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Brain Morphological and Connectivity Basis of Adolescent Impulsivity: Self-report vs. Inhibitory Performance

청소년 충동성의 뇌 구조 및 연결망적 기반: 자기보고 대 억제수행

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심리학과 임상심리학 전공

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Abstract

Adolescent impulsivity is one of the main causes of adolescent risky behaviors often times associated with fatal outcomes. This study was designed to investigate the relationship between the multi-facets of impulsivity measured by self-report and task-based assessments and how these measurements relate to the developing adolescent brain. Brain morphology and intrinsic connectivity was measured with functional magnetic resonance imaging. The results showed that the impulsivity measures did not correlated with each other. Weaker inhibitory control was correlated with smaller bilateral dorsal striatum volume and thicker cortical thickness in the frontal lobe. Inhibitory control performance positively correlated with the connectivity between left putamen and right temporal pole, and was negatively correlated with right caudate nucleus' s connectivity with right insular and lateral occipital cortex. The results imply the dimensional difference between the two types of impulsivity measurements and adolescent unique neural system for impulsivity and cognitive control.

Keyword : Adolescents, impulsivity, inhibition, cortex, subcortex, brain morphology, resting state functional connectivity

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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1. Impulsivity and Adolescent Risky Behavior

Adolescents have been characterized to seek novel stimulus, have social sensitivity, and show high levels of activity (Spear, 2000; Crews & Boettiger, 2009), which all are within the sphere of 'impulsivity.' Understanding adolescent impulsivity is important for a number of reasons. Impulsivity makes adolescents prone to risky activities (Cao et al., 2007; Johnston et al., 2009; Kim, 2012; Lee, 2014; Lee, 2015; Jeong & Oh, 2008; Tarter et al., 2003; Vitaro et al., 1999; Von Diemen et al., 2008), which have dire consequences in their future wellbeing. For example, the results from the 2005 National Youth Risk Behavior Survey (YRBS) of the United States have shown that adolescents engage in behaviors that increase their likelihood of death or illness by driving under the influence, carrying weapons, consuming illegal substances, and engaging in unprotected sex to contract sexually transmitted diseases and unwanted pregnancies (Eaton et al., 2006). Studies have also shown that most of adult addiction begins during the adolescence (Kandel et al., 1992; Wagner et al., 2002). Childhood and adolescent impulsivity do not simply provide explanation to their maladaptive, risky behaviors, but also are important as a fundamental personality trait that can influence subsequence developmental trajectories and even emergence of psychopathology (Caspi & Roberts, 2001; Dodge & Pettit, 2003; Ge et al., 1996; Rutter et al., 1997). Therefore, understanding impulsivity and its biological makeup in adolescents may provide the basis for scientific evidence-based intervention that can prevent adolescents from engaging in harmful activities and developing mental illnesses.

1.2. Current Dilemma with Assessing Impulsivity

While there exists a number of attempts to quantify and measure impulsivity, they can generally be divided into two categories of measurement: self reports and task-based measurements (White et al., 1994). Although 'impulsivity' is an umbrella term encompassing many cognitive and personality characteristics, many previous studies failed to specify the facet of impulsivity they have observed by treating as if self reported impulsivity and task-based impulsivity are not different. There so far have been mixed reports on whether there are correlates between the two types of measurements; some found the relationship between self-reported impulsivity and task-based measurements (Cao et al., 2007; Enticott et al., 2006; Gay et al., 2008; Kjome et al., 2010; Keilp et al., 2005; Kooijmans et al., 2000; Marsh et al., 2002) while others have failed to do so (Claes et al., 2006; Horn et al., 2003; Lane et al., 2003; Lansbergen et al., 2007; Lawrence et al., 2009; Lijffijt et al., 2004; Reynolds et al., 2006;

Visser et al., 1996). No study so far has purposefully explained why such discrepency occurs. In order to understand why mixed results are reported regarding different impulsivity measurements, this study attempted to observe any differences in their underlying neural correlates.

1.3. Impulsivity and its Facets

So far, there has not been a singular definition of impulsivity. The more traditional attempts that tried to make the simplest of an illustration has been like those made by Frosch and Wortis (1954), who attempted to define impulsivity as "the sudden, unpremeditated welling-up of a drive towards some action, which usually has the quality of hastiness and a lack of deliberation." Eysenck and Eyesenck (1978) also sought to label the components constructing impulsivity and defined impulsivity in terms of hypothetical primaries: risk-taking, non-planning, liveliness, and (narrow) impulsivity.

Soon after in the late 80's and the 90's, Barratt and colleagues (Barratt, 1993; Gerbing et al., 1987; Patton et al., 1995; Stanford & Barratt, 1992) developed a comprehensive approach to describing impulsivity by including information from four different perspectives of the social model, the behavioral model, the psychological model, and the medical model. They engaged in a variety of measures including self-report questionnaires, cognitive and behavioral tasks, and brain-behavioral research using animals to identify three higher-order factors of which the researchers argue to convey different components of impulsivity: attentional impulsiveness (the ability to focus on the tasks at hand, failure to do so may illustrate cognitive instability), motor impulsiveness (acting impromptu and portrays perseverance), and non-planning (self-control and cognitive complexity) (Barratt, 1993). However, it is worth to note that the last component failed to secure its reliability (Whiteside & Lynam, 2001).

There also had been efforts to understand and define impulsivity in the physiological perspective, as Newman and colleagues (Newman & Wallace, 1993; Wallace et al., 1991) had done combining Eysenck' s system of personality with Gray' s neuropsycholoigcal model (Gray, 1987) regarding approach/avoidance learning. Gray explains in his model that behavior arises from three physiological systems: the Behavioral Activation System (BAS; reacts to reward and punishment eradication by approaching or actively avoiding the stimuli), the Behavioral Inhibition System (BIS; responds outside punishment and absence of reward by passively avoiding or stopping a previously active behavior), and Non-specific Arousal System (NAS; receives excitatory input from BAS and BIS to regulate the frequency and intensity of the behavior of interest). This theory lead Newman and his colleagues to identify the three independent pathways that leads to impulsive reactions. The pathways coin the terms normal impulsivity (the first pathway), anxious impulsivity (the second pathway), and the deficient P−constraint (the third pathway). The pathways each illustrate the dominant or recessive relationship between BAS and BIS, which with NAS' s control causes behaviors that can be thought of as either over−responsive to rewards, over−constrained, or psychopathic.

However, unfortunately, none of the theories has succeeded in becoming accepted as the dominant framework for impulsivity. To find clarity in the overabundance of theories and models explicating impulsivity, an effort was made by Whiteman and Lynam (2001) to identify facets of impulsivity that were common across various existing questionnaires, developed based on independent theories and models on impulsivity, and incorporate them into an inclusive model of personality, the Five−Factor Model of personality (FFM; McCrae & Costa, 1990). The model, also represented in the Revised NEO Personality Inventory (NEO−PI−R), identifies five broad personality domains as Neuroticism, Extraversion, Openness to Experience, Agreeableness, and Conscientiousness (Costa & McCrae, 1995). Further explanation regarding the integrative measurement, the UPPS−P Impulsive Behavior Scale (UPPS−P), created by Whiteman and Lynam is discussed when explaining self−reports of impulsivity (p. 7, 17).

Meanwhile, there also had been movements to observe impulsivity in relation to cognitive functioning, especially that of inhibitory control (Andrew-Hanna et al., 2011; Logan et al., 1997; Miller, 2000). Under the notion that cognitive processes must precede the behavioral response, Kagan (1966) conceptualized 'reflection impulsivity,' which is a form of impulsivity that is displayed by not taking all the relevant information into account before making a decision (Clark et al., 2005). This may be conceptually in line with Barratt and colleagues' attentional impulsivity, they differ in that while attentional impulsivity is self-reported, reflection impulsivity based on All the while, Evenden (1999a, b) proposed that to assess reflection impulsivity, a task that incorporates the ability to discriminate unreliable visual stimuli is necessary. Tasks attempting to measure the reaction time, resisting interference and proactive (preferred or automatic) response, ability to focus and sustain attention have been used. These tasks include the Stroop task, Wisconsin Card Sorting Test, and five-choice serial reaction time task (Basar et al,, 2010). Interestingly enough, these tasks area also tasks known to measure one' s inhibitory control. Of these, the Stroop task will be discussing in further detail (p. 18).

Even with the abundant conceptualization of impulsivity, the limitation in its understanding lies in that there has been very few experimental attempts to measure and observe the relationship behind the dimensions within impulsivity. Their neural basis, especially in the adolescents, is a topic that is currently under heavy investigation.

1.4 Impulsivity Assessment

1.4.1. Self-reports

UPPS-P is considered to be the most wholesome impulsivity questionnaire as it was designed to comprehensively select the items best measuring impulsivity from almost all preexisting self-report assessments on impulsivity. The grouped items were then labeled within the frameworks within FFM. The FFM was chosen for its extensiveness and its explicit inclusion of several separate traits that have been formerly described as impulsivity. After performing factor analysis on all the items of preexisting self-report impulsivity surveys, items with the highest correlation with each factor scores were selected for the makeup of UPPS-P. The preexisting assessments used for UPPS-P' s development were EASI-III Impulsivity Scales, Dickman' s Functional and Dysfunctional Impulsivity Scales, Barratt Impulsiveness Scale-11 (BIS-11), I-7 Impulsiveness Questionnaire, Personality Research Form Impulsivity Scale, Multidimensional Personality Questionnaire

Control Scale, Temperament and Character Inventory, Sensation Seeking Scale, and NEO-PI-R (Whiteman & Lynam, 2001).

The developers identified these selected items to show best fit to five different personality traits that dispose individuals to make rash, impulsive judgements and actions (Cyders & Smith, 2007). These traits, labeled after content analysis, were Urgency, (lack of) Premeditation, (lack of) Perseverance, and Sensation Seeking. Urgency was later divided into positive or negative urgency, depending on the emotional valence. Urgency refers to the tendency to experience strong impulses, frequently under conditions of positive or negative affect. High scores in urgency makes one likely to engage in impulsive behaviors to alleviate or express emotions despite the possible long-term harmful consequences of those behaviors. Of the FFM factors, urgency was found to be aligned with Neuroticism. The second facet, (lack of) premeditation, identified with the (low) deliberation facet of FFM and is the tendency to think and reflect on the consequences of an action before engaging in it. Low scores on this facet are considered to convey thoughtful and deliberate decision making. The third facet, (lack of) perserverance, falls into the self-discipline facet of FFM and it refers to the one's ability to stay focused on a possibly boring or difficult task. Those who score high in this facet "cannot force themselves to do what they want themselves to do" (Costa & McCrae, 1992, p.18). The final facet, sensation seeking, is linked to the excitement seeking of FFM and it is thought to show one’ s tendency to pursue and enjoy exciting activities and be open to try new experiences that may be dangerous. Those who receive high scores in this facet are interpreted to enjoy taking risks and engage in dangerous activities, while those who score low are thought to prefer avoiding risk and danger.

1.4.2. Task−based

Task−based measurements of impulsivity are mainly used for one of the two purposes to observe: (1) one’ s ability to make decisions and take risks to win larger, delayed reward than to win smaller, immediate gratifications, and (2) one’ s ability to inhibit distracting information that leads to automatic, rash responses and selectively chose preferred information before taking action. For the first purpose, tasks such as Iowa Gambling task, delay−discounting task, and Balloon Analogue Risk Task have been used (Christodoulou et al., 2006; Van Leijenhorst et al., 2010; Romer et al., 2009; Van Den Bos et al., 2015), Other tasks that focus on measuring inhibitory control are Stroop task, Go/No Go Task, and Stop−Delayed Signal Task (Congdon et al., 2010; Ding et al., 2014; Romer et al., 2009). Multi−source Intereference Task is a relatively new task that incorporates previously existing Stroop task, Flanker task, and Simon’ s effect task that measure one’ s ability to ignore two interfering stimuli to make the task−abiding favorable choice. It mainly uses visual and motor cognitive domains (Bush et al., 2003).

1.5. Impulsivity and the Brain

1.5.1. Impulsivity and the Adult Brain

The relationship between the brain and impulsivity have been investigated using various methodologies, ranging from brain morphology, white matter connectivity, resting state connectivity, and task-based functional activation. Previous studies have defined cortical brain regions related to impulsivity as the insular cortex (INS), subregions of the temporal cortex (superior, middle, and inferior) and subregions of the prefrontal cortex (superior, middle, inferior, orbitofrontal, and anterior cingulate (Asahi et al., 2004; Cho et al., 2013; Crunelle et al., 2014; Ersche et al., 2011; Matsuo et al., 2009; Moreno-Lopez et al., 2012; Schilling et al., 2012; Wilbertz et al., 2012). Commonly investigated subcortical regions related to impulsivity are dorsal striatum, ventral striatum, amygdala, hippocampus, and thalamus (Balleine et al., 2007; Buchwald et al., 1961; Congdon et al., 2010; Garavan et al., 2012). These areas are known also known to be involved in reward processing and inhibitory control.

