*, *9*(1), 588. https://doi.org/10.1038/s41467-018-03126-x.

Demirci, K., Akgonul, M., & Akpinar, A. (2015). Relationship of smartphone use severity with sleep quality, depression, and anxiety in university students. *Journal of Behavioral Addictions*, *4*(2), 85–92. https://doi.org/10.1556/2006.4.2015.010.

Derevensky, J. L., Hayman, V., & Lynette, G. (2019). Behavioral addictions: excessive gambling, gaming, internet, and smartphone use among children and adolescents. *Pediatric Clinics of North America*, *66*(6), 1163–1182. https://doi.org/10.1016/j.pcl.2019.08.008.

Dong, G., Hu, Y., & Lin, X. (2013). Reward/punishment sensitivities among internet addicts: Implications for their addictive behaviors. *Progress in Neuro-Psychopharmacology & Biological Psychiatry*, *46*, 139–145. https://doi.org/10.1016/j.pnpbp.2013.07.007.

Dong, G., Wang, Z., Wang, Y., Du, X., & Potenza, M. N. (2019). Gender-related functional connectivity and craving during gaming and immediate abstinence during a mandatory break: Implications for development and progression of internet gaming disorder. *Progress in Neuro-Psychopharmacology & Biological Psychiatry*, *88*, 1–10. https://doi.org/10.1016/j.pnpbp.2018.04.009.

Downar, J., Geraci, J., Salomons, T. V., Dunlop, K., Wheeler, S., McAndrews, M. P., ... Giacobbe, P. (2014). Anhedonia and

reward-circuit connectivity distinguish nonresponders from responders to dorsomedial prefrontal repetitive transcranial magnetic stimulation in major depression. *Biological Psychiatry*, *76*(3), 176–185. https://doi.org/10.1016/j.biopsych.2013.10.026.

Elhai, J. D., Dvorak, R. D., Levine, J. C., & Hall, B. J. (2017). Problematic smartphone use: A conceptual overview and systematic review of relations with anxiety and depression psychopathology. *Journal of Affective Disorders*, *207*, 251–259. https://doi.org/10.1016/j.jad.2016.08.030.

Fan, L., Li, H., Zhuo, J., Zhang, Y., Wang, J., Chen, L., ... Jiang, T. (2016). The human brainnetome Atlas: A new brain Atlas based on connectional architecture. *Cerebral Cortex*, *26*(8), 3508–3526. https://doi.org/10.1093/cercor/bhw157.

Haluza, D., Naszay, M., Stockinger, A., & Jungwirth, D. (2017). Digital natives versus digital immigrants: Influence of online health information seeking on the doctor-patient relationship. *Health Communication*, *32*(11), 1342–1349. https://doi.org/10.1080/10410236.2016.1220044.

Hampshire, A., Chamberlain, S. R., Monti, M. M., Duncan, J., & Owen, A. M. (2010). The role of the right inferior frontal gyrus: Inhibition and attentional control. *NeuroImage*, *50*(3), 1313–1319. https://doi.org/10.1016/j.neuroimage.2009.12.109.

Hayes, A. F., & Rockwood, N. J. (2017). Regression-based statistical mediation and moderation analysis in clinical research: Observations, recommendations, and implementation. *Behaviour Research and Therapy*, *98*, 39–57. https://doi.org/10.1016/j.brat.2016.11.001.

Horvath, J., Mundinger, C., Schmitgen, M. M., Wolf, N. D., Sambataro, F., Hirjak, D., ... Christian Wolf, R. (2020). Structural and functional correlates of smartphone addiction. *Addictive Behaviors*, *105*, 106334. https://doi.org/10.1016/j.addbeh.2020.106334.

Keren, H., O'Callaghan, G., Vidal-Ribas, P., Buzzell, G. A., Brotman, M. A., Leibenluft, E., ... Stringaris, A. (2018). Reward processing in depression: A conceptual and meta-analytic review across fMRI and EEG studies. *The American Journal of Psychiatry*, *175*(11), 1111–1120. https://doi.org/10.1176/appi.ajp.2018.17101124.

Lapierre, M. A., Zhao, P., & Custer, B. E. (2019). Short-term longitudinal relationships between smartphone use/dependency and psychological well-being among late adolescents. *The Journal of Adolescent Health : Official Publication of the Society for Adolescent Medicine*, *65*(5), 607–612. https://doi.org/10.1016/j.jadohealth.2019.06.001.

Lee, D., Namkoong, K., Lee, J., Lee, B. O., & Jung, Y. C. (2019). Lateral orbitofrontal gray matter abnormalities in subjects with problematic smartphone use. *Journal of Behavioral Addictions*, *8*(3), 404–411. https://doi.org/10.1556/2006.8.2019.50.

Li, Y., Li, G., Liu, L., & Wu, H. (2020). Correlations between mobile phone addiction and anxiety, depression, impulsivity, and poor sleep quality among college students: A systematic review and meta-analysis. *Journal of Behavioral Addictions*, *9*(3), 551–571. https://doi.org/10.1556/2006.2020.00057.

Liu, S., Wing, Y. K., Hao, Y., Li, W., Zhang, J., & Zhang, B. (2019). The associations of long-time mobile phone use with sleep disturbances and mental distress in technical college students: A prospective cohort study. *Sleep*, *42*(2). https://doi.org/10.1093/sleep/zsy213.

