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Association of Prefrontal Cortex Thinning with High Impulsivity in Healthy Adults

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Objective Studies have been conducted to identify brain structural alterations related to high impulsivity in psychiatric populations. However, research on healthy subjects is relatively less extensive. Therefore, we aimed to investigate the correlation between the cortical thickness of whole brain regions and the impulsivity level in a healthy population.

Methods We included 100 healthy participants aged 19–65 years. Their T1-weighted magnetic resonance images and the 23-item Barratt Impulsiveness Scale (BIS) score were obtained. The patients were divided into high and low impulsivity groups according to the 75th percentile score of the BIS in the sample. The thickness of each cortical region was calculated using the FreeSurfer, and the difference in cortical thickness of the whole brain between the high and low impulsivity groups was analyzed using one-way analysis of covariance including age, sex, education level, and total intracranial cavity volume as covariates.

Results The high impulsivity group showed significant cortical thinning in the left pars opercularis. The cortical thickness of the left pars opercularis significantly correlated negatively with the total, attention, and motor scores of the BIS scale.

Conclusion Our findings suggest that prefrontal cortex thinning may play an important role in the development of high impulsivity in healthy adults.

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Key Words Impulsivity, Cortical thickness, Prefrontal cortex, Ventrolateral prefrontal cortex, Barratt Impulsiveness Scale.

INTRODUCTION

Impulsivity is known as the tendency to react immediately to a stimulus and to behave in an unplanned manner without carefully reckoning the outcome of the action.[1,2] People with high impulsivity tend to engage in risky and rash behavior and have difficulty adhering to set instructions.[1] High impulsivity is related to addiction, such as substance use disorders and behavioral addiction like gambling disorder,[3-5] increased suicide ideation,[6] increased suicide attempts, and violence of the suicide attempt.[6,7] Impulsivity can be a symptom of some psychopathological conditions, such as attention-deficit/hyperactivity disorder,[8,9] major depressive disorder (MDD),[10] and anxiety disorders.[11] It can also be a trait of some personality types, such as antisocial personality disorder and borderline personality disorder.[1,12]

The neural mechanisms of impulsivity have not been fully explained; several studies have attempted to identify the brain regions responsible for impulsivity and identify the related neural circuitry. Brain lesion studies have identified that frontal lobe lesions, especially prefrontal cortex (PFC) lesions, lead to an increase in impulsivity.[13,14] Functional neuroimaging studies have shown that the PFC is engaged in the control of impulsivity. Increased activity in the orbitofrontal cortex (OFC) has been associated with decreased impulsivity in adults[15] and adolescents[7] with borderline personality disorders. Experimental evidence using transcranial direct current stimulation showed that stimulation of the right dorsolateral PFC (dlPFC) decreased impulsivity.[16] The right inferior fron-

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tal gyrus and pre-supplementary motor area activity also correlate negatively with increasing attentional impulsivity scores.[17]

Extensive structural neuroimaging studies have investigated the correlation between the PFC and impulsivity in terms of cortical thickness, gray matter volume, and white matter integrity. The cortical thickness of the OFC, superior frontal gyrus, and middle frontal gyrus correlates negatively with the impulsivity level in healthy subjects.[18,19] In a study of adolescents, impulsive decision-making showed a strong negative correlation with cortical thickness in the ventromedial PFC, OFC, temporal pole, and temporoparietal junction.[20] Another study suggested reduced cortical thickness in the frontal pole, rostral middle frontal gyrus, and pars orbitalis in healthy children and adolescents with high level of impulaivity.[21] These findings suggest that the cortical thinning of brain areas known to be involved in higher cognitive functions is associated with increased impulsivity. Regarding gray matter volume, the volume of the OFC[22,23] and dorsomedial PFC, right temporal pole, and left ventral striatum[24] correlate negatively with the impulsivity level in healthy subjects, while, gray and white matter volumes of the left anterior cingulate gyrus, left medial frontal gyrus, and left middle frontal gyrus positively correlate with impulsivity in healthy subjects.[25]

As mentioned above, many studies have attempted to clarify the neural correlates of impulsivity since it constitutes a significant axis of personality traits in human psychology. However, the characteristic neurobiology of impulsivity is not completely understood. Accumulating evidence suggests a core role of the PFC in impulsivity control.[18,19] However, although the studies have identified that structural changes in the PFC are correlated with impulsivity, the involved sub-regions in the PFC vary in each study.[18-25] This makes further structural neuroimaging studies of impulsivity elucidating its neural correlation useful. Therefore, we aimed to investigate the correlation between the cortical thickness of whole brain regions and impulsivity, measured using the 23-item Barratt Impulsiveness Scale (BIS) in a non-clinical population. The BIS is widely used in psychiatric or psychological studies on impulsivity.[1,26] We divided the non-clinical participants into high and low impulsivity groups and compared the cortical thickness. By dividing the participants into high and low impulsivity groups, we found distinct brain regions that showed significant structural changes in the high impulsivity group.

Our a priori hypothesis is that non-clinical individuals in the high impulsivity group will have thinner cortical gray matter in the PFC compared to those in the low impulsivity group. Furthermore, we aimed to identify a more specific sub-region in the PFC that shows cortical thinning in the high impulsivity group.

METHODS

Participants

The present study included 100 healthy participants aged 19−65 years recruited from the community using an advertisement between February 2010 and December 2017. The participants were assessed by two board-certified psychiatrists (Han KM and Ham BJ), who confirmed that none of the participants had any current or previous psychiatric diseases. The exclusion criteria were: 1) any psychiatric disorders (including personality and substance use disorders) on the DSM-IV-TR (Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text-revised); 2) history of taking psychotropic medications within the last 6 months; 3) primary neurological illness (e.g., Parkinson's disease, epilepsy, or cerebrovascular disease); 4) any contraindication for magnetic resonance imaging (MRI), including claustrophobia. The severity of depressive symptoms in all subjects was assessed using the 17-item Hamilton Depression Rating Scale (HDRS)[27] on the day of the MRI scan. Participants were also assessed using the BIS at the same time.[28] The study protocol was approved by the Institutional Review Board of the Korea University Anam Hospital (IRB No. 2017AN0185) and the study was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation.

Assessment of impulsivity

The participants' degree of impulsivity was measured using the 23-item Korean version of the BIS. The original version of the BIS, 11th edition[26] was translated into Korean,[29] and the Korean version of the BIS was standardized in the Korean population.[30] The Korean version of the BIS is a self-reporting questionnaire consisting of 23 items with 4-point Likert scale (1=never to 4=always) and has shown high reliability in previous studies.[31,32] The BIS consists of three subscales−attention (a lack of focus on the ongoing task, 6 items), motor (acting without thinking, 8 items), and non-planning (orientation to the present rather than to the future, 9 items).[31,33] Higher scores indicate higher degrees of impulsivity. The Korean version of the BIS has been widely used in psychiatric studies on impulsivity.[34-37] In the present study, both total and subscale scores were used. There is no cut-off score for the BIS, therefore, we determined that the high impulsivity group has a 53 or higher total BIS score−which is a 75th percentile score in our sample, while the low impulsivity group has a total BIS score of 52 or lower.

MRI data acquisition

In the present study, T1-weighted images were obtained parallel to the anterior commissure-posterior commissure line using a 3.0-T Siemens Trio whole-body imaging system (Siemens Healthineers, Munich, Germany), using T1-weighted magnetization-prepared rapid gradient-echo with the following parameters: repetition time, 1,900 ms; echo time, 2.6 ms; field of view, 220 mm; matrix size, 256×256; slice thickness, 1 mm; coronal slices without gap, 176; voxels, 0.86×0.86×1 mm^3; flip angle, 16°; and number of excitations, 1.