However, studies so far have reported similar yet different brain areas to be related to impulsivity depending on what assessment they chose to measure impulsivity. While there are strong evidence for the neural correlates behind task-based impulsivity, an organized consensus for self-report based impulsivity does not exist. For example, Robbins and colleagues (2011) estimated the cortical areas and subcortical areas involved in the impulsivity facets observed by task-based measurements: when engaging in discounting tasks, ventromedial prefrontal cortex and subgenual cingulate cortex interact with the ventral striatum, for inhibitory control tasks, ventrolateral prefrontal cortex, anterior cingulate cortex (ACC), and pre-supplementary motor area communicate with the dorsal striatum, and when performing cognitive shifting tasks, dorsolateral prefrontal cortex (dlPFC), ventrolateral prefrontal cortex, and lateral orbitofrontal cortex (lateral OFC) interact with the caudate nuclues (CN).

A clear consensus on the neural correlates of self-report based impulsivity measures has not yet been made. For example, BIS-11 were found to be related to the surface area of superior temporal cortex and insula (INS) in one study (Kaag et al., 2014), while another study reported that it was related to the cortical thickness (CT) of the left middle frontal, orbitofrontal, and superior frontal cortex (Schilling et al., 2012). Another study that observed the relationship between BIS-11 and brain areas that activated during the Go/NoGo task reported that greater activation in the anterior medial superior frontal gyrus and the temporoparietal association area were associated with low BIS scores, while activation in the left superior temporal gyrus was associated with greater BIS impulsivity (Horn et al., 2003). The lack of research explaining the relationships between the different impulsivity measures and a coherent report on their association with the brain hinders the understanding of an integrated picture of these psychological and biological variables.

1.5.2. Impulsivity and the Adolescent Brain

The question turns more complex when it comes to adolescents. Adolescent impulsivity is considered different compared to that of adults, which in turn requires additional theories for its make up. The main regions of interests (ROIs) related to impulsivity are centered on the various regions within the prefrontal cortex and subcortical areas including the dorsal striatum, ventral striatum, and the amygdala (Babbs et al., 2013; Bjork et al., 2004; Boes et al., 2009; Churchwell et al., 2013; Ernst et al., 2005; Eshel et al., 2007; Galvan et al., 2006; Geier et al., 2010; Hare et al., 2008; Mills et al., 2014; Moreno-Lopez et al., 2012; Somerville et al., 2011; Van Leijenhorst et al., 2009; Van Leijenhorst et al., 2010), based on existing theories on how brain areas interact with each other in forming adolescent impulsivity. The two main theories in adolescent impulsivity are the 'dual systems model' (Luna & Wright, 2016; Steinberg et al., 2008) and the 'imbalance model'

(Casey et al., 2016). According to the dual systems model, adolescent impulsive behavior is hypothesized to be stimulated by "a rapid and dramatic increase in dopaminergic activity within the socioemotional system around the time of puberty, which is presumed to lead to increase in reward seeking. However, this increase in reward seeking precedes the structural maturation of the cognitive control system and its connections to areas of the socioemotional system, a maturational process that is gradual, unfolds over the course of adolescence, and permits more advanced self-regulation and impulse control" (Steinberg et al., 2008). To reiterate, the subcortical areas responsible for the 'urges' mature faster than the cortical areas that control these urges, which results in adolescents' risky behavior. The imbalance model differs from the dual systems model in that it purports that it is the fine-tuning of connections that occurs between the cortical and subcortial regions responsible for adolescent impulsivity. In other words, adolescents use unique neural circuitry different from that of adults, which makes them vulnerable to make ill-judgements. Meanwhile, despite the copious amount of study to understand adolescent impulsivity in terms of brain development, there lacks amount of research dedicated to find the neural correlates of different impulsivity facets in adolescents.

1.6. Hypothesis and Purpose of Study

The purpose of this study was to investigate the unique neural correlates of different facets of impulsivity in adolescents. This was done so by examining (1) how the different facets of impulsivity measured by using either self-report or task-based assessments relate to each other in adolescents and (2) whether adolescent impulsivity measures related to those brain areas essential to adult impulsivity. The study's first hypothesis stated that the different facets of impulsivity measured by different acquisition means will not correlate with each other. The second hypothesis was that impulsivity measured by different assessments will have different neural correlates.

As for the variables for neural basis, brain morphology represented by subcortical volumes (SV) and CT was used, along with resting state functional connectivities. While brain morphology fairly represents the degree of brain growth and maturation, resting state connectivity will be used to supplement the relationship between the subcortical and cortical areas. Intrinsic network organization of the brain researched using fMRI of the resting state or task-free state brain can provide further information as it has been known to make it possible to identify task-positive networks during the resting state. (Sadaghiani & D'Esposito, 2014). Therefore, understanding the intrinsic connectivity may help researchers to outline the anatomical settings of a network that serves as the template for its performance (Sadaghiani & Kleinschmidt, 2013). Bilateral dlPFC, medial prefrontal cortex (mPFC), ACC, OFC, and INS were chosen as ROIs among cortical areas, while bilateral caudate nucleus (CN), putamen (PT), amygdala (AD), and nucleus accumbens (NA) were chosen among the subcortical areas. These areas were selected based on previous studies that reported them to have strong correlation between adolescent impulsivity (Mills et al., 2014).

2. Methods

2.1. Participants

Participants consisted of 7^{th} grade and 8^{th} grade adolescents. The participants were recruited from public middle schools, private educational institutes, and websites, throughout February of 2016 to August of 2016. Exemption criteria were History of neuropsychological illness, brain trauma, auditory or visual problems, left-handedness, and ambidexterity. Out of 71 participants initially recruited, 4 were excluded due to attention deficit/hyperactivity disorder, impulsive disorder, and depression. Participants' health and educational history were collected with parent interviews. Of the remainder, 3 refused to participate further during assessment resulting in total of 64 participants for the research. Participants were all in their early teens, ranging from 11 to 14 years of age in which 30 were girls and 34 were boys. Their average age was 13.20±0.62 years (range 11.99 to 14.52 years).

This study was approved of the Seoul National University Institutional Review Board and all research participants were informed of the research process and provided with written consents. Those participants under 12 showed their voluntary intention for participation by signing on the child agreement form under the supervision of their legal guardian.

2.2. UPPS-P Impulsive Behavior Scale

UPPS-P was used to assess self-reported impulsivity (Appendix 1). Developed originally by Whiteside and Lynam (2001), It was devised to measure the emotional or behavioral impulsivity participants show in their daily lives. UPPS-P is based on the FFM to factorize the comprehensive nature of impulsivity. UPPS-P provides scores for five dimensions of impulsivity: Negative Urgency (U1), Lack of Perseverance (U2), Lack of Premeditation (U3), Sensation Seeking (U4), and Positive Urgency (U5) from its 59 questions. Each items were rated on a 4-point Likert scale ranging from 1 (strongly agree) to 4 (strongly disagree). The questionnaire was adopted and statistically validated by Lim and Lee (2014) to Korean. D' Acremont & Van der Linden (2005) reported the same 5 dimensions to be found for adolescents. The hierarchical cluster analysis of our participants' UPPS-P scores done using Rstudio showed definite clustering among the five dimension items in the questionnaire (Figure 1). Although Whiteside and Lynam does not propose UPPS-P' s sum scores to be driven from the higher factors that cluster the five aforementioned factors according to the hierarchical model (Lim & Lee, 2014), this study utilized sum scores for urgency (URG; U1+U5), cautiousness (CTN; U2+U3) and total score (UT;

U1+U2+U3+U4+U5).

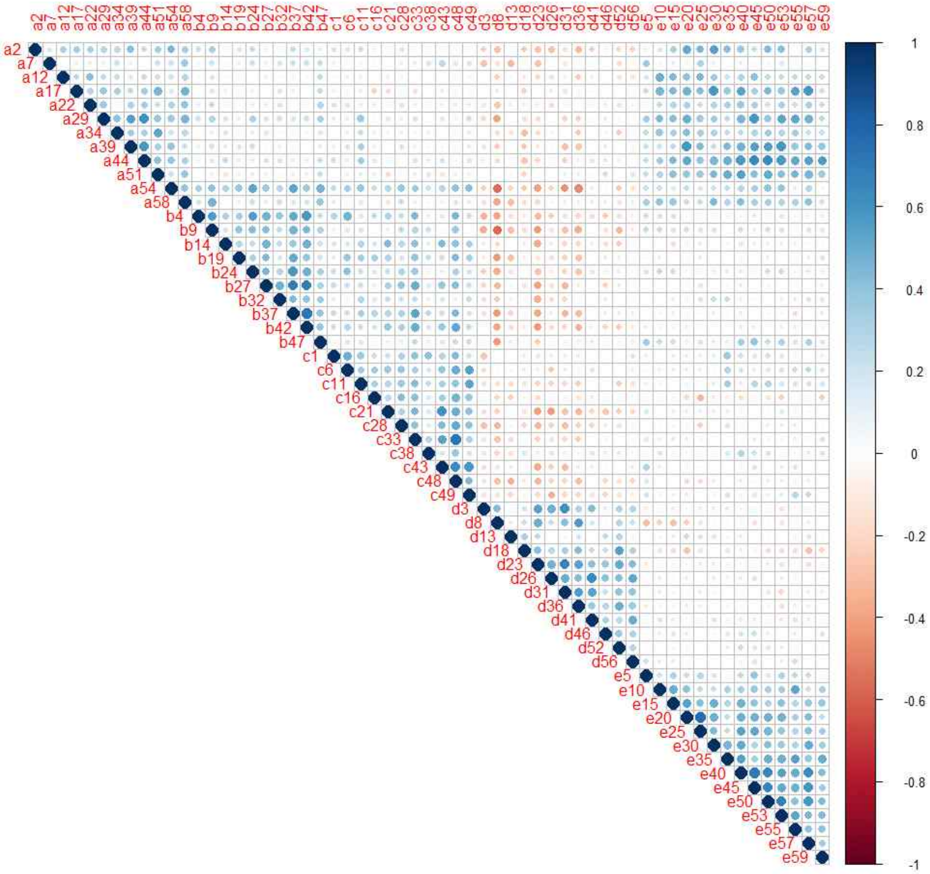


Figure 1. Hierarchical cluster analysis of UPPS−P.

Note. a: Negative Urgency, b: Lack of Perseverance, c: Lack of Premeditation, d: Sensation Seeking, e: Positive Urgency.

2.3. Inhibition Tasks

2.3.1. Stroop Task

Stoop color and word test children' s version (Shim & Park,

2007) was devised to measure inhibition efficiency (Golden et al., 2003). The task consist of 3 phases in which the participants were given 45 seconds each. For the first phase ('word'), participants are asked to read out loud the words written in blank ink as fast and accurate as possible (e.g. read 'blue' as 'blue.) For the second phase ('color'), participants say out loud the name of the color of the ink in which 'XXXX's are printed in. For the last phase('color/word', participants are asked to say out loud the name of the color of the ink the words are printed in, while this time the written word does not match the printed ink color (e.g. the word 'red' will be printed in blue ink, making the correct answer 'blue.') In the last phase, participants are forced to inhibit the automatic reaction to read the words but focus on saying the ink color. This requires the prefrontal lobe's inhibition process, which slows down the reaction time (Dempster, 1992). Performances are measured based on the number of correct words the participants have read within the given time. Stroop data was collected for only 63 participants with one participant data missing during task administration. Stroop intereference score (SI) was calculating using the equation provided by the Stroop manual (c= 'color,' cw= 'color/word') (Shim & Park, 2007).

$$SI = c - cw$$

Larger SI means that the subject had experienced stronger or struggled more to overcome the interference during the interference conditions.

2.3.2. Multi−source Interference task

MSIT, developed by Bush et al. (2003), have been assessed to various demographics ranging from adolescents to the elderly (Dwyer et al., 2014; Kim, 2016). It also had been used to assess cognitive control of diverse clinical demographics including those with Attention deficit/hyperactivity disorder (Bush et al., 2008; Bush et al., 2011). Stimuli within MSIT consists of factors of Erikson Flaker task, Stroop task, Simon effect task and also includes indirect factors.

The participants are shown with either three numbers or symbols and are asked to respond to the one number that is different from the rest. Participants are to place their index finger, middle finger, and ring finger on three buttons that each are matched to numbers 1, 2, and 3. This task consists of interference trials and control trials. For an interference trial, the location of the number that is the right answer does not match the location of the button. The numbers other than the right answer cause interference. For a control trial, the location of the number that is the right answer matches the location of the button. Symbol ‘x’ is presented instead of numbers for those other than the right answer (Figure 2). The participants reported for 12 interference and control trials each. Their performance were recorded for their accuracy and reaction time in the control and interference trials. The difference in accuracy (M_{acc} = $Acc_{control}-Acc_{interference}$) and reaction time ($M_{rt}$ = $RT_{interference}-RT_{control}$) during these trials were each used as the interference scores. Larger interference score represents more struggle in processing the interference.