Liu, L., Yao, Y. W., Li, C. R., Zhang, J. T., Xia, C. C., Lan, J., ... Fang, X. Y. (2018). The comorbidity between internet gaming disorder and depression: Interrelationship and neural mechanisms. *Frontiers in Psychiatry*, *9*, 154. https://doi.org/10.3389/fpsyt.2018.00154.

Luking, K. R., Pagliaccio, D., Luby, J. L., & Barch, D. M. (2016). Reward processing and risk for depression across development. *Trends in Cognitive Sciences*, *20*(6), 456–468. https://doi.org/10.1016/j.tics.2016.04.002.

Mohammadi, B., Hammer, A., Miedl, S. F., Wiswede, D., Marco-Pallarés, J., Herrmann, M., & Münte, T. F. (2016). Intertemporal choice behavior is constrained by brain structure in healthy participants and pathological gamblers. *Brain Structure & Function*, *221*(6), 3157–3170. https://doi.org/10.1007/s00429-015-1093-9.

Ng, K. C., Wu, L. H., Lam, H. Y., Lam, L. K., Nip, P. Y., Ng, C. M., ... Leung, S. F. (2020). The relationships between mobile phone use and depressive symptoms, bodily pain, and daytime sleepiness in Hong Kong secondary school students. *Addictive Behaviors*, *101*, 105975. https://doi.org/10.1016/j.addbeh.2019.04.033.

Park, S. Y., Yang, S., Shin, C. S., Jang, H., & Park, S. Y. (2019). Long-term symptoms of mobile phone use on mobile phone addiction and depression among Korean adolescents. *International Journal of Environmental Research and Public Health*, *16*(19). https://doi.org/10.3390/ijerph16193584.

Pizzagalli, D. A., Iosifescu, D., Hallett, L. A., Ratner, K. G., & Fava, M. (2008). Reduced hedonic capacity in major depressive disorder: evidence from a probabilistic reward task. *Journal of Psychiatric Research*, *43*(1), 76–87. https://doi.org/10.1016/j.jpsychires.2008.03.001.

Salvador, R., Suckling, J., Coleman, M. R., Pickard, J. D., Menon, D., & Bullmore, E. (2005). Neurophysiological architecture of functional magnetic resonance images of human brain. *Cerebral Cortex*, *15*(9), 1332–1342. https://doi.org/10.1093/cercor/bhi016.

Stringaris, A., Vidal-Ribas Belil, P., Artiges, E., Lemaitre, H., Gollier-Briant, F., Wolke, S., ... Consortium, I. (2015). The brain's response to reward anticipation and depression in adolescence: Dimensionality, specificity, and longitudinal predictions in a community-based sample. *The American Journal of Psychiatry*, *172*(12), 1215–1223. https://doi.org/10.1176/appi.ajp.2015.14101298.

Tao, S., Fu, J., Wang, H., Hao, J., & Tao, F. (2013). The development of self-rating questionnaire for adolescent problematic mobile phone use and the psychometric evaluation in undergraduates. *Chinese Journal of School Health*, *34*(1), 26–29.

Wallis, J. D. (2007). Orbitofrontal cortex and its contribution to decision-making. *Annual Review of Neuroscience*, *30*, 31–56. https://doi.org/10.1146/annurev.neuro.30.051606.094334.

Wang, K., Shi, H. S., Geng, F. L., Zou, L. Q., Tan, S. P., Wang, Y., ... Chan, R. C. (2016). Cross-cultural validation of the depression anxiety stress scale-21 in China. *Psychological Assessment*, *28*(5), e88–e100. https://doi.org/10.1037/pas0000207.

Wang, Y., Zou, Z., Song, H., Xu, X., Wang, H., d'Oleire Uquillas, F., & Huang, X. (2016). Altered gray matter volume and white matter integrity in college students with mobile phone

dependence. *Frontiers in Psychology*, *7*, 597. https://doi.org/10.3389/fpsyg.2016.00597.

Weinstein, A., Livny, A., & Weizman, A. (2017). New developments in brain research of internet and gaming disorder. *Neuroscience and Biobehavioral Reviews*, *75*, 314–330. https://doi.org/10.1016/j.neubiorev.2017.01.040.

Yao, Y. W., Liu, L., Ma, S. S., Shi, X. H., Zhou, N., Zhang, J. T., & Potenza, M. N. (2017). Functional and structural neural alterations in internet gaming disorder: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews*, *83*, 313–324. https://doi.org/10.1016/j.neubiorev.2017.10.029.

Zhang, G., Yang, X., Tu, X., Ding, N., & Lau, J. T. F. (2020). Prospective relationships between mobile phone dependence and mental health status among Chinese undergraduate students with college adjustment as a mediator. *Journal of Affective Disorders*, *260*, 498–505. https://doi.org/10.1016/j.jad.2019.09.047.

Zou, L., Wu, X., Tao, S., Xu, H., Xie, Y., Yang, Y., & Tao, F. (2019). Mediating effect of sleep quality on the relationship between problematic mobile phone use and depressive symptoms in college students. *Frontiers in Psychiatry*, *10*, 822. https://doi.org/10.3389/fpsyt.2019.00822.

Zou, L., Wu, X., Tao, S., Yang, Y., Zhang, Q., Hong, X., . . . Tao, F. (2021). Anterior cingulate gyrus acts as a moderator of the relationship between problematic mobile phone use and depressive symptoms in college students. *Social Cognitive and Affective Neuroscience*, *16*(5), 484–491. https://doi.org/10.1093/scan/nsab016.