Image processing

From the T1 image data obtained from the participants, we calculated the cortical thickness using the three-dimensional model of the cortical surface reconstructions implemented in the FreeSurfer version 5.3 (Laboratory for Computational Neuroimaging, Athinoula A. Martinos Center for Biomedical Imaging, Charlestown, MA, USA; http://surfer.nmr.mgh.harvard.edu). Based on the atlas by Destrieux et al.,[38] each hemisphere was parcellated into 74 cortical gyri and sulci, and then, we extracted cortical thickness values of 38 cortical gyri from each hemisphere using automated processes in the FreeSurfer.[39] The cortical thickness was determined by calculating the distance between the pia mater and white matter surface using the surface deformation algorithm.[40] We inspected cortical reconstructions for the automatic segmentation of gray and white matter boundaries, and data with inaccuracies were discarded. Smoothing of the cortical map was performed using a Gaussian kernel with a full width at half maximum of 20 mm for all cortex analyses. Detailed information about the protocol of procedures in the FreeSurfer have been described in our previous publications.[39-42] We also measured total intracranial cavity volume (TICV) manually based on previous literature,[43] and TICV was used as a covariate in the analysis.

Statistical analyses

The comparison of cortical thickness between the high and low impulsivity groups was performed using one-way analysis of covariance (ANCOVA), including cortical thickness as the dependent variable, group (high vs. low impulsivity group) as independent variables, and age, sex, education level, and TICV as covariates. The extracted cortical thickness values of 76 cortical gyri in the bilateral hemispheres from automated procedures of the FreeSurfer were used in the analysis. We applied the Bonferroni correction to the multiple comparisons in the main analysis to avoid type I error [i.e., $p<0.05/76=0.000657$ (76 cortical regions in the bilateral hemispheres)]. To investigate the correlation between the BIS score and cortical thickness, Pearson's partial correlation analysis, including age, sex, education level, and TICV as covariates, was performed for cortical regions with significant differences between the two groups ($p<0.05$). All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 24.0 (IBM Corporation, Armonk, NY, USA).

RESULTS

Sociodemographic and psychological characteristics

Information regarding age, sex, education level, total and sub-score of BIS, HDRS score, and TICV is shown in Table 1. The high impulsivity group showed significantly higher total

Table 1. Sociodemographic and clinical characteristics of participants

Characteristics	Total (N=100)	High (N=28)	Low (N=72)	p value (t, χ^2)
Age	38.84±13.33	39.54±15.12	38.57±12.67	0.766 (t=0.300)
Sex				
Female	57	12	45	0.075 (χ^2=3.174)
Male	43	16	27	
Education level				
Elementary and middle school	14	2	12	0.463 (χ^2=1.542)
High school or college/university	72	22	50	
Above graduate school	14	4	10	
HDRS score	1.53±1.82	1.29±1.51	1.63±1.92	0.405 (t=-0.837)
BIS (total)	47.20±8.63	58.00±4.16	43.00±5.78	<0.001 (t=12.511)
BIS (attention)	13.89±2.46	16.32±1.83	12.94±1.99	<0.001 (t=7.805)
BIS (motor)	13.87±3.60	18.00±2.31	12.26±2.60	<0.001 (t=10.223)
BIS (non-planning)	19.44±4.02	23.68±2.74	17.79±3.144	<0.001 (t=8.703)
TICV (cm^3)	1506.53±137.01	1516.89±164.22	1502.50±125.94	0.640 (t=0.470)

Data are presented as mean±standard deviation for age, HDRS-17 scores, and BIS scores. The p values for the distribution of sex and education level were obtained using a chi-squared test. High group: BIS=53 or higher; Low group: BIS=52 or lower (75%ile score was 53). BIS: Barratt Impulsiveness Scale, HDRS: 17-item Hamilton Depression Rating Scale, TICV: total intracranial cavity volume

BIS scores and sub-scores in attention, motor, and non-planning compared to the low impulsivity group ($p<0.001$ for all, Table 1). We did not find any significant differences in terms of age, sex, education level, HDRS score, and TICV ($p>0.05$, Table 1).

Cortical thickness difference between the groups

The high impulsivity group showed significant cortical thinning in the pars opercularis (inferior frontal gyrus) in the left hemisphere compared to the low impulsivity group ($F_{(1, 94)}$=13.380, $p=4.19\times10^{-4}$) (Table 2, Figure 1). This finding remained significant after Bonferroni correction. The high impulsivity group also showed cortical thinning in the anterior cingulate gyrus, inferior occipital gyrus, supramarginal gyrus, lateral superior temporal gyrus, inferior temporal gyrus in the bilateral hemispheres, parahippocampal gyrus, angular gyrus, and planum polare in the left hemisphere, and subcentral gyrus, orbital gyrus, and straight gyrus in the right hemisphere than in the low impulsivity group ($p<0.05$ for all) (Table 2). However, these differences were not significant after Bonferroni correction. None of the cortical regions showed significant thickening in the high impulsivity group compared to the low impulsivity group.

As an exploratory analysis, we examined whether sex and age have moderating effects on the association between impulsivity level and cortical thickness in healthy adults. The total sample was sub-grouped based on sex and age (i.e., 19−39 years vs. ≥40 years), and the cortical thickness was compared between the high and low impulsivity groups. We found that cortical thinning of the left pars opercularis was only observed in female ($F_{(1, 38)}$=11.420, p=0.002) and younger ($F_{(1, 51)}$=10.510, p=0.002) participants, but not in male or older participants (both $p>0.1$). However, these findings were not significant after Bonferroni correction. Detailed information and findings of other cortical regions are presented in the Supplementary Materials (in the online-only Data Supplement) (Supplementary Tables 1-4 in the online-only Data Supplement).

Exploratory correlation analysis between the BIS score and cortical thickness

As an exploratory analysis, we performed Pearson's partial correlation analyses on the left pars opercularis and aforementioned 16 cortical regions with significant differences in thickness between the two groups at a level of $p<0.05$ (Table 3). To investigate the correlation between the BIS score and cortical thickness, Pearson's partial correlation analysis, including age, sex, education level, and TICV as covariates was performed. In the correlation analysis, the cortical thickness of the left pars opercularis showed a significant inverse correlation with the total score (r=-0.277, p=0.006) and attention (r=-0.294, p=0.004) and motor sub-scores (r=-0.286, p=0.005) of the BIS, but not with the non-planning sub-score (Table 3, Figure 2). The total BIS score also inversely correlated with cortical thickness in the left parahippocampal gyrus (r=-0.233, p=0.022), left inferior temporal gyrus (r=-0.239, p=0.019), right subcentral gyrus (r=-0.294, p=0.004), right anterior cingulate gyrus (r=-0.236, p=0.021), and right orbital gyrus (r=-0.208, p=0.042).

DISCUSSION

Our results show cortical thinning in the pars opercularis (inferior frontal gyrus) in the left hemisphere in the high impulsivity group, which was significant after Bonferroni correction. We also observed that the cortical thickness of the left pars opercularis had significant negative correlations with the total, attention, and motor scores of the BIS scale. Moreover, the BIS total score correlated negatively with the cortical thickness of the left parahippocampal gyrus, left inferior temporal gyrus, right subcentral gyrus, right anterior cingulate gyrus, and right orbital gyrus, which showed cortical thinning in the high impulsivity group, but was not significant after Bonferroni correction compared to the low impulsivity group. In the exploratory analysis, we also observed that sex and age have moderating effects on the association between impulsivity level and cortical thickness; however, they were not significant after Bonferroni correction.

Previous studies have reported that the cortical thickness of the PFC is inversely correlated with impulsivity levels in both healthy and clinical populations.[18,44] This is in accordance with our findings. Compared to other regions in the PFC, however, pars opercularis, which corresponds to the ventrolateral prefrontal cortex (vlPFC) is a less evidently studied brain region in previous impulsivity studies.[15,18,24,45-48] Previous studies on the function of the vlPFC suggest that it is associated with motor inhibition, reflexive reorientation and action updating as well as in decision making.[49-51] Furthermore, the cortico-limbic model of emotion regulation in mood disorders suggests that vlPFC is associated with voluntary and cognitive regulation of negative emotions generated by the amygdala.[52] Another study suggested that the vlPFC activity is correlated positively with successful inhibition of motor impulsivity.[53] These findings indicate that vlPFC have regulatory role on emotion and inhibitory role in motor control, which all are related to impulse control. The decrease in cortical thickness, therefore, may be associated with a decreased level of impulsivity inhibitory function.

