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ORIGINAL PAPER

Brain gray matter correlates of general psychological need satisfaction: a voxel-based morphometry study

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Abstract
Basic psychological needs lie at the heart of the self-determination theory (SDT) explanatory framework. SDT researchers have recently undertaken neuroscientific programs of research to investigate the neural bases of psychological need satisfaction, and many have done so by using functional neuroimaging data collection methods. According to these studies, the activities of the striatum, orbitofrontal cortex (OFC), insula, and anterior cingulate cortex (ACC) represent central neural mechanisms of psychological need satisfaction. These findings led us to now investigate the possibility that people might possess individual differences in the capacity to experience need satisfaction and that these individual differences would be based on differences in their structural brain volumes in these brain areas. Region of interest and whole-brain voxel-based morphometry analyses of 50 participants' anatomic MRI scans to predict their self-reported need satisfaction over the last year found that only ventral striatum gray matter volume, but not the gray matter volumes of the dorsal striatum, OFC, insula, and ACC, positively correlated with extent of psychological need satisfaction. These neuroanatomic findings offer unique insights to understand the neuroanatomic bases of psychological need satisfaction.

Keywords Basic psychological need theory · Nucleus accumbens · Self-determination theory · Ventral striatum · Voxel-based morphometry

Self-determination theory (SDT) is an organismic theory of motivation and personality to explain human flourishing (Ryan and Deci 2017; Vansteenkiste et al. 2010). According to SDT, people have inherent and spontaneous propensities that, when supported by environmental conditions, enable adaptive functioning, development, and wellness. In particular, the basic psychological need theory (BPNT) suggests that the basic psychological needs of autonomy, competence, and relatedness lie at the heart of the SDT explanatory framework. Though all people have the same set of basic psychological needs irrespective of their age, gender, culture, and other demographics, SDT acknowledges that the capacity to experience psychological need satisfaction and autonomous motivation more generally may arise as an individual difference characteristic that stems from some people having a developmental history of being exposed to need-satisfying and autonomy-supportive relationships and environments while other people have a developmental history of being exposed to need-frustrating and interpersonally-controlling relationships and environments (Deci and Ryan 1985; Reeve et al. 2018; Ryan and Connell 1989). If so, then people may develop, over time, differential capacities to experience psychological need satisfaction.

Psychological need satisfaction has traditionally been investigated as a psychologically-experienced phenomenon that reflects subjective experience that can be reported in a reliable way on a self-report questionnaire (Chen et al. 2015). Recently, researchers interested in BPNT have undertaken neuroscientific programs of research to discover the neural bases of the psychological need subjective experience that can be measured objectively using neuroimaging

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methodologies, such as functional magnetic resonance imaging (fMRI; Lee and Reeve 2013, 2017; Marsden et al. 2015; Murayama et al. 2010) and electroencephalogram (EEG; Di Domenico et al. 2016; Legault and Inzlicht 2013; Zougkou et al. 2017). These researchers have conducted a number of neuroimaging studies to identify the functional activations of the brain areas associated with the moment-to-moment experience of psychological need satisfaction. Primarily, the functional activations of the striatum, orbitofrontal cortex (OFC), insula, and anterior cingulate cortex (ACC) have consistently been observed, which suggests that reward processing and self-related processing appear to be central in the neural processes of basic psychological needs (Di Domenico and Ryan 2017; Lee 2017; Reeve and Lee 2019a).

Numerous functional neuroimaging studies have consistently demonstrated that the striatum, particularly the ventral part of the striatum, and OFC are the key brain areas for reward processing. The striatum is divided into a ventral (lower) division, which consists mainly of the nucleus accumbens (but also the ventral parts of the caudate nucleus and putamen), and a dorsal (upper) division, which consists of the dorsal parts of the caudate nucleus and putamen (Haber 2011). The "Actor-Critic" model suggests that the ventral striatum plays a key role in the hedonic reactions to rewarding and pleasurable stimuli or situations while the dorsal striatum utilizes the hedonic information to regulate decision-making, self-control (e.g., delay of immediate gratification), and goal-directed action (O'Doherty et al. 2004). The hedonic information formulated in the ventral striatum is relayed as value-based information to and stored in the ventral parts of the prefrontal cortex (e.g., OFC), and then the value-based information is represented and compared with other values in a same scale when it is needed during the decision-making processes (Montague and Berns 2002; O'Doherty et al. 2001). Neuroimaging studies about BPNT have recently suggested that the brain areas related to reward processing are crucial not only for human motivation initiated and regulated by external forces but also for human motivation initiated and regulated by internal forces (Murayama et al. 2010, 2015; Lee and Reeve 2017).