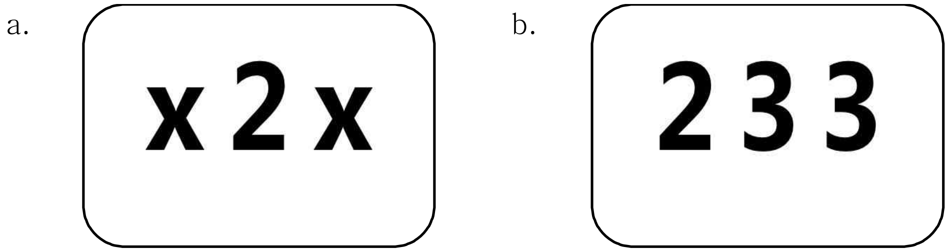


Figure 2. Example of stimuli presented for MSIT.

Note. a. Example illustration of a control trial. b. Example illustration of an interference trial.

2.4. Structural and Resting State Functional Magnetic Resonance Imaging Acquisition

Magnetic resonance imaging (MRI) was performed on a 3-Tesla MRI (MAGNETOM Trio; Simense, Germany) at Seoul National University. To minimize the discomfort from the machine's noise, participants were provided with sponge earplugs. Participants laid down on their backs, their head secured on the 12 channel head coil. Sponge was inserted around the head to minimize head movements. T1 sagittal slices were obtained to observer brain structure (slice thickness 1mm, repetition time (TR) = 2300ms, echo time (TE) = 2.36ms, field-of-view (FOV) = 256x256mm^2, flip angle (FA) = 9° , voxel size 1.0x1.0x1.0mm^3. All participants underwent a resting-state fMRI scan of 6 min. They were asked to relax and remain awake while gradient-echo EPI data were acquired (TR = 2200 ms, TE = 30 ms, 33 axial slices, 3.0x3.0x3.5 mm^3 voxels, flip angle 79° , FOV = 240mm.

2.5. Brain Morphology and Resting State Connectivity

2.5.1. Brain Morphology

Freesurfer v5.3.0 was used to preprocess the brain image for motion correction, averaging T1 weighted images, skull stripping, reconstruction of cortical surface models, grey-white matter segmentation, normalization, and labeling of regions on the cortical surface and subcortical brain structures according to automatic Talairach transformation (Dale et al., 1999; Fischl et al., 2001; Fischl et al., 1999a; Fischl et al., 1999b; Fischl et al., 2004b; Han et al., 2006; Jovicich et al., 2006; Segonne et al., 2004; Sereno, 1993; Reuter et al., 2010; Reuter et al., 2012). The images were normalized to Montral Neurological Institute (MNI) template. CT and SV were also calculated with the same program (Fischl & Dale, 2000; Fischl et al., 2002; Fischl et al., 2004a). SV was obtained for those areas including AD, CN, PT, and NA.

For this study, the bilateral CN, PT, NA and AD were chosen as ROIs based on previous studies (Cai et al., 2016; Geier et al., 2009;

Mills et al., 2014). Cortical areas were segmented using the Destrieux Atlas and regions of interest were of the following based on previous studies: bilateral dlPFC (regions 15, 16, 52, 53, and 54), bilateral ACC (regions 6 and 7), bilateral OFC (regions 24, 31, 32, 62, 63, 64, and 70), bilateral INS (regions 17, 18, 47, 48, and 49), bilateral mPFC (regions 6 and 16) (Destrieux et al., 2010; Appendix 2). These cortical areas were chosen based on previous studies that reported brain areas related to adolescent impulsivity and inhibitory control (Boes et al., 2009; Casey et al., 208; Churchwell et al., 2013; Mills et al., 2014).

2.5.2. Brain Resting State Connectivity

Resting functional connectivity analysis was performed using a ROI-driven approach with CONN Functional Connectivity Tool box (Conn v.18.a; http://www.nitrc.org/projects/conn, RRID:SCR_009550) (Whitfield-Gabrieli & Nieto-Castanon, 2012) for Statistical Parametric Mapping SPM12 (http://www.fil.ion.ucl.ac.uk/spm/software/spm12/) on Matlab R2015b (Mathworks). For the preprocessing step, function realignment and unwarp took place to estimate and correct subject motion. Each structural and functional image was translated to have (0, 0, 0) function center and were corrected for their slice-timing. Functional Outlier was detected using ART-based identification of outlier scans for scrubbing. Gray, white matter, and CSF of the structural and functional images were segmented and directly normalized ingo MNI space. Harvard Oxford Brain Atlas installed within Conn was used for cortical and subcortical segmentation. For functional smoothing and spatial convolution, Gaussian kernel (full width half maximum = 8 mm) was used. The denoising procedure took place, using the anatomical CompCor provided by Conn, to address a number of residual global physiological and motion effects that are present and very salient on the data even after the preprocessing steps. The time course for each voxel was temporally band-pass filtered (0.008<f<0.09 Hz). The main effect of impulsivity measures that showed significant correlation with brain morphologies was investigated. Seed-to-voxel analysis was used to observe ROIs' intrinsic functional connectivity with impulsivity measures as independent variables. The ROIs used for this step were those subcortical regions that showed statistically significant correlations with the impulsivity measures.

2.6. Statistical Analysis

IBM SPSS Statistics 23 and RStudio version 1.1.447 was used for statistics. Hierarchical cluster analysis using the participants' UPPS-P results was performed on R. Partial correlation was observed between the survey-based and task-based impulsivity scores and brain measures, Age and sex were used as covariates. To better quantify the practical significance SV has without the effect of the intracranial volume (ICV), SV was divided by the ICV for adjustment (SV_{adj}).

Age, sex, and subjects' performance on Korean-Wechsler's Intelligence Scale for Children-IV's (Gwak et al., 2011) Vocabulary (VC) subtest were used as covariates. VC was chosen to represent subject's general ability index. VC measures the subjects' verbal fluency, concept formation, word knowledge, and word usage. In an un-timed test, the subjects are shown a picture or a word in which they are asked to say what the picture depicts and what the definition of the word is.

False discovery rate for the correlations was found using the 'fdrtool' (Strimmer, 2008) and 'p-adjust' (Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001; Hochberg, 1988; Holm, 1979; Hommel, 1988; Sarkar, 1998; Sarkar & Chang, 1997; Shaffer, 1995; Wright, 1992) on RStudio .

3. Results

3.1. Impulsivity Measures

The results from the psychological and task based measurements are shown in Table 1. Since UPPS-P does not provide diagnostic standards necessary to draw conclusions about the scores, most of our participants were in the average range compared to average results Lim and Lee (2014) showed for their 625 university students (306 women, average age 21.23±0.14 years). The participants overall showed high performance in both the control and interference conditions, which resulted in relatively low differences and range in the accuracy and reaction time between the two conditions. Stroop task showed no such ceiling effect. The distribution of the psychological measurements also revealed that while UPPS-P scores and SI fairly follow the bell-shaped normal distribution with the exception of U4 that shows a bimodal distribution, Meanwhile, MSIT scores are positively skewed (Figure 3). None of the UPPS-P measures were significantly correlated with Stroop or MSIT interference scores. Stroop and MSIT interference scores did not show significant correlation to each other (Table 2).

Table 1.

Self-reported assessment and inhibitory performance scores.

UPPS-P	Mean±S.D.	Assessment	Mean±S.D.
U1	27.58±5.90	SI	20.21±7.81
U2	20.78±5.30	M_{acc}	0.05±0.04
U3	23.17±5.54	M_{rt} (ms)	0.31±0.07
U4	33.95±7.69	VC	53.86±7.02
U5	28.05±7.60		
URG	55.63±12.92		
CTN	43.95±9.53		
UT	133.53±16.95		

Note. U1: Negative Urgency, U2: Lack of Perseverance, U3: Lack of Premeditation, U4: Sensation Seeking, U5: Positive Urgency, URG: Urgency, CTN: Cautiousness, UT: UPPS-P Total, SI: Stroop interference score, M_{acc}: MSIT accuracy difference, M_{rt}: MSIT reaction time difference; VC: Vocabulary

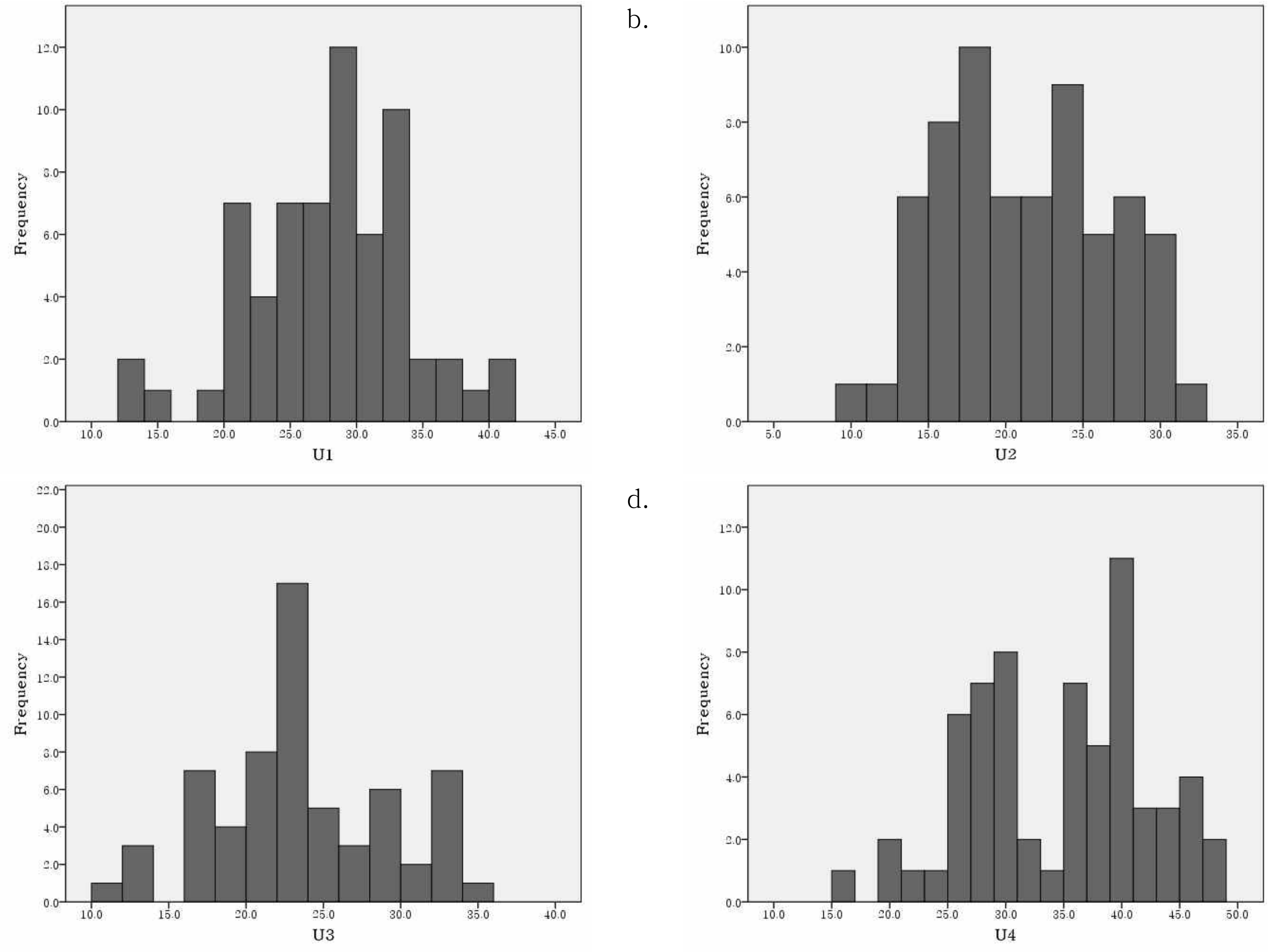
Table 2.

Correlation between impulsivity measures.

	SI	M_{acc}	M_{rt}
U1	−.072	.172	.073
U2	.199	.130	.190
U3	.146	−.009	.050
U4	−.120	−.004	−.230
U5	−.188	.189	.027
URG	−.143	.189	.049
CTN	.194	.067	.134
UT	−.056	.185	.008
SI	1.000	−.043	−.084
M_{acc}	−	1.000	.479**
M_{rt}	−	−	1.000

Note. ** p<.01 (p-uncorrected)
Covariates: age, sex, VC

a. b. c. d.