Further study may be required to explain the gray matter cortical thinning in the left vlPFC alone. This may be explained by the lateralization of hemispheric functions, since with dom-

Table 2. Comparison of cortical thickness between high and low impulsivity group

Cortical regions	High group (N=28)		Low group (N=72)		$F_{(1, 94)}$	p-value
	Mean	SD	Mean	SD		
Left hemisphere						
L Frontomarginal gyrus	2.341	0.137	2.359	0.170	0.804	0.372
L Inferior occipital gyrus	2.493	0.184	2.570	0.195	4.226	0.043
L Paracentral lobule	2.366	0.210	2.424	0.170	0.704	0.404
L Subcentral gyrus	2.693	0.198	2.729	0.170	0.807	0.371
L Transverse frontopolar gyrus	2.589	0.208	2.672	0.208	2.101	0.151
L Anterior cingulate gyrus	2.723	0.161	2.789	0.147	4.181	0.044
L Anterior mid-cingulate gyrus	2.679	0.154	2.731	0.159	1.525	0.220
L Posterior mid-cingulate gyrus	2.560	0.221	2.595	0.185	0.826	0.366
L Dorsal posterior cingulate gyrus	2.654	0.485	2.797	0.425	2.544	0.114
L Ventral posterior cingulate gyrus	2.490	0.287	2.570	0.286	3.825	0.053
L Cuneus	1.861	0.318	1.842	0.357	0.295	0.588
L Pars opercularis	2.711	0.217	2.841	0.154	13.380	4.19×10^{-4}
L Pars orbitalis	2.682	0.308	2.806	0.214	3.625	0.060
L Pars triangularis	2.666	0.190	2.718	0.176	0.815	0.369
L Middle frontal gyrus	2.748	0.233	2.763	0.169	0.068	0.794
L Superior frontal gyrus	3.010	0.268	3.054	0.242	0.232	0.631
L Long insular gyrus	2.907	0.292	3.007	0.258	2.184	0.143
L Short insular gyrus	3.173	0.564	3.359	0.492	2.241	0.138
L Middle occipital gyrus	2.542	0.185	2.603	0.158	2.489	0.118
L Superior occipital gyrus	2.082	0.245	2.134	0.201	1.079	0.302
L Lateral occipito-temporal gyrus	2.739	0.327	2.783	0.240	0.828	0.365
L Lingual gyrus	1.999	0.258	1.946	0.223	0.932	0.337
L Parahippocampal gyrus	2.866	0.275	2.977	0.224	4.977	0.028
L Orbital gyrus	2.650	0.171	2.694	0.172	0.764	0.384
L Angular gyrus	2.593	0.182	2.678	0.164	4.329	0.040
L Supramarginal gyrus	2.606	0.314	2.749	0.250	5.515	0.021
L Superior parietal lobule	2.429	0.202	2.441	0.147	0.014	0.907
L Postcentral gyrus	2.180	0.167	2.245	0.177	1.627	0.205
L Precentral gyrus	2.778	0.209	2.840	0.204	0.998	0.320
L Precuneus	2.467	0.181	2.531	0.145	2.657	0.106
L Straight gyrus	2.534	0.299	2.653	0.337	3.779	0.055
L Subcallosal gyrus	2.469	0.295	2.500	0.414	0.001	0.978
L Anterior transverse temporal gyrus	2.416	0.431	2.309	0.397	2.898	0.092
L Lateral superior temporal gyrus	2.903	0.261	3.035	0.263	4.258	0.042
L Planum polare	3.233	0.355	3.377	0.295	5.249	0.024
L Planum temporale	2.569	0.200	2.653	0.207	2.597	0.110
L Inferior temporal gyrus	2.748	0.291	2.917	0.266	9.316	0.003
L Middle temporal gyrus	2.960	0.316	3.043	0.248	2.443	0.121
Right hemisphere						
R Frontomarginal gyrus	2.339	0.220	2.396	0.173	1.731	0.191
R Inferior occipital gyrus	2.629	0.214	2.714	0.211	5.123	0.026
R Paracentral lobule	2.395	0.197	2.408	0.210	0.009	0.923

Table 2. Comparison of cortical thickness between high and low impulsivity group (continued)

Cortical regions	High group (N=28)		Low group (N=72)		$F_{(1, 94)}$	p-value
	Mean	SD	Mean	SD		
R Subcentral gyrus	2.653	0.166	2.766	0.179	7.433	0.008
R Transverse frontopolar gyrus	2.616	0.193	2.645	0.181	0.130	0.719
R Anterior cingulate gyrus	2.698	0.157	2.775	0.139	6.199	0.015
R Anterior mid-cingulate gyrus	2.778	0.161	2.816	0.124	1.118	0.293
R Posterior mid-cingulate gyrus	2.632	0.135	2.638	0.198	0.029	0.864
R Dorsal posterior cingulate gyrus	2.697	0.479	2.830	0.401	2.621	0.109
R Ventral posterior cingulate gyrus	2.586	0.313	2.668	0.313	3.302	0.072
R Cuneus	1.911	0.350	1.863	0.316	0.877	0.352
R Pars opercularis	2.775	0.170	2.835	0.174	2.312	0.132
R Pars orbitalis	2.721	0.209	2.827	0.218	3.647	0.059
R Pars triangularis	2.684	0.158	2.752	0.162	3.379	0.069
R Middle frontal gyrus	2.772	0.258	2.809	0.201	0.189	0.665
R Superior frontal gyrus	3.031	0.260	3.050	0.220	0.000	0.993
R Long insular gyrus	3.005	0.388	3.102	0.315	0.897	0.346
R Short insular gyrus	3.053	0.552	3.215	0.438	2.118	0.149
R Middle occipital gyrus	2.585	0.168	2.631	0.167	1.690	0.197
R Superior occipital gyrus	2.112	0.210	2.174	0.176	1.632	0.205
R Lateral occipito-temporal gyrus	2.753	0.301	2.794	0.197	1.194	0.277
R Lingual gyrus	2.072	0.264	1.994	0.233	2.205	0.141
R Parahippocampal gyrus	2.969	0.349	3.053	0.276	1.597	0.209
R Orbital gyrus	2.637	0.194	2.745	0.180	4.753	0.032
R Angular gyrus	2.587	0.196	2.667	0.147	3.867	0.052
R Supramarginal gyrus	2.564	0.323	2.717	0.269	5.242	0.024
R Superior parietal lobule	2.382	0.182	2.426	0.150	1.002	0.319
R Postcentral gyrus	2.126	0.184	2.210	0.177	2.434	0.122
R Precentral gyrus	2.768	0.239	2.825	0.171	1.601	0.209
R Precuneus	2.516	0.199	2.549	0.185	0.368	0.545
R Straight gyrus	2.520	0.321	2.659	0.267	4.755	0.032
R Subcallosal gyrus	2.616	0.484	2.616	0.497	0.009	0.926
R Anterior transverse temporal gyrus	2.407	0.416	2.414	0.382	0.091	0.763
R Lateral superior temporal gyrus	2.887	0.316	3.040	0.280	5.056	0.027
R Planum polare	3.118	0.359	3.159	0.289	0.570	0.452
R Planum temporale	2.600	0.193	2.632	0.212	0.087	0.769
R Inferior temporal gyrus	2.796	0.299	2.923	0.256	4.282	0.041
R Middle temporal gyrus	2.896	0.289	3.012	0.257	3.738	0.056

One-way ANCOVA including age, sex, education level, and total intracranial volume as covariates, was performed. Significant group differences after Bonferroni correction were presented in a bold face. Bonferroni correction was applied for multiple comparisons: $p<0.05/76=0.000658$. L: left hemisphere, R: right hemisphere

inance, the left and right hemispheres have different roles.[54] The exact mechanism for the functional lateralization of the PFC in impulse control cannot be clearly explained. However, previous studies on impulsivity have identified more regions in the left PFC than in the right PFC to be structurally correlated with impulsivity.[18,19,24,25] Therefore, based on the evidence from previous studies and the present study, the left PFC may be more involved in impulsivity control.