The neural activities of the insula and medial frontal cortex (e.g., ACC) are generally observed in the self-related processes (Craig 2009; Enzi et al. 2009). The insula receives, monitors, becomes aware of changes in interoceptive (visceral, homeostatic) bodily states, and constructs a consciously-aware representation of how one feels (Craig 2009). People consolidate this "gut-felt" feeling-state information with social-contextual information about the task they are involved in and the people around them to form a basis of the conscious experience (subjective awareness) of "How I feel" (Craig 2009). The medial frontal cortex, particularly the ACC, is a well-known brain area for conflict detection (Bush et al. 2002). That is, the ACC detects conflicts or errors, switches plans or strategies based on the error-related information, calculates costs (e.g., mental effort), and supports self-control during the execution of the switched goal-directed action. Particularly, the interactions between the insula and ACC are crucial for higher-order conscious processes of human beings, which is supported by their anatomic interconnections via larger and faster processing neurons called von Economo neurons (Allman et al. 2010). Neuroimaging studies about BPNT have also observed the neural activities of the insula and ACC as well as the neural activities of the striatum during the processes of self-determination (Lee and Reeve 2013; Leotti and Delgado 2011).

Some functional neuroimaging studies have examined individual differences in participants' perceptions of psychological need satisfaction (Di Domenico et al. 2016) or autonomous motivation (Lee and Reeve 2013; Legault and Inzlicht 2013), but there has been no voxel-based morphometry (VBM) study directly investigating the possibility that differences in brain structure underlie possible differences in the capacity to experience psychological need satisfaction in people's daily lives. Though the VBM can identify inter-individual differences in experience-dependent gray matter volume changes (Mechelli et al. 2005), there have only been a handful of VBM studies about the psychological constructs related to human motivation initiated and regulated by internal forces. Among the handful of studies, the results have been inconsistent. For example, Hashimoto and colleagues (2015) found that the gray matter volumes of the ventral and dorsal striatum, insula, OFC, and ACC showed positive anatomic relationships with the degree of the sense of personal control. Takeuchi and colleagues (2014) found, however, that the gray matter volumes of the OFC showed negative anatomic relationships with the degree of self-fulfilled achievement motivation. Furthermore, Ming and colleagues (2016) found negative anatomic correlations between OFC gray matter volume and approach motivation and between ACC gray matter volume and avoidance motivation.

By brain structure, we mean the gray matter volume of particular brain structures. People's brain sizes vary, so the person's overall brain size is treated as a covariate in determining the gray matter volume of any one brain structure. The volume of a brain structure is mostly a function of genetics and maturation, but it is also affected by variations in environmental conditions. For instance, maternal sensitivity (i.e., how timely and accurate a mother's responsiveness is to the infant's distress signals) significantly affects limbic structure (e.g., hippocampus, amygdala) volumes (Rifkin-Graboi et al. 2015). We investigated the possibility that people might possess individual differences in the capacity to experience psychological need satisfaction and that these individual differences would be based on differences in their structural gray matter volumes in their striatum, OFC, insula, and ACC. The logic that led to the present investigation was that, because (1) neural correlates of the subjective experience of psychological need satisfaction have been fairly well established, (2) chronic environmental conditions affect the structural volumes of these same brain areas functionally related to psychological need satisfaction, (3) individual differences in these structural brain volumes may emerge over time to then affect experience and behavior, and therefore (4) individual differences in these identified structural brain volumes may predict the capacity to experience general psychological need satisfaction in life.

In the present study, we sought to investigate the extent to which the structural volume of each of these previously-established important brain areas might be related to the global experiences of psychological need satisfaction. As variations in gray matter volumes of brain areas reflect extent of experience-dependent neuroanatomic adaptation (Zatorre et al. 2012), we particularly examined which brain areas' gray matter volumes were associated with extent of general psychological need satisfaction. Considering the neural findings from the functional neuroimaging studies about psychological need satisfaction and autonomous motivation, we can hypothesize that the brain areas related to reward processing and self-related processing show *anatomic relations* with the degree of psychological need satisfaction. That is, the anatomic differences in people's gray matter volumes of the striatum (i.e., nucleus accumbens, caudate nucleus, putamen), OFC, insula, and medial frontal cortex (i.e., ACC) would predict people's general experiences of psychological need satisfaction in their daily lives.