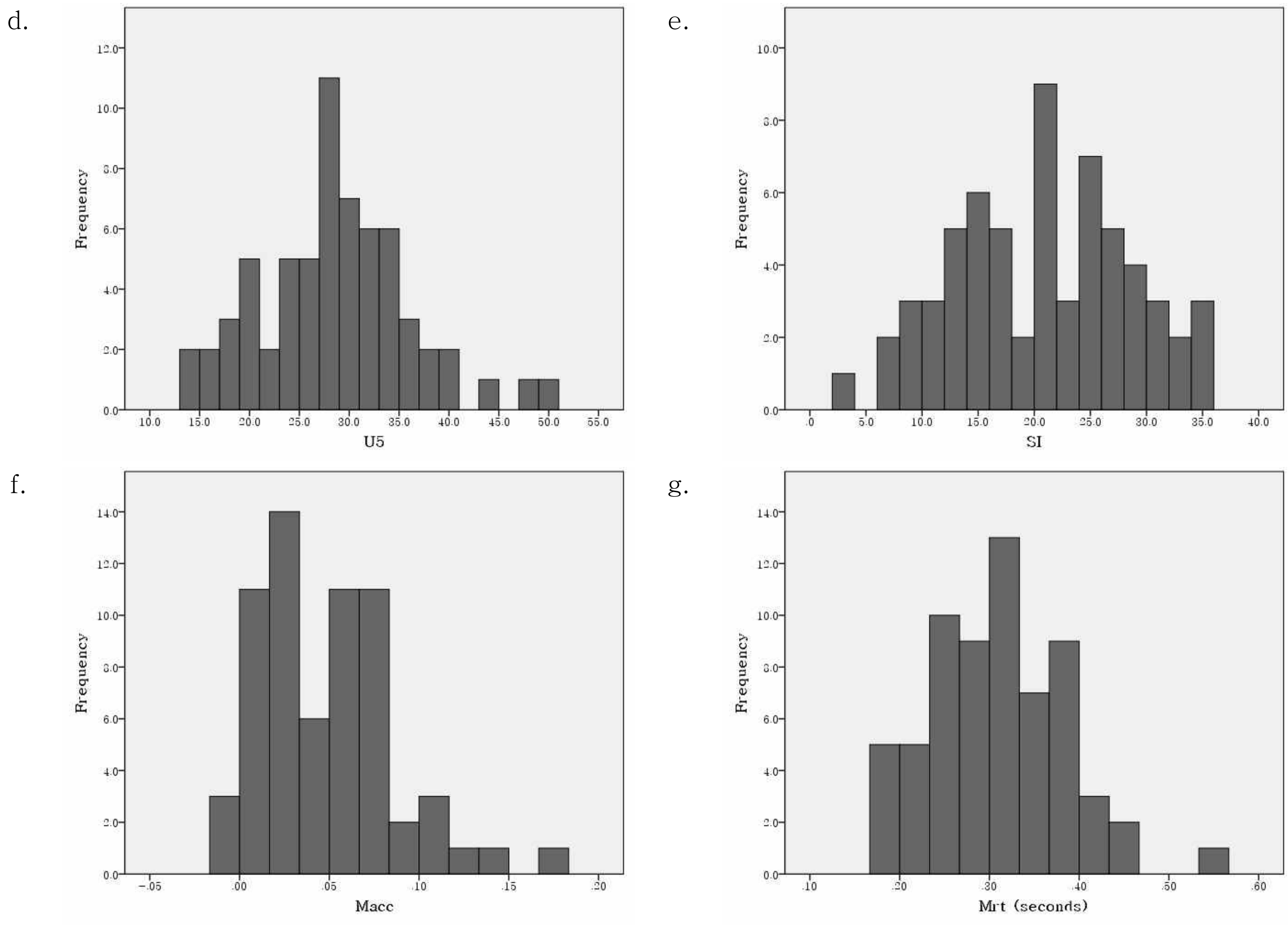


Figure 3. Subject distribution per impulsivity measurements.

3.2. Impulsivity and the Brain

3.2.1. Brain Morphology

When factors of UPPS-P were partially correlated with SV_{adj} with age and sex as covariates, U5 was positively correlated with left PT volume. However, when p-values were adjusted for multiple correlation, SI showed significant negative correlation with the bilateral CN and PT volumes even when adjusted for multiple correlation ($p<0.01$) (Figure 4). M_{rt} was negatively correlated with bilateral NA volumes when p-uncorrected (Table 3).

Table 3.

Correlation between impulsivity measures and subcoritcal volumes.

	Left				Right			
	CN	PT	AD	NA	CN	PT	AD	NA
U1	.112	.213	−.012	−.097	−.011	.067	−.045	.131
U2	−.199	−.042	.014	.017	−.154	−.032	.050	−.043
U3	−.176	−.128	.138	.085	−.106	−.054	.096	.090
U4	.128	.154	.035	.111	.188	.217	.073	−.035
U5	.074	.296*	−.045	−.087	.078	.095	−.180	−.007
URG	.095	.217*	−.032	−.095	.041	.087	−.126	.055
CTN	.211	−.097	.071	.058	−.146	−.048	.082	.028
UT	.013	.224	.032	.01	.035	.138	.018	.042
SI	−.421 **†††	−.382 **††	−.193	−.191	−.414 **††	−.343 **†	−.175	−.090
M_{acc}	.174	.137	.033	.215	.122	.126	.140	.213
M_{rt}	.032	.082	.198	.334**	.070	.129	.273*	.285*

Note. * p<.05 (p−uncorrected), ** p<.01 (p−uncorrected); † p<0.05 (FDR corrected); †† p<0.01 (FDR corrected), ††† p<0.001 (FDR corrected)

CN: Caudate nucleus, PT: Putamen, AD: Amygdala, NA: Nucleus Accumbens

Covariates: age, sex, VC

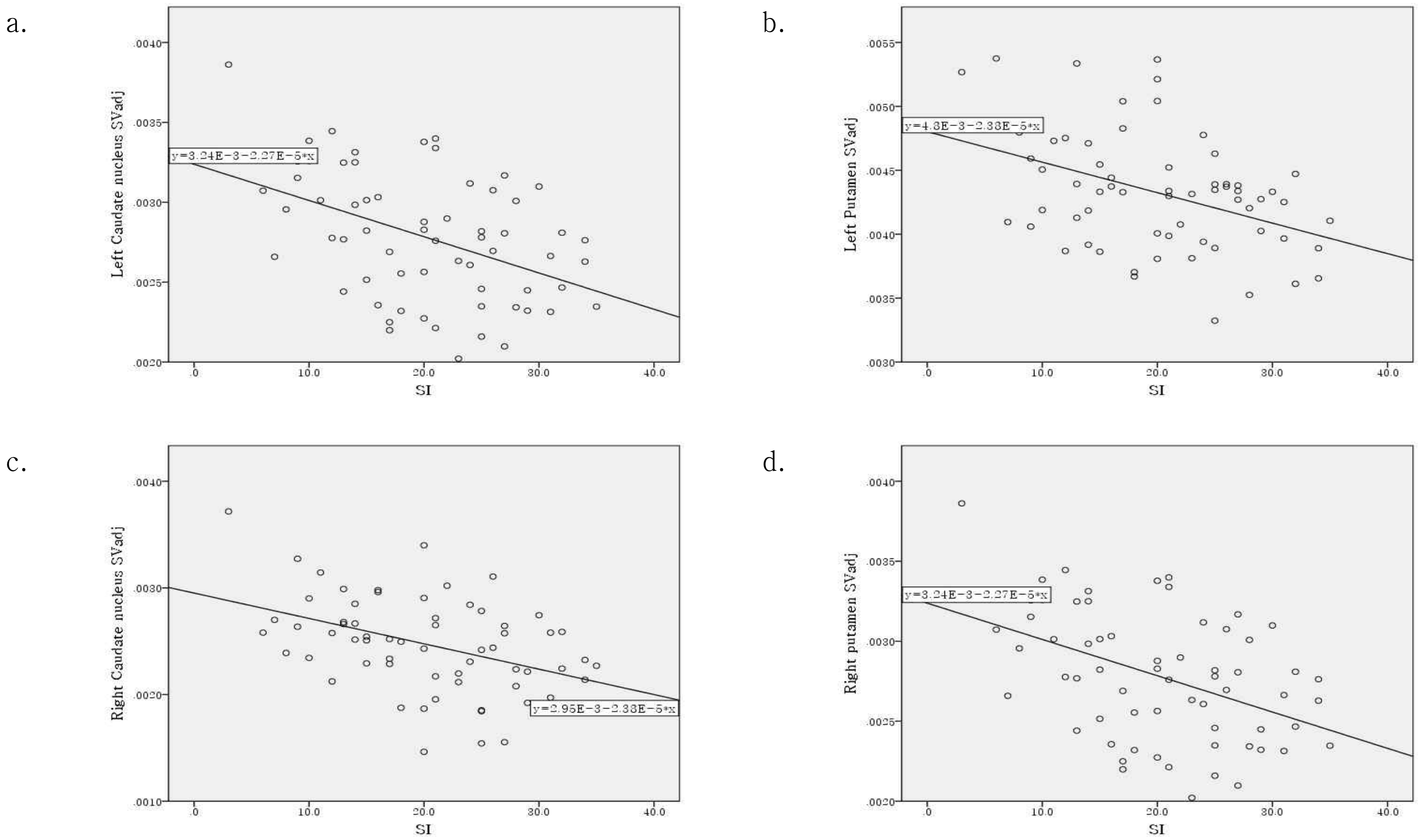


Figure 4. Correlations between SI and SV_{adj}.

Note. p−FDR<0.05.

Meanwhile, of the UPPS-P factors, U1 showed positive correlation with left dlPFC, left mPFC, left ACC, and right mPFC CT, U2 with left INS CT, U5 with left dlPFC, left mPFC, right dlPFC, and right mPFC CT. SI showed positive correlation with right OFC CT. However, these correlations did not survive p-FDR correction. M_{acc} was positively correlated with left dlPFC, bilateral OFC, left mPFC, and bilateral ACC CT. Of these, correlations with dlPFC, left mPFC, left ACC, right OFC, and right ACC survived FDR correction (FDR $p<0.05$, Figure 5). M_{rt} showed positive correlation with bilateral INS that did not survive FDR correction (Table 4).

Table 4.

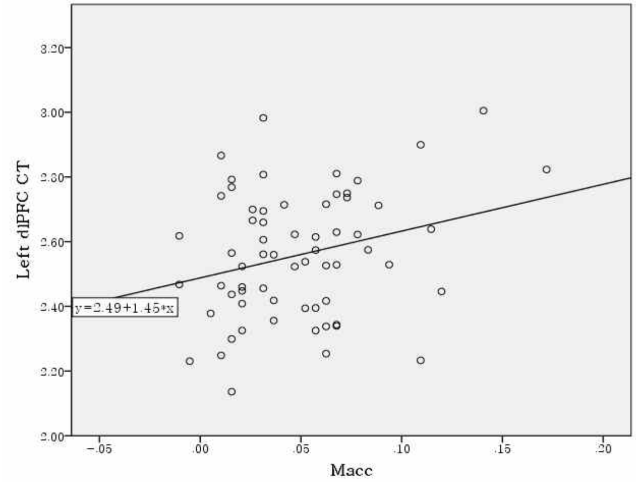
Correlation between impulsivity measures and CTs.

	Left					Right			
	dlPFC	OFC	mPFC	ACC	INS	dlPFC	OFC	mPFC	ACC
U1	.291*	.203	.304*	.310*	.171	.217	.103	.259*	.237
U2	.099	.082	.024	−.014	.261*	.017	.039	−.006	.028
U3	.106	−.037	.017	−.115	.181	−.053	.080	−.099	−.128
U4	−.023	−.070	.049	.122	−.027	.107	−.078	.089	.106
U5	.258*	.084	.304*	.246	.008	.310*	.032	.304*	.237
URG	.284*	.142	.317*	.286*	.082	.282*	.065	.296*	.247
CTN	.115	.024	.023	−.074	.248	−.021	.067	−.053	−.058
UT	.273*	.091	.279*	.234	.190	.254	.052	.239	.206
SI	.124	.231	.151	.169	.023	.127	.318*	.046	.039
M_{acc}	.309*†	.265*	.342**†	.373**†	.107	.248	.173	.360*†	.357**†
M_{rt}	.208	.159	.148	.212	.283*	.167	.202	.200	.170

Note.

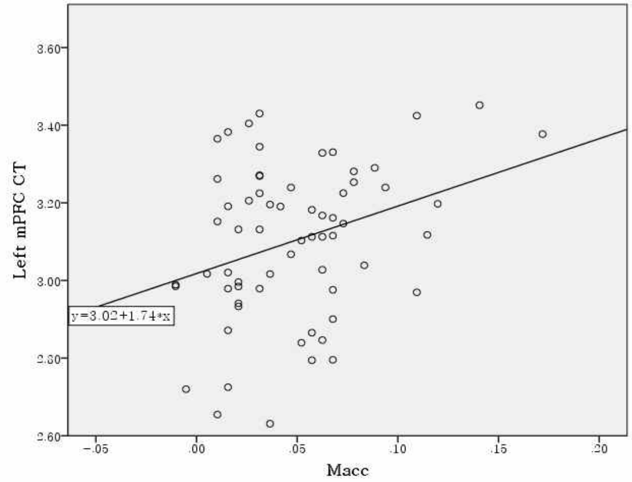
* p<.05 (p−uncorrected), ** p<.01 (p−uncorrected), † p<0.05 (FDR corrected)

dlPFC: dorsolateral prefrontal cortex, mPFC: OFC: orbitofrontal cortex, mPFC: medial prefrontal cortex, ACC: anterior cingulate cortex, INS: insula, Covariates: age, sex, VC a.