There are possible explanations for the decrease in cortical thickness of the pars opercularis in individuals with high im-

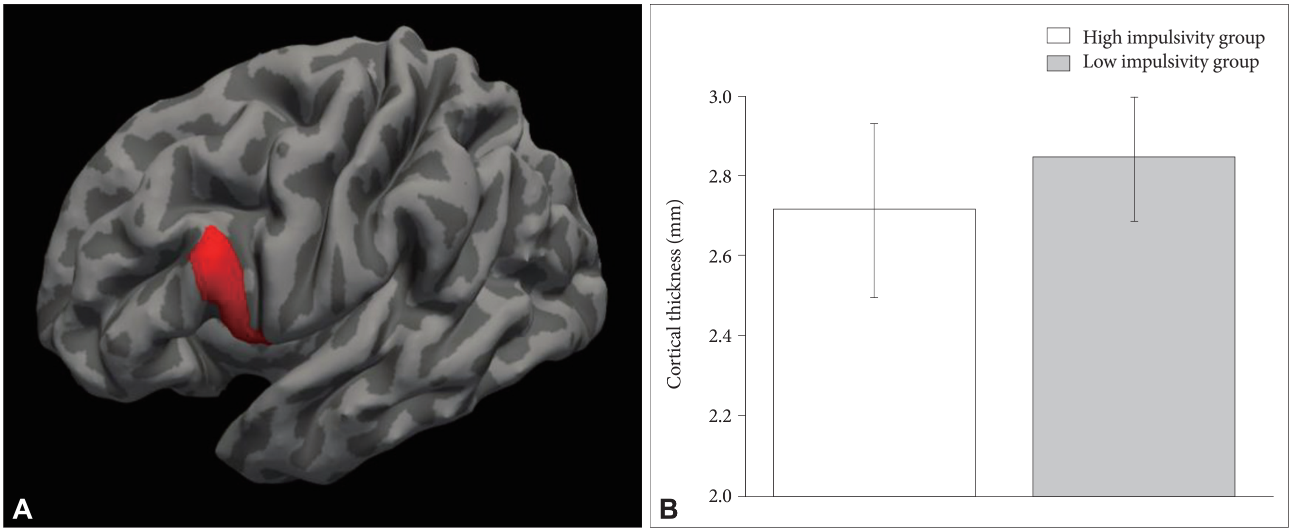

Figure 1. Cortical thinning of the left pars opercularis in the high impulsivity group. (A) shows the left pars opercularis (inferior frontal gyrus) in the Destrieux atlas (Red colored brain region). (B) shows a comparison of the cortical thickness of the left pars opercularis between the high and low impulsivity groups. The error bar represents one standard deviation.

Table 3. Correlation between cortical thickness and impulsivity

Cortical regions	Total		Attention		Motor		Non-planning	
	r	p-value	r	p-value	r	p-value	r	p-value
L Inferior occipital gyrus	-0.181	0.078	-0.141	0.169	-0.228	0.026	-0.096	0.350
L Anterior cingulate gyrus	-0.166	0.105	-0.166	0.107	-0.171	0.096	-0.102	0.321
L Pars opercularis	-0.277	0.006	-0.294	0.004	-0.286	0.005	-0.156	0.129
L Parahippocampal gyrus	-0.233	0.022	-0.171	0.095	-0.253	0.013	-0.170	0.098
L Angular gyrus	-0.175	0.088	-0.112	0.279	-0.162	0.114	-0.164	0.111
L Supramarginal gyrus	-0.177	0.085	-0.208	0.042	-0.143	0.164	-0.124	0.230
L Lateral superior temporal gyrus	-0.125	0.223	-0.106	0.304	-0.153	0.135	-0.066	0.523
L Planum polare	-0.185	0.071	-0.211	0.039	-0.150	0.145	-0.133	0.196
L Inferior temporal gyrus	-0.239	0.019	-0.210	0.040	-0.263	0.010	-0.149	0.147
R Inferior occipital gyrus	-0.186	0.070	-0.204	0.046	-0.154	0.135	-0.136	0.188
R Subcentral gyrus	-0.294	0.004	-0.235	0.021	-0.268	0.008	-0.250	0.014
R Anterior cingulate gyrus	-0.236	0.021	-0.203	0.048	-0.240	0.018	-0.167	0.104
R Orbital gyrus	-0.208	0.042	-0.094	0.360	-0.255	0.012	-0.160	0.120
R Supramarginal gyrus	-0.159	0.122	-0.191	0.062	-0.119	0.248	-0.118	0.254
R Straight gyrus	-0.185	0.071	-0.176	0.085	-0.170	0.097	-0.138	0.181
R Lateral superior temporal gyrus	-0.145	0.158	-0.143	0.165	-0.151	0.143	-0.089	0.391
R Inferior temporal gyrus	-0.122	0.236	-0.186	0.070	-0.153	0.136	-0.008	0.940

Pearson's partial correlation adjusted for age, sex, education level, and total intracranial cavity volume was performed. L: left hemisphere, R: right hemisphere

pulsivity. Several biological mechanisms may account for this association. According to the Hebbian law, neurons "fire together wire together".[55] This theory suggests that when neurons do not fire together, the connection slowly dissociates. Therefore, the number and volume of dendritic spines in the neurons decrease with a decrease in concurrent firing and its use.[55] As the activity in the PFC declines, the number and quality of neuronal connections may have decreased, showing a decrease in cortical thickness. Although the causal relationship between cortical thickness and impulsivity cannot be determined through this research, the decrease in the number of neurons may be associated with the decreased cortical thickness leading to an impaired function. In addition to neurons, astrocytes may account for the decrease in cortical thickness.

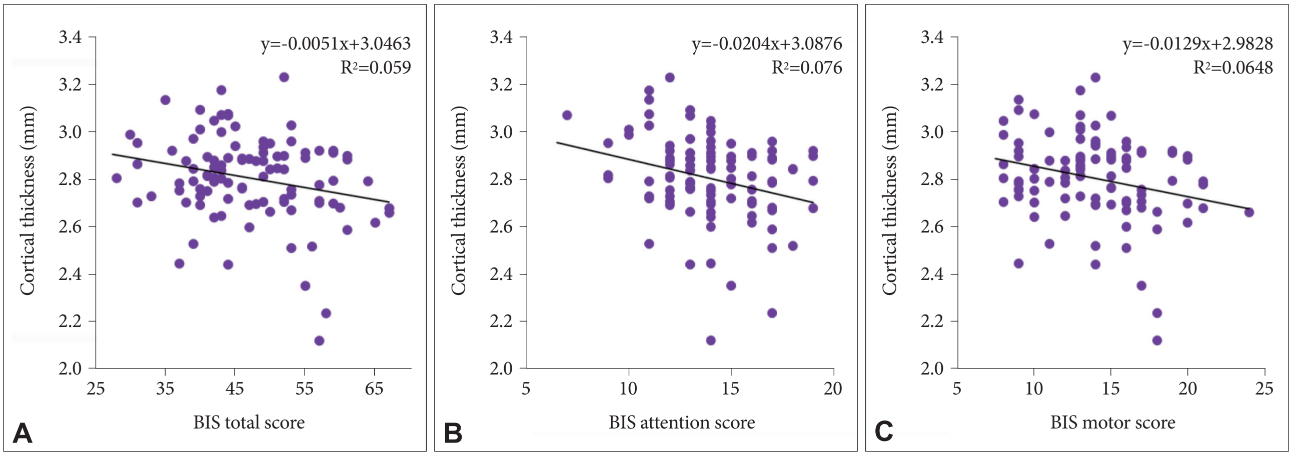

Figure 2. Correlation between BIS score and cortical thickness of the left pars opercularis. (A-C) show scatter plots of the correlations of cortical thickness of the left pars opercularis with the total, attention, and motor scores of the BIS, respectively. BIS: Barratt Impulsiveness Scale.