Method

Participants

Fifty Korean undergraduates (25 females and 25 males; mean age 23.1 ± 2.72 years), recruited from a large private university in Seoul, Korea, participated in this VBM study that used a magnetic resonance imaging methodology. Data from 22 (44%) of these participants were taken from a previous functional neuroimaging study (Lee and Reeve 2017) so that we could test our hypotheses with a more sufficiently powered sample size (Faul et al. 2007). All participants were right-handed and had no history of neurological illness. The participants provided informed consent and received compensation for their participation. This study was approved by the institutional review board of Korea University.

Measure

General psychological need satisfaction

To assess the degree of generally experienced psychological need satisfaction in each participant's life, 6 items assessing the satisfaction dimension of the psychological needs for autonomy and competence were used.[1] We adopted these items from the Balanced Measure of Psychological Needs scale (BMPN; Sheldon and Hilpert 2012), a previously-validated and widely-used measure in BPNT literature (Sheldon and Schüler 2011; Young et al. 2015). Sample items, using the stem "During the last year…", include "My choices expressed my 'true self'" and "I was doing what really interests me" (autonomy satisfaction), and "I took on and mastered hard challenges" and "I was successful in completing difficult tasks and projects" (competence satisfaction). The BMPN scale also includes the scale to assess relatedness satisfaction, but we did not include the scale in the data collection because we focused only on the two psychological needs most directly related to intrinsically motivated processes. To complete our measure, participants responded on a 1 (*Strongly disagree*) to 7 (*Strongly agree*) scale. To translate the validated measure originally written in English into Korean, we followed the guidelines of Brislin (1980). Two graduate students who were fluent in both languages first carried out separate back-translations. Then, a consensus translation was reached after any discrepancies that emerged between the translators were discussed and eliminated. The six-item measure showed acceptable reliability ($\alpha = .75$), and autonomy and competence satisfaction showed a positive correlation ($r = .54$, $p < .01$) in the present study.

MRI data acquisition

A 3T Trio MRI scanner (Siemens, Erlangen, Germany) was used for anatomic imaging. High-resolution T1-weighted anatomic images were acquired by using a MP-RAGE

[1] The degree of generally experienced psychological need frustration was also assessed. Sample items were "I have had a lot of pressure on me that I could do without" (autonomy frustration) and "I have been doing things that made me feel incompetent" (competence frustration). The six-item measure showed acceptable reliability ($\alpha = .63$), and the correlation coefficient between general psychological need satisfaction and frustration was $r = -.34$ ($p < .05$). We could not, however, set a priori hypotheses about the brain gray matter correlates of general psychological need frustration because the functional neuroimaging studies about psychological need frustration are relatively sparse and because the neural findings from these studies are somewhat inconsistent. So, we had decided to focus on identifying the brain gray matter correlates of general psychological need satisfaction in the present study. The results of the ROI and VBM analyses of general psychological need frustration are presented in supplementary Tables.

Table 1 Partial correlations of gray matter volumes of the ROIs with general psychological need satisfaction after controlling for the effects of total gray matter volume, gender, and age

Brain area	Partial correlation with general psychological need satisfaction	
	Left side of brain	Right side of brain
Striatum		
Caudate nucleus (mostly dorsal striatum)	.21	.18
Putamen (mostly dorsal striatum)	−.10	−.13
Nucleus accumbens (ventral striatum)	.20	**.29***
Orbitofrontal cortex	.10	.23
Insula	.01	.03
Anterior cingulate cortex	.03	−.07

ROI region of interest

$N = 50$. * $p < .05$

sequence with the following parameters: TR = 1900 ms, TE = 2.52 ms, flip angle = 9°, field of view = 256 × 256, in-plane resolution = 1 × 1 mm, and slice thickness = 1 mm with no gap.