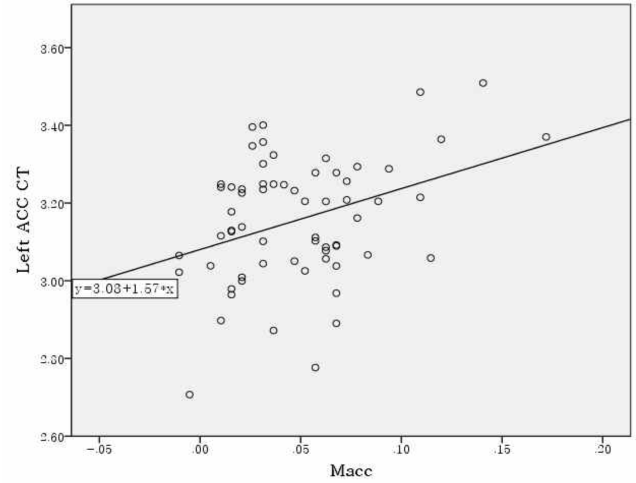
Left dlPRC CT
y=2.49+1.45*x
Macc

b.



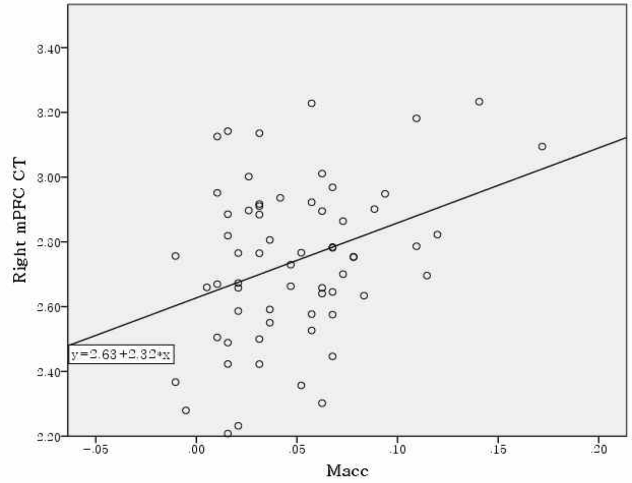
Left mPRC CT
y=3.02+1.74*x
Macc

c.



Left ACC CT
y=3.08+1.57*x
Macc

d.



Right mPRC CT
y=2.63+2.32*x
Macc

e.

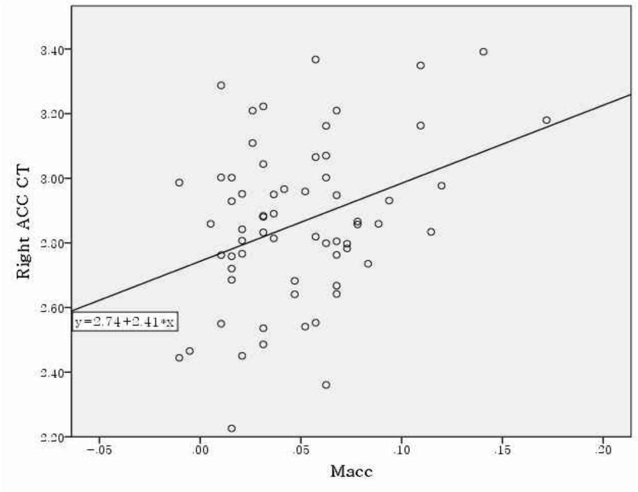


Figure 5. Correlations between M_{acc} and CT.

Note. p−FDR<0.05

3.2.2. Brain Resting State Connectivity

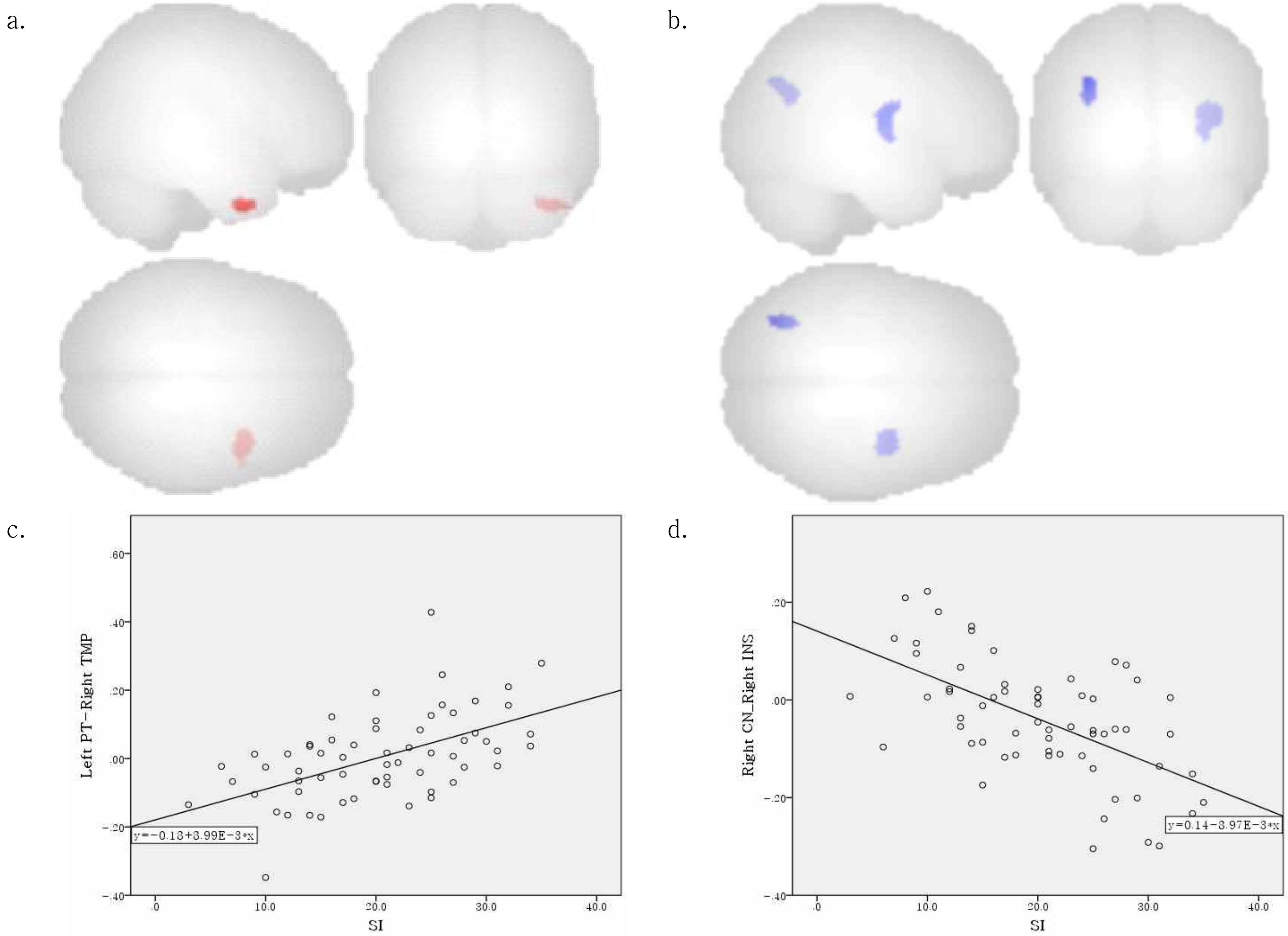
Based on the correlation analysis between brain morphology and impulsivity measures, bilateral CN, bilateral PT, left dlPFC, bilateral mPFC, bilateral ACC, each in relation with SI and M_{acc}, were chosen as seeds for seed-to-voxel analysis of resting state connectivity. Only those areas that survived multiple correlation correction were selected. The main effects of the impulsivity measures on the resting state connectivities were considered statistically significant when it satisfied height threshold $p<0.001$ (p-uncorrected), cluster threshold $p<0.05$ (cluster-size p-FDR corrected), and two-sided. SI was positively correlated (Figure 6c) with the connectivity between left PT to right temporal pole (Figure 6a), while it was also negatively correlated (Figure 6d, e) with right CN to right INS connectivity and right lateral occipital cortex (Figure 6b). M_{acc} showed no correlation with the functional connectivities with cortical regions as seeds. Specific coordinates and number of cluster voxels of brain regions in which functional connectivity correlated with SI are shown in Table 5.

Table 5.

Brain regions in which functional connectivity correlated with SI.

Seed region	Peak MNI coordinate region	Peak MNI coordinates			Number of cluster voxels	Size p−FWE	Size p−FDR	size p−unc	peak p−FWE	peak p−unc
		x	y	z						
Left PT	Right TMP	+46	+04	−44	130	.037867	.045771	.001387	.336858	.000005
Right CN	Right INS	+32	−08	+06	251	.001029	.001442	.000037	.290610	.000004
	Right LOC	−36	−68	+30	116	.060508	.043720	.002242	.239702	.000003

Note. CN: Caudate nucleus, PT: Putamen, TMP: Temporal pole, INS: Insula, LOC: Lateral occipital cortex


a.
b.
c.
d.
Left PT–Right TMP
y=−0.18+8.99E−3*x
Right CN_Right INS
y=0.14−8.97E−3*x
SI
SI
.60
.40
.20
.00
−.20
−.40
.0
10.0
20.0
30.0
40.0

e.

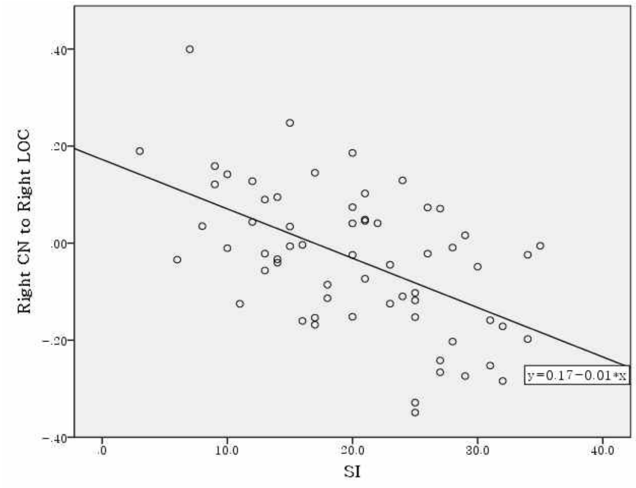


Figure 6. SI's main effect on resting state connectivity.

4. Discussion

This study aimed to observe the relationship between UPPS-P, Stroop task, and MSIT impulsivity measures and their neurological correlates in adolescents. Although these impulsivity measures have each mainly theoretically been discussed to measure differing facets of impulsivity, there had not been an integrated study that addressed to experimentally observe their differences and compare their neurological correlates. Impulsivity have also been observed mostly in adults, which imposes hinderance in understanding adolescent impulsivity. The study' s results showed that the three impulsivity measures do not correlate with each other and that they each have differing neural correlates: while UPPS-P scores did not show any significant neural correlates, SI and MSIT scores each showed correlation with either dorsal striatal volume or cortical thickness. Only SI showed significant correlation between the dorsal striatum and cortical connectivity in the resting state. The study has its significance in that it provides neurological evidences for the difference between the three impulsivity measures. The study also has importance in its novelty in that it focused on observing the three impulsivity measures and their neurological correlates in adolescents. Detailed interpretation of the study’ s results are as follows.

4.1. Impulsivity Measures

UPPS-P, SI, and MSIT interference scores did not show any significant correlation to each other, which confirmed the study’ s first hypothesis. Lack of correlation between the three impulsivity measurements has significant meaning in that it highlights the importance of differentiating the different facets of impulsivity not only theoretically but also experimentally; many a time have previous studies used a myriad of impulsivity measures without considering the existence and differences between impulsivity sub-components. This observation follows what had been commonly observed in past studies; while there are studies that purport the link between the self-reported impulsivity scores and inhibitory measures (Cao et al., 2007; Enticott et al., 2006; Gay et al., 2008; Kjome et al., 2010), there are also mounting number of studies that have failed to reproduce such correlation (Horn et al., 2003; Lansbergen et al., 2007; Lawrence et al., 2009; Lijffift et al., 2004; Romer et al., 2009; Visser et al., 1996).

Moreover, the discrepancy between the measurements can be understood when considering how each measurements are aimed to observe different facets of impulsivity. Aforementioned in the introduction, impulsivity is a multifaceted human characteristic existing in different dimensions whether it happens in a cognitive level or in a behavioral level or in a social level. While UPPS-P was developed on the basis of the FFM to include lack of premeditation, sensation seeking, lack of perseverance, and urgency (Whiteside & Lynam, 2001), it does not encompass the entire scope of impulsivity. According to Basar and colleagues (2010), Stroop task assesses the reflection facet of impulsivity as it measures the failure to ignore information that is irrelevant to the execution of a desired response. Impairment in these forms of cognitive inhibition is thought to influence behavior. This is not a factor included in the UPPS-P.