Astrocytes take up about 20–40% of the brain volume,[56] provide homeostasis, and support the neurons in the central nervous system.[57] Therefore, as the activities of the neurons in the PFC decrease, the number and volume of astrocytes may also decrease. With this change in astrocytes, the amount of vascularization may be altered, accounting for the change in cortical thickness.

Our research, as a cross-sectional study, successfully identified the cortical region involved in impulsivity in healthy adults; however, it still has several limitations. First, dividing the subjects into high and low impulsivity groups by the 75th percentile of the BIS-11 total score may seem arbitrary. Based on the recommendation of Stanford et al.,[58] individuals with a total score of 72 or above should be considered to have high impulsivity. Our cut-off score was 53, which was lower than the suggested upper cut-off score. However, they recommended considering individuals with total scores of 52 or below to be extremely over-controlled, suggesting a lower cut-off score.[58] A BIS-11 total score of 52 corresponded to the 75th percentile score of our subjects, 53. Taking the score distribution of our subjects and the cut-off scores of previous studies on the BIS scale, our standard of grouping may be appropriate. Second, since our study was a cross-sectional study, it could not determine the causal relationship between cortical thickness and impulsivity, which is a limitation of all cross-sectional studies. Nonetheless, our study provides a neuroimaging biomarker for impulsivity in healthy subjects in a cross-sectional design, which may be extensively studied in a future study. A future longitudinal follow-up study may provide a causal relationship between impulsivity and cortical thickness.

In conclusion, we observed that the healthy adults with high impulsivity traits showed a thinner cortex in the left pars opercularis compared to those with low impulsivity traits. We also observed that cortical thickness of the left pars opercularis had a significant negative correlation with the total, attention, and motor scores of the BIS scale. As left pars opercularis is significant in motor control, human mirror neuron system and the language production, our research suggests that the highly impulsive individuals may have some functional alteration with left pars opercularis cortical thinning. Further studies should be conducted to confirm the suggested functional alteration in the highly impulsive individuals with left pars opercularis thinning.

Supplementary Materials

The online-only Data Supplement is available with this article at https://doi.org/10.30773/pi.2020.0404.

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Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Kyu-Man Han. Data curation: Kyu-Man Han. Formal analysis: Kyu-Man Han. Funding acquisition: Kyu-Man Han. Investigation: Ji-Eun Lim, Seoyeon Kim, Surin Seo. Methodology: Kyu-Man Han. Project administration: Wooyoung Kang, Youbin Kang, Aram Kim. Resources: Byung-Joo Ham, Wooyoung Kang, Youbin Kang, Aram Kim. Software: Kyu-Man Han. Supervision: Byung-Joo Ham, Woo-Suk Tae. Validation: Kwan Woo Choi. Visualization: Wooyoung Kang, Youbin Kang. Writing—original draft: Ji-Eun Lim, Seoyeon Kim, Surin Seo, Kyu-Man Han. Writing—review & editing: Ji-Eun Lim, Seoyeon Kim, Surin Seo, Kyu-Man Han.

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Supplementary Table 1. Comparison of cortical thickness according to impulsivity level in female participants

Cortical regions	High impulsivity group (N=16)		Low impulsivity group (N=27)		$F_{(1, 38)}$	p-value
	Mean	SD	Mean	SD		
Left hemisphere						
Frontomarginal gyrus	2.377	0.153	2.388	0.128	0.092	0.763
Inferior occipital gyrus	2.489	0.141	2.602	0.185	2.222	0.144
Paracentral lobule	2.321	0.244	2.378	0.143	0.331	0.569
Subcentral gyrus	2.718	0.192	2.752	0.177	0.084	0.774
Transverse frontopolar gyrus	2.564	0.199	2.639	0.205	1.091	0.303
Anterior cingulate gyrus	2.685	0.163	2.805	0.103	12.101	0.001
Anterior mid-cingulate gyrus	2.698	0.134	2.726	0.150	0.171	0.682
Posterior mid-cingulate gyrus	2.571	0.202	2.625	0.145	1.775	0.191
Dorsal posterior cingulate gyrus	2.632	0.546	2.834	0.420	2.267	0.140
Ventral posterior cingulate gyrus	2.579	0.193	2.670	0.297	1.133	0.294
Cuneus	1.852	0.284	1.821	0.245	0.801	0.376
Pars opercularis	2.705	0.234	2.885	0.151	11.420	0.002
Pars orbitalis	2.671	0.291	2.789	0.245	1.797	0.188
Pars triangularis	2.652	0.197	2.700	0.175	0.389	0.536
Middle frontal gyrus	2.766	0.300	2.788	0.193	0.002	0.966
Superior frontal gyrus	2.988	0.318	3.054	0.267	0.093	0.763
Long insular gyrus	2.841	0.344	2.963	0.231	1.955	0.170
Short insular gyrus	3.127	0.633	3.318	0.485	2.107	0.155
Middle occipital gyrus	2.516	0.128	2.632	0.134	5.186	0.028
Superior occipital gyrus	2.029	0.208	2.089	0.187	1.009	0.322
Lateral occipito-temporal gyrus	2.770	0.231	2.783	0.195	0.616	0.437
Lingual gyrus	2.032	0.290	1.985	0.163	1.183	0.284
Parahippocampal gyrus	2.851	0.280	2.932	0.215	1.869	0.180
Orbital gyrus	2.637	0.206	2.691	0.147	1.274	0.266
Angular gyrus	2.538	0.181	2.674	0.154	6.884	0.012
Supramarginal gyrus	2.554	0.324	2.759	0.244	6.884	0.012
Superior parietal lobule	2.404	0.180	2.423	0.166	0.018	0.894
Postcentral gyrus	2.164	0.194	2.216	0.154	0.330	0.569
Precentral gyrus	2.724	0.209	2.798	0.243	1.211	0.278
Precuneus	2.435	0.156	2.538	0.128	5.823	0.021
Straight gyrus	2.531	0.319	2.753	0.252	8.808	0.005
Subcallosal gyrus	2.464	0.283	2.459	0.309	0.064	0.801
Anterior transverse temporal gyrus	2.469	0.479	2.220	0.370	5.561	0.024
Lateral superior temporal gyrus	2.832	0.253	2.991	0.227	5.579	0.023
Planum polare	3.241	0.354	3.429	0.270	3.898	0.056
Planum temporale	2.548	0.206	2.642	0.198	1.951	0.171
Inferior temporal gyrus	2.724	0.291	2.980	0.254	7.944	0.008
Middle temporal gyrus	2.934	0.266	3.111	0.175	7.011	0.012
Right hemisphere						
Frontomarginal gyrus	2.304	0.209	2.393	0.195	2.219	0.145
Inferior occipital gyrus	2.596	0.174	2.771	0.223	6.391	0.016
Paracentral lobule	2.359	0.196	2.346	0.260	0.028	0.868
Subcentral gyrus	2.642	0.166	2.787	0.176	5.648	0.023
Transverse frontopolar gyrus	2.588	0.224	2.604	0.168	0.054	0.818
Anterior cingulate gyrus	2.686	0.182	2.792	0.137	5.878	0.020
Anterior mid-cingulate gyrus	2.736	0.153	2.821	0.124	3.126	0.085
Posterior mid-cingulate gyrus	2.603	0.155	2.667	0.183	1.181	0.284
Dorsal posterior cingulate gyrus	2.658	0.543	2.862	0.394	2.620	0.114
Ventral posterior cingulate gyrus	2.658	0.240	2.812	0.278	2.858	0.099
Cuneus	1.926	0.354	1.852	0.266	1.374	0.248
Pars opercularis	2.769	0.172	2.839	0.187	2.962	0.093
Pars orbitalis	2.647	0.175	2.851	0.227	10.638	0.002
Pars triangularis	2.657	0.170	2.777	0.158	7.109	0.011
Middle frontal gyrus	2.776	0.297	2.819	0.231	0.051	0.822
Superior frontal gyrus	3.001	0.304	3.052	0.228	0.161	0.691
Long insular gyrus	2.851	0.361	3.121	0.364	7.016	0.012
Short insular gyrus	2.978	0.584	3.164	0.427	3.436	0.072
Middle occipital gyrus	2.565	0.110	2.644	0.145	2.639	0.113
Superior occipital gyrus	2.065	0.197	2.162	0.170	2.614	0.114
Lateral occipito-temporal gyrus	2.792	0.226	2.837	0.168	0.502	0.483
Lingual gyrus	2.114	0.289	2.009	0.212	2.595	0.116
Parahippocampal gyrus	2.902	0.301	2.977	0.311	2.158	0.150
Orbital gyrus	2.599	0.216	2.717	0.186	4.177	0.048
Angular gyrus	2.530	0.193	2.642	0.135	6.974	0.012
Supramarginal gyrus	2.492	0.324	2.708	0.274	6.939	0.012
Superior parietal lobule	2.365	0.165	2.426	0.132	1.720	0.198
Postcentral gyrus	2.082	0.194	2.176	0.136	3.066	0.088
Precentral gyrus	2.713	0.236	2.817	0.193	3.574	0.066
Precuneus	2.521	0.217	2.526	0.184	0.009	0.925
Straight gyrus	2.502	0.362	2.679	0.241	3.705	0.062
Subcallosal gyrus	2.653	0.404	2.581	0.480	0.119	0.732
Anterior transverse temporal gyrus	2.401	0.483	2.355	0.391	0.511	0.479
Lateral superior temporal gyrus	2.803	0.352	3.041	0.274	7.983	0.007
Planum polare	3.059	0.336	3.193	0.292	3.057	0.088
Planum temporale	2.545	0.186	2.588	0.221	0.724	0.400
Inferior temporal gyrus	2.740	0.269	2.919	0.278	3.993	0.053
Middle temporal gyrus	2.848	0.299	3.033	0.244	5.206	0.028