Imaging data analysis

Voxel-based morphometry

The imaging data were analyzed by the Computational Anatomy Toolbox (CAT12; http://www.neuro.uni-jena.de/cat/) implemented in the Statistical Parametric Mapping (SPM 12; http://www.fil.ion.ucl.ac.uk/spm/software/spm12/) software using the default setting. Each participant's brain volume was first segmented into gray matter, white matter, and cerebrospinal fluid for specifically examining the gray matter volumes. The gray matter volume values of the regions of interest (ROIs), which were specified using the Hammers atlas (Hammers et al. 2003), in the native space were extracted. The gray matter volumes in the native space were then registered, normalized, and modulated using the DARTEL template in the Montreal Neurological Institute (MNI) space (Ashburner, 2007). After the quality of the segmentation and normalization was checked, the gray matter volume was spatially smoothed with an 8-mm full-width at half-maximum (FWHM) Gaussian kernel.

As group-level analyses, ROI VBM partial correlation analyses were conducted to identify whether the gray matter volumes of the brain areas related to reward processing and self-related processing were correlated with psychological need satisfaction (i.e., autonomy and competence satisfaction). In these analyses, participants' total gray matter volume, gender, and age were considered as covariates.

A whole-brain VBM regression analysis was additionally conducted to identify and confirm the brain gray matter correlates of psychological need satisfaction. In this analysis, participants' total intracranial volume, gender, and age were considered as covariates. We particularly considered total intracranial volume as a covariate instead of total gray matter volume because it is recommended for the modulated data set in the CAT12 pipeline (Gaser and Kurth 2017). For correcting multiple comparison inferences in this whole-brain analysis, the cluster-wise threshold (corrected $p < .05$) was employed, considering both the voxel-wise threshold ($p < .001$) and cluster size ($n > 71$, the minimum volume of 568 mm^3). This was determined based on the Monte Carlo simulation method (Forman et al. 1995) using the Analysis of Functional NeuroImages (AFNI; http://afni.nimh.nih.gov) software.

Results

To test our hypotheses, we conducted two types of group-level analyses. The first was ROI VBM partial correlation analyses to test the anatomic associations between the gray matter volumes of the ROIs and participants' self-reported scores on need satisfaction. The second was a whole-brain VBM regression analysis to confirm the results from the ROI VBM partial correlation analyses.

ROI VBM partial correlation analyses (Table 1) showed that there was a positive and statistically significant relation between the gray matter volume of the right nucleus accumbens and participants' general psychological need satisfaction scores ($r = .29$; $p < .05$). The scatter plot showing the positive relationship between the gray matter volume of the right nucleus accumbens and participants' general psychological need satisfaction is presented in Fig. 1. The gray matter volumes of other ROIs (i.e., bilateral caudate nucleus, putamen, OFC, insula, ACC, and left nucleus accumbens) did not show any statistically significant relations with the degree of participants' general psychological need satisfaction.

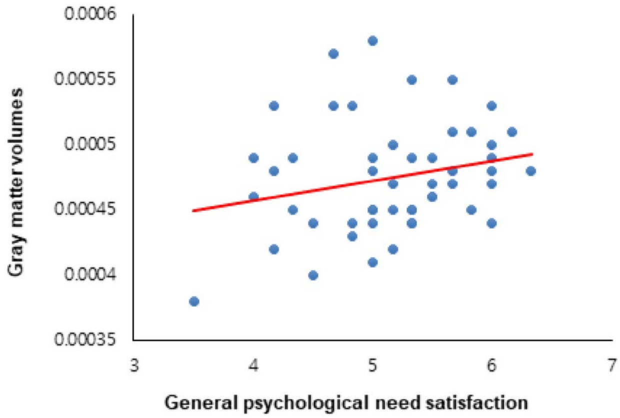

Fig. 1 A scatter plot showing the positive correlation between the gray matter volume of the right nucleus accumbens and participants' general psychological need satisfaction

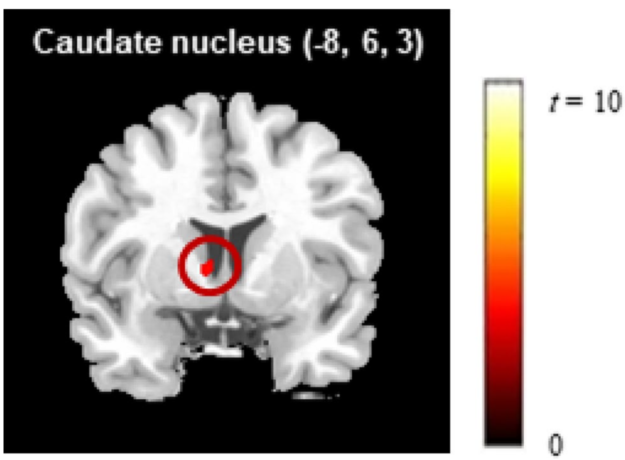

Fig. 2 The gray matter volume of the left ventral striatum (the ventral part of the caudate nucleus) was positively correlated with the degree of participants' general psychological need satisfaction (corrected $p < .05$)