Furthermore, although MSIT has been developed based on Stroop and other tasks measuring inhibitory control, it has its limitations in that its primary purpose of development was not to assess impulsivity or inhibitory performances but to observe robust and salient neural activation signals using brain scanners, especially in dorsal ACC (Bush et al., 2003). It also differs from Stroop in that while the Stroop task is an assessment of visual processing and language, MSIT measures visual attention and motor inhibition. To reiterate, although these two tasks are similar in that it primarily measures inhibitory control, they are different in the cognitive domain that they measure. To add, there may be environmental factors that could have influenced the subjects' performance on these tasks; while Stroop task was performed in a quiet room in front of an administrator, MSIT was performed within the MRI machine as the subject lied down still to view to visual stimuli on a screen with a set of buttons at hand. Presence of an administrator assessing the task may have influenced the performances of subjects whether it may be stronger motivation or performance anxiety or some other psychological influence.

4.2. Impulsivity and the Brain

4.2.1. Brain Morphology

Confirming the second hypothesis, the impulsivity measures each showed correlations to different areas of the brain. Only statistical results that survived p-FDR correction was considered for interretation. SI was negatively correlated with bilateral CN and PT SVadj, while Macc was positively correlated with left dlPFC, left OFC, left mPFC, left ACC, right OFC, and right ACC CT. These findings present a number of issues to be considered for discussion: (1) why had not UPPS-P factors have any brain morphology correlates, (2) why had SI only shown strong correlation with the subcortical areas and why was this not the case for M_{acc} and vice versa, (3) what are the valid, theoretical reasons for each of the correlates, and, finally, (4) what does the directionality of these correlation imply for adolescent impulsivity and the brain?

To answer the first question, one may think back to the origin of each impulsivity measure and what constitutes impulsive personality, behavior, or temperament. As stated by Basar and colleagues (2010), failure in cognitive control is tightly linked to and may precede the subsequent maladaptive behaviors. In another words, cognitive control and behavior may lie in different steps or levels of dimensions that constitute impulsivity (Andrews–Hanna et al., 2011; Lansbergen et al., 2007). If this stands true, it is possible that inhibitory control does neither correlate with the behavioral, temperamental measures nor share the same neurological correlates with them.

Another answer to the first question may be due to unevitable biases that may exist when engaging in certain types of impulsivity measurements. UPPS–P asks one to make predictions about one's thoughts and actions in imagined situations by reflecting on one's own past tendencies, preferences, thoughts, and behaviors. SI and MSIT, meanwhile, are more implicit measurements of one's cognitive ability. Considering UPPS–P's inevitable limitation to rely on subjective judgement, reminiscence, and environmental or parental influences, SI and MSIT may take the upper hand to more closely resemble the brain's biology.

The second question leads one to consider the fundamental differences between the Stroop task and MSIT. As explained previously, subjects utilize different cognitive domains of either language or visual and motor inhibition to engage in each tasks and this may be one of the possible reasons for why Stroop task and MSIT each had different neural correlates. Regarding how CT is related to the Stroop task, Tamnes and colleagues (2010) have reported that levels of performance on Stroop tasks were not significantly related to any regions' CTs. Previous studies that investigated the relationship between CT and executive functions may aid in understanding the lack of correlation between inhibitory measures and CT; some studies have reported that in adolescents and in the elderly, only general intellectual abilities, not performances on specific behavioral indices, were more closely related to the macro-structural brain properties such as CT (Fjell et al., 2006; Shaw et al., 2006; Tamnes et al., 2010).

However, to simply argue that macro-structural brain indices are uncapable to relate to any specific cognitive functions may not be valid when considering the significant correlation existing between MSIT performance and CTs. Yet cautious interpretation is necessary when examining the relationship between adolescent brain morphology and MSIT since there are no existing previous studies on the subject. As aforementioned, MSIT was a task developed with the main purpose of observing strong neural activation, specifically in the dorsal ACC, in the brain scanner. The purpose of MSIT may have given it the advantage to closely relate to not only cortical activation but also CT.

The third question focuses on the specific ROIs the impulsivity measures were correlated to and how these areas contribute to cognitive and behavioral performances. The stroop interference score was strongly correlated with the bilateral dorsal striatum (CN and PT) volume, while Macc was related to left dlPFC, bilateral mPFC, and bilateral ACC CT. It is interesting to note that while NA, or the ventral striatum, has been highlighted in previous studies as the central subcortical region to influence impulsivity, it was the bilateral dorsal striatum that was significantly correlated with SI. NA has been known through numerous functional neuroimaging studies for its involvement in (1) reinforcement learning and assessment of outcome-predicting stimuli with regards to valence and salience and (2) reward anticipation (Basar et al, 2010; Knutson & Cooper, 2005; McClure et al., 2004; Smith et al., 2009; Yacubian et al., 2006). NA D2/3 receptors were in fact found to predict trait impulsivity in impulsive rats (Dalley et al., 2007). However, there are no previous studies reporting activity in the NA in fMRI studies using response inhibition tasks for humans (Basar et al., 2010); Horn and colleagues (2003) have failed to report such correlation in normal subjects using the Go/No Go task and fMRI.

When investigating the relationship between striatum morphology, cognitive control deficits, and symptom severity in internet gaming disorder, Cai and colleagues (2015) reported that while the CN volume was negatively correlated with Stroop task performance, NA was associated with the internet addiction test score in the subjects with internet gaming disorder in early adults. The contradicting directionality of the relationship compared to this study's results is discussed when answering the fourth question. Left PT, meanwhile, was also reported to activate during Stroop task and was speculated by Pardo and colleagues (1990) for its role in processing high-level sensory encoding of the visual information. Furthermore, when young adult subjects engaged in the Stroop task, dorsal striatum blood-oxygenation-level-dependent response (BOLD) signal correlated with the interference subjects experienced during trials with increased cognitive control demands (Robertson et al., 2015). This report may provide another insight as to why only Stroop but not MSIT showed correlation with the dorsal striatum: MSIT was not as cognitively demanding compared to Stroop. One may suspect a possible ceiling effect in the subjects' MSIT performances based on their high average and small score variance.

Besides dorsal striatum's direct involvement in Stroop task performances, there has been studies on its relationship with impulsivity and reward processing. CN has also been reported to have a major role in reward-based behavioral learning, which makes the area as important as the NA when discussing impulsivity (Delgado, 2007; Haruno et al., 2004). In studies with rodents, it has been found that while the ventral striatum is involved in affective and motivational processing, the dorsal striatum has a role in the cognitive and sensorimotor functions related to reward related response learning (Graybiel et al., 1994; Packard & Knowlton, 2002; White & McDonald, 2002). Delgado (2007) specifically pointed out the role of CN based on previous findings that the region is an integral component of a circuit involved in learning and updating rewards to guide the behavior that will maximize reward consumption. In summary, the SI' s relationship with the dorsal striatum may indicate dorsal striatum' s role in the cognitive control aspect of impulsivity.

Those cortical areas that M_{acc} have shown correlation to are areas well known to be associated with impulsivity and inhibitory control. First of all, as previously mentioned, MSIT was developed with the purpose of observing strong activation of the dorsal ACC (Bush et al., 2003). Therefore M_{acc}' s relationship with the thickness of the bilateral ACC was well foreseen. ACC is known through past studies to possibly mediate the processing selection in attentional conflict paradigms (Pardo et al., 1990) and be involved in performance monitoring, selecting target, inhibiting response, and processing reward (Bush et al., 2005; Tian et al., 2006; Yu-Feng et al., 2007). The mPFC are also discussed as one of the critical regions that if damaged can result in poor impulse control (Horn et al., 2003). In terms of cognitive control, mPFC is found to be involved in performance monitoring, evaluating outcome expectancy, and detecting performance errors or conflicting response tendencies (Ridderinkhof et al., 2004); these functions are all involved in MSIT performance. Last but not the least, studies have shown that dlPFC is involved in inhibitory control, especially in response inhibition in motor inhibitory control (Asahi et al., 2004). The results of this study have shown that the subjects in their early adolescents show better inhibitory control when they have larger dorsal striatal SV and thinner prefrontal CTs.

The directionality of each of the correlations are partially in line with the developmental trajectory of the brain morphology. The present study’ s participants are in their early adolescents; their brains are maturing physically which is followed by development of their cognitive functioning and behavior. Longitudinal studies have consistently reported that prefrontal CT decrease with age (Mills et al., 2014; Raznahan et al., 2014; Squeglia et al., 2013). Possible reasons behind the cortical thinning is speculated to be due to such factors including synaptic pruning and myelination (Galvan et al., 2006). Many studies have also shown that thinner prefrontal CT relates to lower impulsivity and better performance in inhibitory control, which may imply that thinner, more developed cortices are capable of better cognitive control (Mackey et al., 2015; Shaw et al., 2006; Squeglia et al., 2013, Tamnes et al., 2010).

Meanwhile, there also are reports with contradicting results especially regarding adolescent impulsive choice making (Pehlivanova et al., 2018; Schilling et al,, 2013). Divergent relations between trait impulsivity and different regions' CT and surface area were also found in cocaine using adults: impulsivity was negatively correlated with superior temporal cortex and INS but positively associated with ACC (Kaag et al., 2014). This mismatch of the reports may be due to the fact that while this study's impulsivity measures mainly centered on the inhibitory control aspect of impulsivity, studies like that of Pehlivanova and colleagues focused on impulsivity that involves reward and perseverance. Another difference that exists between this study and those with contradicting results is that this study's subject age range was small (12 years to 14 years) focusing only on early adolescents, while other studies' subject ages ranged from early childhood (as early as 9 years of age) to early adulthood (as late as 24 years of age). Multiple reports regarding the relationship between impulsivity, addiction, and risky behaviors and CT with adults have stably shown that cortical thinning in the prefrontal cortex may be one of the characteristics of impulsive behaviors in adults (Kuhn et al., 2010; Schilling et al., 2012). It may be that this study was able to capture the intricate change in relationship between impulsivity and inhibitory control in the early adolescents compared to those studies that observed the entire developmental stages.

Unlike CT, the results regarding SV, at first glance, seem not to fit the existing findings on the developmental trajectory of the dorsal striatum. While Raznahan and colleagues (2014) have reported that the striatum volume takes and "inverted-U" shaped trajectory, other studies have consistently shown that striatal volume decreases with age (Østby et al., 2009; Sowell et al., 2002). However, the negative correlation between dorsal striatum SV and SI can also be understood in terms of the dual systems model. Adolescents have been reported to show faster reaction times in inhibitory tasks compared to children and adults, implying their tendency to make rash decisions (Williams et al., 1999). The aforementioned the positive correlation between Stroop performance and CN SV in Cai and colleagues' study may be showing specific characteristics of young adults (average age 17.9±0.9 years) that are different from that of early adolescents. These in all may suggest that while the cortices become thinner as they slowly develop to control the impulsive urges, the subcortical areas that have developed faster takes dominance in cognition and behavior during adolescents to urge them into impulsive behaviors. This phenomena may continue till the fronto-striatal connectivity and cortices fully develop to allow for better cognitive control.

4.2.2. Brain Resting State Connectivity

Those areas that showed significant statistical correlation in their morphology with the impulsive measures were chosen as seeds for their resting state connectivity. When SI was observed for its main effect on the bilateral dorsal striatum's resting state connectivity, SI showed positive correlation with the connectivity between the left PT and the right temporal pole. It was also negatively correlated with right CN’ s connectivity with the right INS and the right lateral occipital cortex.

The correlated cortical regions were not prefrontal areas, which are the areas that were previously known to be strongly involved in inhibitory control (Kelly et al., 2004; Mills et al., 2014; Vijayakumar et al., 2014; Whelan et al., 2012). However, similar results have been reported by Ding and colleagues (2013) for the resting state connectivity of adolescents with internet gaming addiction; participants with internet gaming addiction exhibited increased functional connectivity in the middle temporal gyrus and the bilateral cerebellum posterior lobe, and decreased functional connectivity in the inferior parietal lobule and right inferior temporal gyrus. Several studies regarding impulsivity in adults found areas within the temporal lobe to contribute to impulsivity and inhibitory control (Horn et al., 2003; Kaag et al., 2014).

One possible explanation for these findings may be that while cognitive processes primary supported by the prefrontal circuits are foundations for more strategic performances that may vary greatly per subject, temporal and parietal areas take their role in more basic cognitive processes like response inhibition that may vary to a far lesser degree among subjects (Collette et al., 2005). Another explanation may be that the nature of adolescent resting state connectivity and how adolescents execute cognitive control differ from those of adults. Humans utilize different areas of the brain for successful cognitive and executive performance depending on their developmental stages. In a study with 10 to 26 year-old subjects, Cingulo-Opercular/Salience (CO/Salience) network in the resting state connectivity was found to have robust effect of age in the late adolescent stage when engaging in adult-level inhibitory response (Marek et al., 2015). The CO/Salience network is composed of anterior INS/operculum, dorsal ACC, thalamus, and PT (Sadaghiani & D' Esposito) and its increased integration predict faster reaction time on inhibitory control tasks (Marek et al., 2015; Ordaz et al., 2013; Velanova et al., 2008). Marek and collagues found that while the organization of resting state networks do not change with age, they become more integrated mainly in the CO/Salience network with age allowing them to reach maturity in their cognitive control. This finding agrees with the imbalance model. During the early adolescent stage, the main regions that drive the increase in the integration of the CO/Salience network were found to be the right anterior INS, bilateral dorsal ACC, anterior and mediodorsal nuclei of the thalamus, and PT (Marek et al., 2015). The findings from the present study are in the similar with the developmental trajectory of the resting state, as the weaker connectivity between the right CN and right INS were in fact related with poorer inhibitory control. At the same time, in early adolescents, regional increases mostly occur mainly in the somatomotor network, which encompasses the occipital, parietal, and temporal lobes (Marek et al., 2015). These areas may be needed for visual processing necessary for Stroop performance and also may be areas that adolescents utilize for cognitive control and processing before full neural network maturity. Meanwhile, a study with adults and the relationship between their resting state connectivity and cognitive control performances showed that the basal ganglia network and somatomotor network connectivity explained a considerable amount of variance in the Simon task performance (Haag et al., 2015). It is a possibility that the results of this study may be portraying how early adolescents are in the beginning stages of incorporating mature networks necessary for inhibitory control.