One-way ANCOVA, including age, education level, and total intracranial volume as covariates, was performed. Significant group differences after Bonferroni correction are presented in bold. Bonferroni correction was applied for multiple comparisons: $p<0.05/76=0.000658$. SD: standard deviation

Supplementary Table 2. Comparison of cortical thickness according to impulsivity level in male participants

Cortical regions	High impulsivity group (N=12)		Low impulsivity group (N=45)		$F_{(1, 52)}$	p-value
	Mean	SD	Mean	SD		
Left hemisphere						
Frontomarginal gyrus	2.293	0.098	2.341	0.189	0.926	0.340
Inferior occipital gyrus	2.498	0.237	2.551	0.200	0.825	0.368
Paracentral lobule	2.428	0.142	2.452	0.180	0.073	0.788
Subcentral gyrus	2.660	0.211	2.716	0.166	0.630	0.431
Transverse frontopolar gyrus	2.622	0.223	2.691	0.209	1.195	0.279
Anterior cingulate gyrus	2.775	0.149	2.779	0.169	0.028	0.867
Anterior mid-cingulate gyrus	2.654	0.179	2.734	0.166	1.520	0.223
Posterior mid-cingulate gyrus	2.544	0.253	2.577	0.205	0.225	0.637
Dorsal posterior cingulate gyrus	2.684	0.412	2.775	0.431	0.511	0.478
Ventral posterior cingulate gyrus	2.372	0.353	2.510	0.264	2.517	0.119
Cuneus	1.874	0.372	1.854	0.412	0.120	0.730
Pars opercularis	2.719	0.201	2.814	0.151	2.467	0.122
Pars orbitalis	2.696	0.341	2.816	0.196	1.719	0.196
Pars triangularis	2.686	0.186	2.729	0.179	0.179	0.674
Middle frontal gyrus	2.724	0.093	2.748	0.153	0.298	0.588
Superior frontal gyrus	3.038	0.192	3.055	0.230	0.005	0.945
Long insular gyrus	2.994	0.181	3.033	0.273	0.107	0.745
Short insular gyrus	3.234	0.479	3.384	0.500	0.891	0.350
Middle occipital gyrus	2.577	0.245	2.585	0.170	0.015	0.903
Superior occipital gyrus	2.153	0.280	2.161	0.206	0.218	0.643
Lateral occipito-temporal gyrus	2.697	0.432	2.783	0.266	0.501	0.482
Lingual gyrus	1.954	0.211	1.923	0.251	0.235	0.630
Parahippocampal gyrus	2.887	0.278	3.004	0.228	2.292	0.136
Orbital gyrus	2.668	0.116	2.696	0.187	0.042	0.839
Angular gyrus	2.665	0.164	2.681	0.172	0.055	0.815
Supramarginal gyrus	2.675	0.299	2.743	0.256	0.485	0.489
Superior parietal lobule	2.462	0.232	2.452	0.135	0.069	0.793
Postcentral gyrus	2.200	0.127	2.262	0.189	0.633	0.430
Precentral gyrus	2.851	0.193	2.865	0.174	0.063	0.803
Precuneus	2.510	0.208	2.526	0.156	0.001	0.971
Straight gyrus	2.538	0.283	2.592	0.369	0.225	0.638
Subcallosal gyrus	2.476	0.323	2.525	0.468	0.018	0.893
Anterior transverse temporal gyrus	2.345	0.365	2.363	0.408	0.009	0.925
Lateral superior temporal gyrus	2.999	0.251	3.061	0.282	0.365	0.549
Planum polare	3.223	0.371	3.346	0.308	1.534	0.221
Planum temporale	2.596	0.198	2.660	0.213	0.696	0.408
Inferior temporal gyrus	2.779	0.302	2.880	0.269	1.312	0.257
Middle temporal gyrus	2.994	0.384	3.003	0.277	0.002	0.969
Right hemisphere						
Frontomarginal gyrus	2.386	0.233	2.397	0.161	0.186	0.668
Inferior occipital gyrus	2.672	0.259	2.679	0.198	0.120	0.730
Paracentral lobule	2.444	0.196	2.446	0.166	0.001	0.979
Subcentral gyrus	2.669	0.172	2.753	0.181	1.509	0.225
Transverse frontopolar gyrus	2.653	0.144	2.669	0.186	0.068	0.796
Anterior cingulate gyrus	2.715	0.123	2.766	0.141	1.273	0.264
Anterior mid-cingulate gyrus	2.835	0.159	2.814	0.125	0.168	0.684
Posterior mid-cingulate gyrus	2.670	0.097	2.621	0.206	0.535	0.468
Dorsal posterior cingulate gyrus	2.748	0.394	2.811	0.409	0.343	0.561
Ventral posterior cingulate gyrus	2.490	0.381	2.582	0.304	0.651	0.423
Cuneus	1.891	0.359	1.870	0.345	0.192	0.663
Pars opercularis	2.785	0.176	2.832	0.168	0.508	0.479
Pars orbitalis	2.819	0.217	2.813	0.214	0.040	0.843
Pars triangularis	2.720	0.140	2.737	0.165	0.033	0.856
Middle frontal gyrus	2.767	0.206	2.803	0.184	0.099	0.755
Superior frontal gyrus	3.071	0.193	3.048	0.219	0.327	0.570
Long insular gyrus	3.209	0.334	3.092	0.286	1.840	0.181
Short insular gyrus	3.153	0.513	3.246	0.446	0.608	0.439
Middle occipital gyrus	2.611	0.227	2.623	0.180	0.004	0.949
Superior occipital gyrus	2.176	0.219	2.180	0.181	0.056	0.814
Lateral occipito-temporal gyrus	2.701	0.383	2.768	0.210	0.583	0.449
Lingual gyrus	2.017	0.228	1.986	0.247	0.338	0.563
Parahippocampal gyrus	3.058	0.401	3.099	0.245	0.389	0.535
Orbital gyrus	2.687	0.155	2.761	0.177	1.092	0.301
Angular gyrus	2.664	0.180	2.682	0.153	0.070	0.792
Supramarginal gyrus	2.661	0.307	2.723	0.269	0.515	0.476
Superior parietal lobule	2.404	0.208	2.426	0.161	0.018	0.892
Postcentral gyrus	2.185	0.159	2.230	0.197	0.170	0.682
Precentral gyrus	2.842	0.234	2.830	0.158	0.065	0.800
Precuneus	2.510	0.182	2.563	0.186	0.677	0.415
Straight gyrus	2.544	0.272	2.648	0.283	1.488	0.228
Subcallosal gyrus	2.566	0.590	2.637	0.511	0.058	0.811
Anterior transverse temporal gyrus	2.414	0.327	2.450	0.376	0.017	0.897
Lateral superior temporal gyrus	2.999	0.229	3.039	0.286	0.107	0.745
Planum polare	3.197	0.388	3.139	0.288	0.361	0.551
Planum temporale	2.674	0.182	2.659	0.205	0.134	0.716
Inferior temporal gyrus	2.871	0.333	2.925	0.245	0.340	0.562
Middle temporal gyrus	2.960	0.273	2.999	0.266	0.154	0.697