A whole-brain VBM regression analysis also showed a positive and statistically significant relationship between the gray matter volume of the left ventral striatum (the ventral part of the caudate nucleus) and participants' general psychological need satisfaction (peak activations: − 8, 6, 3; maximum intensity value = 3.97; volume: 648 mm^3; corrected $p < .05$; Fig. 2). There were not any statistically significant relations between the gray matter volumes of other brain areas related to reward processing and self-related processing and participants' general psychological need satisfaction.

Discussion

The structure of each person's brain reflects, in part, his or her unique personal history (Cicchetti, 2002). Depending on the person's recurring exposures to environmental opportunities and sources of support versus restrictions and sources of abuse and neglect that can affect brain morphometry [e.g., cortisol (hormonal) episodes in response to environmental support versus stress; Reeve and Tseng 2011], the brain can change its structure, such as by forming new synapses, modifying existing synapses, growing more synapses per neuron, extending the lengths of dendrites, and growing dendritic spine density. It is now clear that environmental experiences of support-enrichment and of deprivation-frustration (e.g., parenting practices) influence brain morphometry (Belsky and de Haan 2011; Rifkin-Graboi et al. 2015; Sethna et al. 2017). So, in the present study, we investigated the possibility that existing differences in people's gray matter volumes in the brain areas related to reward processing and self-related processing might affect their capacity to experience greater or lesser psychological need satisfaction.

We found an anatomic association between the ventral striatum and general psychological need satisfaction. After controlling for the effects of overall brain size, gender, and age, the ROI VBM analyses showed a positive relation between participants' general psychological need satisfaction and right nucleus accumbens gray matter volume, and the whole-brain VBM analysis also showed a positive relation between participants' general psychological need satisfaction and the gray matter volume of the left ventral part of the caudate nucleus. The ventral striatum (which includes both the nucleus accumbens and the ventral parts of the caudate nucleus and putamen) is a well-known brain area for physiological need satisfaction (Robbins and Everitt 1996). In neuroscience, the hedonic experiences based on physiological need satisfaction (e.g., a cup of water for a thirsty person) can be explained by the neural activity of the ventral striatum (Reeve and Lee 2019b). Recent neuroimaging studies have consistently found that the functional activity of the ventral striatum is crucial not only for physiological need satisfaction but also for psychological need satisfaction. That is, ventral striatum neural activity has been observed when participants had personal choices and subsequently experienced autonomy need satisfaction (Leotti and Delgado 2011) and when participants successfully performed optimally challenging tasks and subsequently experienced competence need satisfaction (Lee and Reeve 2017).

The aforementioned neuroimaging findings suggest that intra-individual functional differences in ventral striatum neural activity are positively associated with extent of people's moment-to-moment psychological need satisfaction. That is, some social contexts (e.g., optimally challenging tasks) support people's psychological need satisfaction while other social contexts (e.g., harsh interpersonal control) thwart people's psychological need satisfaction. In the present study, we can additionally suggest that inter-individual anatomic differences in the ventral striatum are positively associated with extent of individuals' general psychological need satisfaction. That is, extent of ventral striatum gray matter volume can be different across individuals due to their different experiences, and these anatomic differences can influence extent of their psychological need satisfaction in their daily lives. This is consistent with previous findings demonstrating anatomic associations between the ventral striatum and general hedonic strength in the case of other human need satisfaction (Carlson et al. 2015; Hashimoto et al. 2015).