Interestingly, M_{acc} main effect was not observed when its equivalent CT regions were designated as seeds. This may be due to the limitation in the methods: the Destrieux Atlas used in cortical parcellation and labeling for measuring CT did not perfectly match the Harvard Oxford Atlas used for resting state connectivity analysis. The discrepancy existing between the seed regions and CT labels may have made the existing correlation unobservable.

The correlations existing between the impulsivity measures with the brain morphology and brain resting state connectivity did not perfectly align with one another. This phenomenon has also been observed by Kuhn and colleagues (2014) where they failed to associated the correlation pattern existing between pornography consumption and brain morphology and the pattern between pornography consumption and brain resting sate connectivity. It may be that brain morphology and resting state functional connectivity each have different explanatory factors of impulsivity and inhibitory control.

4.3. Limitations and Conclusions

Present study has shown that, in early adolescents, while self-reported impulsivity measure had weak correlations with brain morphology and resting state connectivity, inhibitory control task performances showed strong neural correlates. SI and MSIT scores each had unique neural correlates, although they both showed that weak inhibitory performances was related to smaller SV and thicker CT. Although the relationship between the impulsivity measures and the resting state connectivity were not found within the study' s ROIs, the results were not farfetched considering the shift in the intrinsic network connectivity that occurs in the early adolescent brain. This study provided insight as to the different dimensions of impulsivity and how these dimensions relate to the brain in early adolescents.

Meanwhile, the study also entails a number of limitations. This study is a cross-sectional study that observed normal, Seoul metropolitan region dwelling subjects within a small age range of 12 to 14. A longitudinal study with subjects from diverse age groups would be preferable to observe the drastic age effect and developmental change in behavior and neural mechanisms. A more heterogeneous group of subjects with varying degrees of severity in impulsivity may have allowed for stronger correlational observations. Moreover, the reliability of the self-reported impulsivity scores may have been stronger if parental or observer reports were also provided. Utilizing tasks that measures all the hypothetical facets of impulsivity including not only inhibitory control but also reward sensitive decision making would have drawn a clearer picture of the relationship between the impulsivity constructs and the brain. Lastly, there had been reports of significant difference in impulsivity and the related brain regions between the two sexes (Cross et al., 2011; Kogachi et al., 2016; Silveri et al., 2006). There are also difference in the brain maturation trajectory reported between the two sexes (Raznahan et al., 2014; Sowell et al., 2002). This study did not explore the possible differences each gender might have in regards to the hypotheses. Future studies should investigate the relationship between self-report and task-based impulsivity measures with brain morphology and intrinsic network connectivity longitudinally with narrow observation gaps in between to capture the intricate behavioral and neural changes that occur through early adolescents to late adolescents. How the different facets of impulsivity relates to future developmental neural/cognitive/behavioral outcome would also further deepen our understanding of adolescent impulsivity.

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Appendix 1.

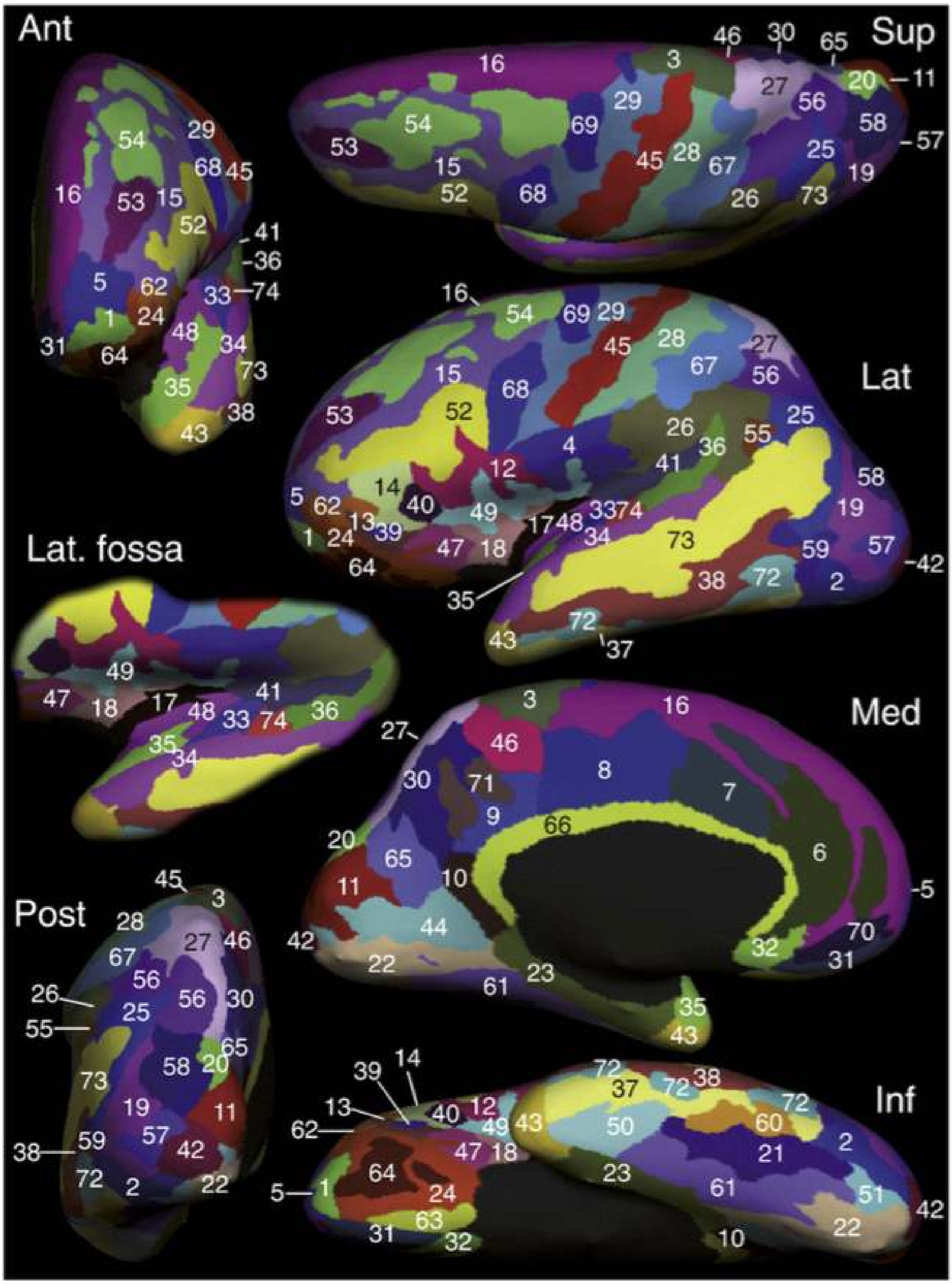
UPPS-P

문항	매우 동의함	약간 동의함	약간 반대함	매우 반대함
1. 나는 삶에 대해서 신중하고 조심스러운 태도를 가지고 있다.	1	2	3	4
2. 나는 충동을 통제하는 데에 어려움이 있다.	1	2	3	4
3. 대체로 나는 새롭고 흥미로운 경험과 감각을 쫓아다닌다.	1	2	3	4
4. 대체로 나는 어떤 일을 끝까지 해내려고 한다.	1	2	3	4
5. 매우 행복하다고 느낄 때는 나쁜 결과를 초래할 수도 있는 행동을 멈출 수가 없을 것 같다.	1	2	3	4
6. 나의 사고방식은 보통 신중하고 목적지향적이다.	1	2	3	4
7. 나의 욕구(음식, 담배 등에 대한)에 저항하는 것이 어렵다.	1	2	3	4
8. 나는 어떤 일이든 일단 시도해보려고 한다.	1	2	3	4
9. 나는 쉽게 포기하는 경향이 있다.	1	2	3	4
10. 아주 기분이 좋을 때, 나는 나에게 문제가 될 수 있는 상황에 빠져 드는 경향이 있다.	1	2	3	4
11. 나는 생각 없이 말을 내뱉는 사람이 아니다.	1	2	3	4
12. 나중에 빠져 나오기를 원하는 일에 종종 말려들곤 한다.	1	2	3	4
13. 나는 재빠르게 다음 움직임을 선택해야 하는 운동경기나 게임을 좋아한다.	1	2	3	4
14. 끝내지 못한 과제는 나를 정말 신경 쓰이게 만든다.	1	2	3	4
15. 매우 행복하다고 느낄 때, 나는 내 삶에 문제를 야기할지도 모르는 일을 해버리는 경향이 있다.	1	2	3	4
16. 나는 어떤 일을 하기 전에 멈춰서 숙고하기를 좋아한다.	1	2	3	4
17. 기분이 나쁠 때면 당장 기분이 좋아지게 하기 위해서 나중에 후회할 일을 종종 하게 된다.	1	2	3	4
18. 나는 수상스키를 즐길 것 같다.	1	2	3	4
19. 일단 어떤 일을 진행하기 시작하면, 도중에 중단하는 것이 싫다.	1	2	3	4
20. 기분이 아주 좋을 때, 나는 통제력을 잃어버리는 경향이 있다.	1	2	3	4

문항	매우 동의함	약간 동의함	약간 반대함	매우 반대함
21. 어떤 프로젝트를 시작하기 전에 나는 그 일이 어떻게 진행되는지를 정확하게 알려고 한다.	1	2	3	4
22. 기분이 나쁠 때면 가끔씩, 내가 하고 있는 일이 내 기분을 더 나쁘게 하더라도 그 일을 멈추기가 어렵다.	1	2	3	4
23. 나는 모험하는 것을 상당히 즐긴다.	1	2	3	4
24. 나는 쉽게 집중할 수 있다.	1	2	3	4
25. 강렬한 환희를 느낄 때, 나는 통제력을 상실하는 경향이 있다.	1	2	3	4
26. 나는 낙하산 점프를 즐길 것 같다.	1	2	3	4
27. 나는 시작한 일은 완수한다.	1	2	3	4
28. 나는 어떤 일을 할 때 합리적이고 이성적인 접근을 중시하며 그렇게 하는 편이다.	1	2	3	4
29. 속이 상할 때, 나는 종종 생각 없이 행동하곤 한다.	1	2	3	4
30. 다른 사람들은 내가 어떤 일로 기분이 매우 좋아졌을 때 잘못된 선택을 한다고 말하곤 한다.	1	2	3	4
31. 나는 다소 두렵고 이색적인 것일지라도 새롭고 자극적인 경험과 감각을 좋아한다.	1	2	3	4
32. 나는 일이 제때에 마무리되도록 스스로 속도조절을 할 수 있다.	1	2	3	4
33. 나는 대개 신중한 숙고를 통해 결정을 내린다.	1	2	3	4
34. 거부당했다고 느끼게 되면, 나는 종종 나중에 후회할 말을 하게 된다.	1	2	3	4
35. 다른 사람들은 내가 매우 기분이 좋아 흥분했을 때 하는 행동에 대해서 충격을 받거나 우려한다.	1	2	3	4
36. 나는 비행기 조종법을 배우고 싶다.	1	2	3	4
37. 나는 항상 일을 마무리 짓는 사람이다.	1	2	3	4
38. 나는 조심성이 많은 사람이다.	1	2	3	4
39. 감정에 따라 행동하는 것을 억제하기 어렵다.	1	2	3	4
40. 어떤 일로 매우 기분이 좋아졌을 때, 나는 나쁜 결과를 가져올 수 있는 일을 하는 경향이 있다.	1	2	3	4

문항	매우 동의함	약간 동의함	약간 반대함	매우 반대함
41. 때때로 나는 다소 두려운 일을 하는 것을 좋아한다.	1	2	3	4
42. 나는 시작한 프로젝트는 거의 완수한다.	1	2	3	4
43. 새로운 상황에 들어가기 전에, 나는 그 상황에서 예상되는 일들을 알아보려고 한다.	1	2	3	4
44. 나는 기분이 나빠지면 생각 없이 행동하기 때문에 종종 문제를 악화시킨다.	1	2	3	4
45. 기쁨에 넘칠 때, 나는 극단적으로 행동하는 것을 멈추기가 어렵다고 느낀다.	1	2	3	4
46. 나는 높은 산비탈에서 빠르게 내려오는 스키의 감각을 즐길 것 같다.	1	2	3	4
47. 해야 할 사소한 일들이 너무 많아서, 때때로 나는 그것들을 모두 무시해버리곤 한다.	1	2	3	4
48. 대체로 나는 어떤 일을 하기 전에 신중하게 생각한다.	1	2	3	4
49. 어떤 결정을 하기 전에, 나는 유리한 점과 불리한 점을 모두 고려한다.	1	2	3	4
50. 정말 기분이 좋아 흥분할 때는 내 행동의 결과를 생각하지 않는 경향이 있다.	1	2	3	4
51. 논쟁이 격해지면, 나는 종종 나중에 후회할 말을 하곤 한다.	1	2	3	4
52. 나는 스쿠버 다이빙을 하고 싶다.	1	2	3	4
53. 정말 기분이 좋아 흥분했을 때, 나는 생각 없이 행동하는 경향이 있다.	1	2	3	4
54. 나는 내 감정들을 항상 잘 통제한다.	1	2	3	4
55. 기분이 매우 좋아졌을 때, 나는 평소라면 편안하게 느끼지 않았을 상황에 처하곤 한다.	1	2	3	4
56. 나는 빠른 속도로 운전하는 것을 즐길 것 같다.	1	2	3	4
57. 매우 기분이 좋을 때, 나는 욕구에 몸을 맡기거나 내 멋대로 해도 괜찮다고 느낀다.	1	2	3	4
58. 나는 때때로 나중에 후회할 충동적인 행동을 한다.	1	2	3	4
59. 기분이 매우 좋은 상태에서 내가 하는 행동에 대해 스스로 놀라곤 한다.	1	2	3	4

Appendix 2.