One-way ANCOVA, including age, education level, and total intracranial volume as covariates, was performed. Significant group differences after Bonferroni correction are presented in bold. Bonferroni correction was applied for multiple comparisons: $p<0.05/76=0.000658$. SD: standard deviation

Supplementary Table 3. Comparison of cortical thickness according to impulsivity level in younger participants

Cortical regions	High impulsivity group (N=15)		Low impulsivity group (N=41)		$F_{(1, 51)}$	p-value
	Mean	SD	Mean	SD		
Left hemisphere						
Frontomarginal gyrus	2.348	0.159	2.340	0.179	0.167	0.684
Inferior occipital gyrus	2.481	0.112	2.536	0.173	1.324	0.255
Paracentral lobule	2.397	0.207	2.431	0.182	0.001	0.975
Subcentral gyrus	2.752	0.235	2.766	0.173	0.024	0.876
Transverse frontopolar gyrus	2.621	0.209	2.666	0.243	0.185	0.669
Anterior cingulate gyrus	2.677	0.159	2.788	0.162	5.499	0.023
Anterior mid-cingulate gyrus	2.716	0.141	2.763	0.160	0.770	0.384
Posterior mid-cingulate gyrus	2.511	0.281	2.609	0.217	2.461	0.123
Dorsal posterior cingulate gyrus	2.516	0.616	2.729	0.519	2.015	0.162
Ventral posterior cingulate gyrus	2.510	0.325	2.613	0.286	1.246	0.270
Cuneus	1.996	0.381	1.901	0.430	1.017	0.318
Pars opercularis	2.665	0.272	2.874	0.168	10.510	0.002
Pars orbitalis	2.754	0.315	2.823	0.214	0.421	0.519
Pars triangularis	2.753	0.185	2.772	0.201	0.092	0.762
Middle frontal gyrus	2.830	0.261	2.817	0.183	0.007	0.932
Superior frontal gyrus	3.092	0.314	3.125	0.288	0.022	0.882
Long insular gyrus	2.821	0.356	3.018	0.291	3.531	0.066
Short insular gyrus	3.016	0.730	3.337	0.618	2.568	0.115
Middle occipital gyrus	2.534	0.209	2.601	0.136	2.128	0.151
Superior occipital gyrus	2.005	0.218	2.057	0.191	0.581	0.450
Lateral occipito-temporal gyrus	2.667	0.414	2.801	0.208	1.776	0.189
Lingual gyrus	2.097	0.319	1.982	0.238	1.928	0.171
Parahippocampal gyrus	2.706	0.244	2.943	0.222	9.496	0.003
Orbital gyrus	2.659	0.215	2.745	0.169	1.722	0.195
Angular gyrus	2.550	0.212	2.688	0.191	4.231	0.045
Supramarginal gyrus	2.539	0.393	2.735	0.312	2.957	0.092
Superior parietal lobule	2.460	0.240	2.467	0.139	0.044	0.835
Postcentral gyrus	2.233	0.197	2.259	0.182	0.006	0.939
Precentral gyrus	2.753	0.246	2.823	0.240	0.530	0.470
Precuneus	2.510	0.188	2.537	0.153	0.046	0.831
Straight gyrus	2.470	0.384	2.675	0.317	4.895	0.031
Subcallosal gyrus	2.529	0.306	2.528	0.449	0.038	0.845
Anterior transverse temporal gyrus	2.635	0.464	2.385	0.466	4.567	0.037
Lateral superior temporal gyrus	2.859	0.305	3.023	0.311	2.032	0.160
Planum polare	3.166	0.443	3.377	0.310	5.138	0.028
Planum temporale	2.618	0.206	2.723	0.224	1.152	0.288
Inferior temporal gyrus	2.655	0.331	2.880	0.310	6.870	0.012
Middle temporal gyrus	2.869	0.389	3.061	0.277	4.558	0.038
Right hemisphere						
Frontomarginal gyrus	2.318	0.196	2.374	0.189	1.308	0.258
Inferior occipital gyrus	2.539	0.225	2.676	0.193	5.028	0.029
Paracentral lobule	2.383	0.210	2.426	0.240	0.025	0.875
Subcentral gyrus	2.675	0.158	2.803	0.177	5.866	0.019
Transverse frontopolar gyrus	2.642	0.158	2.671	0.189	0.079	0.780
Anterior cingulate gyrus	2.707	0.182	2.797	0.153	2.860	0.097
Anterior mid-cingulate gyrus	2.754	0.174	2.836	0.129	3.223	0.079
Posterior mid-cingulate gyrus	2.629	0.157	2.628	0.231	0.001	0.976
Dorsal posterior cingulate gyrus	2.538	0.608	2.784	0.508	2.509	0.119
Ventral posterior cingulate gyrus	2.583	0.374	2.732	0.287	2.849	0.098
Cuneus	2.061	0.425	1.932	0.370	1.578	0.215
Pars opercularis	2.755	0.207	2.876	0.195	3.192	0.080
Pars orbitalis	2.719	0.231	2.851	0.233	3.788	0.057
Pars triangularis	2.723	0.149	2.797	0.178	1.691	0.199
Middle frontal gyrus	2.884	0.291	2.875	0.230	0.050	0.824
Superior frontal gyrus	3.115	0.302	3.121	0.251	0.027	0.869
Long insular gyrus	2.946	0.438	3.120	0.374	1.607	0.211
Short insular gyrus	2.828	0.648	3.184	0.523	3.823	0.056
Middle occipital gyrus	2.570	0.207	2.636	0.145	0.868	0.356
Superior occipital gyrus	2.071	0.214	2.145	0.163	1.448	0.234
Lateral occipito-temporal gyrus	2.737	0.403	2.800	0.172	0.723	0.399
Lingual gyrus	2.175	0.320	2.030	0.259	3.058	0.086
Parahippocampal gyrus	2.769	0.311	3.003	0.302	4.383	0.041
Orbital gyrus	2.653	0.236	2.763	0.199	1.894	0.175
Angular gyrus	2.553	0.234	2.672	0.167	2.826	0.099
Supramarginal gyrus	2.464	0.398	2.697	0.334	4.171	0.046
Superior parietal lobule	2.397	0.229	2.459	0.127	0.587	0.447
Postcentral gyrus	2.187	0.188	2.215	0.193	0.006	0.936
Precentral gyrus	2.701	0.261	2.826	0.184	3.029	0.088
Precuneus	2.557	0.221	2.587	0.209	0.000	0.991
Straight gyrus	2.478	0.401	2.663	0.316	3.497	0.067
Subcallosal gyrus	2.553	0.491	2.653	0.539	0.558	0.459
Anterior transverse temporal gyrus	2.531	0.491	2.484	0.439	0.416	0.522
Lateral superior temporal gyrus	2.832	0.407	3.025	0.331	2.685	0.107
Planum polare	3.016	0.408	3.158	0.284	2.018	0.162
Planum temporale	2.645	0.212	2.644	0.238	0.384	0.538
Inferior temporal gyrus	2.710	0.344	2.868	0.294	3.133	0.083
Middle temporal gyrus	2.818	0.350	3.007	0.288	3.713	0.060