Index	Short name	Long name (TA nomenclature is bold typed)	Visible on views	CI_c		Area (cm^2)	
				Rh	Lh	Rh	Lh
1	G_and_S_frontomargin	Fronto-marginal gyrus (of Wernicke) and sulcus	A, L, I	0.68	0.73	7.71	9.55
2	G_and_S_occipital_inf	Inferior occipital gyrus (O3) and sulcus	L, P, I	0.56	0.75	10.74	13.22
3	G_and_S_paracentral	**Paracentral lobule and sulcus**	S, P, M	0.85	0.84	12.18	13.62
4	G_and_S_subcentral	Subcentral gyrus (central operculum) and sulci	L	0.78	0.77	11.54	12.24
5	G_and_S_transv_frontopol	Transverse frontopolar gyri and sulci	A, L, M, I	0.67	0.63	9.39	5.80
6	G_and_S_cingul-Ant	Anterior part of the **cingulate gyrus and sulcus** (ACC)	M	0.91	0.84	24.49	18.89
7	G_and_S_cingul-Mid-Ant	Middle-anterior part of the **cingulate gyrus and sulcus** (aMCC)	M	0.85	0.85	12.32	12.23
8	G_and_S_cingul-Mid-Post	Middle-posterior part of the **cingulate gyrus and sulcus** (pMCC)	M	0.86	0.88	13.25	12.38
9	G_cingul-Post-dorsal	Posterior-dorsal part of the **cingulate gyrus** (dPCC)	M	0.79	0.84	4.12	4.44
10	G_cingul-Post-ventral	Posterior-ventral part of the cingulate gyrus (vPCC, **isthmus of the cingulate gyrus**)	M, I	0.85	0.70	2.61	2.50
11	G_cuneus	**Cuneus** (O6)	S, P, M	0.83	0.85	15.41	14.52
12	G_front_inf-Opercular	**Opercular part of the inferior frontal gyrus**	L, I	0.78	0.83	9.98	10.43
13	G_front_inf-Orbital	**Orbital part of the inferior frontal gyrus**	L, I	0.49	0.31	3.15	2.77
14	G_front_inf-Triangul	**Triangular part of the inferior frontal gyrus**	L, I	0.76	0.81	7.88	7.79
15	G_front_middle	**Middle frontal gyrus** (F2)	S, A, L	0.83	0.85	30.67	34.29
16	G_front_sup	**Superior frontal gyrus** (F1)	S, A, L, M	0.90	0.90	52.97	57.05
17	G_Ins_lg_and_S_cent_ins	**Long insular gyrus and central sulcus of the insula**	L	0.79	0.78	4.98	4.61
18	G_insular_short	**Short insular gyri**	L	0.79	0.75	4.58	5.32
19	G_occipital_middle	Middle occipital gyrus (O2, lateral occipital gyrus)	S, L, P	0.77	0.77	17.01	16.68
20	G_occipital_sup	Superior occipital gyrus (O1)	S, L, P	0.68	0.76	11.98	10.66
21	G_oc-temp_lat-fusifor	**Lateral occipito-temporal gyrus** (fusiform gyrus, O4-T4)	I	0.85	0.85	13.60	13.48
22	G_oc-temp_med-Lingual	**Lingual gyrus**, ligual part of the **medial occipito-temporal gyrus**, (O5)	P, M, I	0.84	0.90	20.82	21.22
23	G_oc-temp_med-Parahip	**Parahippocampal gyrus**, parahippocampal part of the **medial occipito-temporal gyrus**, (T5)	M, I	0.89	0.92	13.48	14.44
24	G_orbital	**Orbital gyri**	A, L, I	0.85	0.86	20.57	18.79
25	G_pariet_inf-Angular	**Angular gyrus**	S, L, P	0.82	0.82	23.07	19.32
26	G_pariet_inf-Supramar	**Supramarginal gyrus**	S, L, P	0.79	0.83	19.58	23.18
27	G_parietal_sup	**Superior parietal lobule** (lateral part of P1)	S, L, P, M	0.80	0.81	18.77	22.04
28	G_postcentral	**Postcentral gyrus**	S, L, P	0.91	0.89	17.55	19.53
29	G_precentral	**Precentral gyrus**	S, A, L	0.91	0.91	22.55	22.22
30	G_precuneus	**Precuneus** (medial part of P1)	S, P, M	0.84	0.86	19.26	19.32
31	G_rectus	**Straight gyrus**, Gyrus rectus	A, M, I	0.84	0.84	5.80	7.11
32	G_subcallosal	**Subcallosal area, subcallosal gyrus**	M, I	0.61	0.60	2.41	2.13
33	G_temp_sup-G_T_transv	**Anterior transverse temporal gyrus** (of Heschl)	A, L	0.79	0.83	3.42	4.27
34	G_temp_sup-Lateral	Lateral aspect of the **superior temporal gyrus**	A, L	0.89	0.90	15.20	15.46
35	G_temp_sup-Plan_polar	Planum polare of the **superior temporal gyrus**	A, L, M	0.82	0.71	6.90	6.08
36	G_temp_sup-Plan_tempo	**Planum temporale or temporal plane** of the superior temporal gyrus	A, L	0.82	0.85	7.52	9.48
37	G_temporal_inf	**Inferior temporal gyrus** (T3)	L, I	0.81	0.81	18.05	21.27
38	G_temporal_middle	**Middle temporal gyrus** (T2)	A, L, P, I	0.88	0.84	22.59	20.52
39	Lat_Fis-ant-Horizont	Horizontal ramus of the **anterior segment of the lateral sulcus** (or fissure)	L, I	0.87	0.71	3.22	2.59
40	Lat_Fis-ant-Vertical	Vertical ramus of the **anterior segment of the lateral sulcus** (or fissure)	L, I	0.71	0.70	2.43	2.87
41	Lat_Fis-post	**Posterior ramus** (or segment) **of the lateral sulcus** (or fissure)	A, L	0.82	0.93	12.15	9.73
42	Pole_occipital	**Occipital pole**	L, P, M, I	0.67	0.70	23.43	14.62
43	Pole_temporal	**Temporal pole**	A, L, M, I	0.85	0.85	11.91	12.71
44	S_calcarine	**Calcarine sulcus**	M	0.91	0.94	18.51	19.69
45	S_central	**Central sulcus** (Rolando's fissure)	S, A, L, P	0.97	0.97	25.02	25.98
46	S_cingul-Marginalis	**Marginal branch** (or part) **of the cingulate sulcus**	S, P, M	0.87	0.92	11.23	9.88
47	S_circular_insula_ant	Anterior segment of the **circular sulcus of the insula**	L, I	0.81	0.82	5.05	4.39
48	S_circular_insula_inf	Inferior segment of the **circular sulcus of the insula**	A, L	0.84	0.87	11.13	13.27
49	S_circular_insula_sup	Superior segment of the **circular sulcus of the insula**	L, I	0.84	0.83	12.50	15.06
50	S_collat_transv_ant	Anterior transverse collateral sulcus	I	0.87	0.84	8.81	8.63
51	S_collat_transv_post	Posterior transverse collateral sulcus	I	0.64	0.69	4.43	3.93
52	S_front_inf	**Inferior frontal sulcus**	S, A, L	0.77	0.86	18.17	20.68
53	S_front_middle	Middle frontal sulcus	S, A, L	0.77	0.67	17.16	12.65
54	S_front_sup	**Superior frontal sulcus**	S, A, L	0.87	0.83	23.64	25.82
55	S_interm_prim-Jensen	Sulcus intermedius primus (of Jensen)	S, L, P	0.55	0.58	4.88	3.83
56	S_intrapariet_and_P_trans	**Intraparietal sulcus** (interparietal sulcus) and transverse parietal sulci	S, L, P	0.79	0.85	28.44	27.14
57	S_oc_middle_and_Lunatus	Middle occipital sulcus and lunatus sulcus	S, L, P	0.84	0.88	8.29	9.55
58	S_oc_sup_and_transversal	Superior occipital sulcus and **transverse occipital sulcus**	S, L, P	0.88	0.87	12.70	10.38
59	S_occipital_ant	Anterior occipital sulcus and **preoccipital notch** (temporo-occipital incisure)	L, P	0.50	0.51	6.64	6.60
60	S_oc-temp_lat	Lateral occipito-temporal sulcus	I	0.77	0.72	9.13	8.53
61	S_oc-temp_med_and_Lingual	Medial occipito-temporal sulcus (**collateral sulcus**) and lingual sulcus	M, I	0.90	0.90	18.57	19.40
62	S_orbital_lateral	Lateral orbital sulcus	A, L, I	0.63	0.72	3.46	3.13
63	S_orbital_med-olfact	Medial orbital sulcus (**olfactory sulcus**)	I	0.96	0.95	5.60	5.34
64	S_orbital-H_Shaped	**Orbital sulci** (H-shaped sulci)	I, L	0.96	0.96	12.84	12.19
65	S_parieto_occipital	**Parieto-occipital sulcus** (or fissure)	S, P, M	0.90	0.95	17.70	17.13
66	S_pericallosal	Pericallosal sulcus (**S of corpus callosum**)	M	0.94	0.86	10.21	9.08
67	S_postcentral	**Postcentral sulcus**	S, L, P	0.87	0.89	21.32	25.27
68	S_precentral-inf-part	Inferior part of the **precentral sulcus**	S, A, L	0.88	0.85	14.92	13.58
69	S_precentral-sup-part	Superior part of the **precentral sulcus**	S, L	0.85	0.83	12.16	12.16
70	S_suborbital	Suborbital sulcus (sulcus rostrales, supraorbital sulcus)	M	0.60	0.60	2.74	5.67
71	S_subparietal	**Subparietal sulcus**	M	0.84	0.91	10.92	9.21
72	S_temporal_inf	**Inferior temporal sulcus**	L, P, I	0.72	0.69	11.04	13.63
73	S_temporal_sup	**Superior temporal sulcus** (parallel sulcus)	S, A, L, P	0.91	0.93	54.83	49.45
74	S_temporal_transverse	**Transverse temporal sulcus**	A, L	0.72	0.70	2.59	3.24

Note. Dextrieux Atlas: A gyral morphology based atlas dividing the cortical surface into 75 areas. Pial surface color coded image and table provided by Freesurfer (https://surfer.nmr.mgh.harvard.edu/fswiki/CorticalParcellation).

Abstract in Korean

청소년 충동성은 치명적인 결과를 야기할 수 있는 청소년 위험 행동의 주원인 중 하나이다. 본 연구는 자기보고 및 억제수행으로 측정된 충동성의 다측면 간의 상관관계를 살펴보고 이러한 측정치들이 발달 중인 청소년 뇌와 어떠한 관계를 지니는지 탐색했다. 뇌 형태와 고유 연결성은 기능적 자기 공명 영상을 통해 측정되었다. 그 결과 충동성의 다측면 간에는 그 어떤 상관관계도 발견되지 않았다. 낮은 수준의 억제 수행을 보일 수록 등쪽 선조체 부피가 작았고, 전두엽의 다양한 영역들의 두께와 컸다. 억제 수행은 또한 좌측 피곡과 우측 측두극 사이의 연결과 정적 상관을 보였고, 우측 미상핵과 우측 대뇌섬 및 측면 후두엽 사이의 연결과 부적 상관을 보였다. 본 결과는 충동성 측정치들 간의 차원적 차이가 존재함을 암시하며, 충동성과 인지조절에 청소년 특이적 신경학적 체계가 존재하는 것을 보여준다.