One-way ANCOVA, including age, sex, education level, and total intracranial volume as covariates, was performed. Significant group differences after Bonferroni correction are presented in bold. Bonferroni correction was applied for multiple comparisons: $p<0.05/76=0.000658$.
SD: standard deviation

Supplementary Table 4. Comparison of cortical thickness according to impulsivity level in older participants

Cortical regions	High impulsivity group (N=13)		Low impulsivity group (N=31)		$F_{(1, 39)}$	p-value
	Mean	SD	Mean	SD		
Left hemisphere						
Frontomarginal gyrus	2.334	0.113	2.383	0.156	1.466	0.233
Inferior occipital gyrus	2.506	0.247	2.615	0.214	2.014	0.164
Paracentral lobule	2.331	0.217	2.416	0.156	0.674	0.417
Subcentral gyrus	2.625	0.121	2.682	0.156	0.935	0.340
Transverse frontopolar gyrus	2.553	0.208	2.679	0.152	2.931	0.095
Anterior cingulate gyrus	2.777	0.151	2.789	0.129	0.222	0.640
Anterior mid-cingulate gyrus	2.637	0.162	2.688	0.151	0.154	0.697
Posterior mid-cingulate gyrus	2.615	0.108	2.576	0.133	1.992	0.166
Dorsal posterior cingulate gyrus	2.814	0.188	2.887	0.231	0.613	0.438
Ventral posterior cingulate gyrus	2.468	0.247	2.513	0.280	1.605	0.213
Cuneus	1.706	0.096	1.763	0.209	0.885	0.353
Pars opercularis	2.763	0.118	2.796	0.120	1.992	0.166
Pars orbitalis	2.598	0.289	2.783	0.216	3.224	0.080
Pars triangularis	2.566	0.145	2.648	0.103	2.380	0.131
Middle frontal gyrus	2.653	0.155	2.692	0.116	1.036	0.315
Superior frontal gyrus	2.915	0.169	2.961	0.113	0.340	0.563
Long insular gyrus	3.005	0.155	2.991	0.211	0.053	0.819
Short insular gyrus	3.354	0.170	3.388	0.249	0.025	0.875
Middle occipital gyrus	2.553	0.162	2.605	0.186	0.356	0.554
Superior occipital gyrus	2.170	0.251	2.236	0.168	0.947	0.336
Lateral occipito-temporal gyrus	2.821	0.166	2.759	0.279	0.692	0.411
Lingual gyrus	1.885	0.068	1.898	0.194	0.197	0.660
Parahippocampal gyrus	3.052	0.176	3.021	0.223	0.084	0.773
Orbital gyrus	2.639	0.108	2.626	0.153	0.449	0.507
Angular gyrus	2.642	0.132	2.666	0.123	0.492	0.487
Supramarginal gyrus	2.683	0.171	2.768	0.133	3.353	0.075
Superior parietal lobule	2.392	0.148	2.407	0.153	0.140	0.711
Postcentral gyrus	2.118	0.097	2.226	0.170	2.705	0.108
Precentral gyrus	2.808	0.160	2.862	0.144	0.602	0.443
Precuneus	2.417	0.165	2.522	0.136	4.594	0.038
Straight gyrus	2.607	0.133	2.622	0.365	0.004	0.951
Subcallosal gyrus	2.399	0.278	2.464	0.368	0.036	0.850
Anterior transverse temporal gyrus	2.163	0.194	2.208	0.257	0.061	0.806
Lateral superior temporal gyrus	2.955	0.199	3.050	0.186	3.372	0.074
Planum polare	3.311	0.205	3.377	0.279	0.574	0.453
Planum temporale	2.511	0.184	2.561	0.136	0.941	0.338
Inferior temporal gyrus	2.854	0.200	2.966	0.187	1.505	0.227
Middle temporal gyrus	3.064	0.165	3.019	0.206	0.795	0.378
Right hemisphere						
Frontomarginal gyrus	2.363	0.250	2.424	0.147	1.349	0.253
Inferior occipital gyrus	2.733	0.149	2.763	0.226	0.002	0.963
Paracentral lobule	2.410	0.189	2.385	0.164	0.126	0.725
Subcentral gyrus	2.628	0.178	2.718	0.172	0.964	0.332
Transverse frontopolar gyrus	2.586	0.231	2.610	0.166	0.054	0.817
Anterior cingulate gyrus	2.688	0.130	2.747	0.116	2.348	0.134
Anterior mid-cingulate gyrus	2.806	0.146	2.790	0.114	0.150	0.700
Posterior mid-cingulate gyrus	2.635	0.111	2.652	0.145	0.112	0.740
Dorsal posterior cingulate gyrus	2.880	0.126	2.892	0.174	0.269	0.607
Ventral posterior cingulate gyrus	2.590	0.241	2.584	0.331	0.204	0.654
Cuneus	1.738	0.069	1.773	0.196	0.370	0.547
Pars opercularis	2.799	0.120	2.780	0.125	0.151	0.700
Pars orbitalis	2.722	0.189	2.796	0.196	0.371	0.546
Pars triangularis	2.639	0.163	2.693	0.117	1.638	0.208
Middle frontal gyrus	2.642	0.130	2.723	0.108	2.501	0.122
Superior frontal gyrus	2.933	0.165	2.955	0.121	0.063	0.803
Long insular gyrus	3.072	0.324	3.080	0.218	0.718	0.402
Short insular gyrus	3.313	0.245	3.257	0.291	1.653	0.206
Middle occipital gyrus	2.601	0.114	2.625	0.194	0.131	0.719
Superior occipital gyrus	2.160	0.204	2.211	0.187	0.385	0.539
Lateral occipito-temporal gyrus	2.771	0.113	2.786	0.228	0.024	0.877
Lingual gyrus	1.953	0.097	1.948	0.187	0.044	0.836
Parahippocampal gyrus	3.200	0.231	3.119	0.225	3.905	0.055
Orbital gyrus	2.618	0.139	2.720	0.151	2.223	0.144
Angular gyrus	2.627	0.139	2.661	0.117	1.034	0.316
Supramarginal gyrus	2.680	0.150	2.744	0.146	0.983	0.328
Superior parietal lobule	2.364	0.114	2.382	0.168	0.008	0.928
Postcentral gyrus	2.057	0.159	2.203	0.156	4.495	0.040
Precentral gyrus	2.846	0.193	2.824	0.154	0.144	0.706
Precuneus	2.468	0.166	2.499	0.135	0.431	0.515
Straight gyrus	2.568	0.200	2.654	0.188	1.249	0.271
Subcallosal gyrus	2.688	0.485	2.566	0.438	1.652	0.206
Anterior transverse temporal gyrus	2.263	0.257	2.323	0.270	0.277	0.602
Lateral superior temporal gyrus	2.952	0.151	3.061	0.195	3.315	0.076
Planum polare	3.236	0.261	3.162	0.300	0.647	0.426
Planum temporale	2.549	0.160	2.617	0.175	1.462	0.234
Inferior temporal gyrus	2.895	0.209	2.996	0.173	2.296	0.138
Middle temporal gyrus	2.986	0.168	3.018	0.212	0.000	0.985

One-way ANCOVA, including age, sex, education level, and total intracranial volume as covariates, was performed. Significant group differences after Bonferroni correction are presented in bold. Bonferroni correction was applied for multiple comparisons: $p<0.05/76=0.000658$.
SD: standard deviation