Inconsistent with our hypothesis, we could not find any meaningful anatomic associations of general psychological need satisfaction with the gray matter volumes of the brain areas functionally related to reward processing and self-related processing except the ventral striatum. Particularly, the dorsal striatum and OFC, key brain areas related to reward processing, did not show any statistically significant anatomic relations with the degree of general psychological need satisfaction. According to the functional neuroimaging studies, ventral striatum neural activity is associated with the hedonic reactions to stimuli or situations while the neural activities of the dorsal striatum and OFC are important for storing and utilizing the hedonic information of the stimuli or situations in the higher-order conscious processes such as goal-directed behavior and decision-making (O'Doherty et al. 2001, 2004). In the case of VBM studies, the inter-individual differences in the gray matter volumes of the dorsal striatum and OFC showed greater influences when comparing their own beliefs and socially-acquired values in value-competing situations (Hashimoto et al. 2015; Takeuchi et al. 2014). Based on these functional and VBM findings, we can suggest that inter-individual differences in the conscious utilization of the hedonic information (i.e., gray matter volumes of the dorsal striatum and OFC) are not associated with extent of individuals' general experiences of psychological need satisfaction whereas inter-individual differences in the primitive hedonic reactions (i.e., ventral striatum gray matter volume) are.

In addition, the gray matter volumes of the insula and ACC did not demonstrate any statistically significant anatomic relations with the degree of general psychological need satisfaction. The insula and ACC play crucial roles for self-related processes such as self-reflection and self-integration (Craig 2009; Enzi et al. 2009). Because of this self-related nature, the insula and ACC have received attention as key brain areas for the pursuit and satisfaction of basic psychological needs (Di Domenico and Ryan 2017; Reeve and Lee 2019a). Though previous VBM studies have observed the correlations of the gray matter volumes of the insula and ACC with conscious agentic beliefs (Hashimoto et al. 2015; Ming et al. 2016), in the present study, we found that the insula and ACC do not show any inter-individual anatomic differences in terms of general psychological need satisfaction. One possible explanation is that, different from the ventral striatum, the insula and ACC contribute to the experience of psychological need satisfaction in different ways. In a recent neuroimaging study (Reeve and Lee, in preparation), we found that the neural processes of psychological need satisfaction could be parsed into two parts: early-stage neural activities of the insula and medial frontal cortex reflecting the pursuit, anticipation, or regulation of basic psychological needs and late-stage ventral striatum neural activity reflecting the actual satisfaction experience of these basic psychological needs. Connecting these functional and VBM results, people do not seem to show individual differences in their neural capacity to anticipate, pursue, and regulate basic psychological need experiences, but they do show individual differences in their neural capacity to experience psychological need satisfaction once and if it occurs.

Limitations

The conclusions that can be drawn from the present findings are limited by five methodological features of our research design. First, we did not consider all possible confounding psychological variables such as other positively-valenced motivational, emotional, and personality variables (e.g., self-efficacy, positive emotionality, extraversion). Without statistically controlling for the full range of motivational, emotional, and personality variables, we cannot rule out alternative interpretations to our findings (i.e., one of these unmeasured variables might be a third variable that correlates with both need satisfaction and gray matter volume). That said, the uniqueness of the finding that only the ventral striatum correlated with need satisfaction suggests some specificity beyond these other positively-valenced third variables.

Second, the present study included the psychological needs for autonomy and competence but excluded the psychological need for relatedness. We had made this decision before collecting the anatomic data. In addition, we did not examine the unique gray matter correlates of psychological needs for autonomy and competence separately because our primary research goal as the first VBM study of psychological need satisfaction was to identify the gray matter correlates of general psychological need satisfaction and because of small sample size. In future investigations, we encourage researchers to examine the unique gray matter correlates not only of autonomy and competence but of relatedness as well.

Third, our findings were obtained with a relatively small sample size ($N=50$). This limitation rendered our capacity to detect significant associations between anatomical structures and need satisfaction to be conservative, as our risk of making a Type II error was greater than our risk of making a Type I error. To understand how much of a limitation our sample size might have been, we calculated what the ideal sample size would need to be for an *F*-test-based multiple regression to detect just one moderately strong predictor ($f^2=.15$) using conventional statistics ($alpha=.05$, $power=.90$). That sample size was 73, based on Faul and colleagues' (2007) G*Power software program. Given our under-powered sample size, larger-scaled future research might keep an open mind to the possibility of detecting statistically significant associations between those brain areas shown in Table 1 that were moderately associated with general need satisfaction (e.g., caudate nucleus).

Fourth, causal inferences are difficult to draw. It is not clear whether ventral striatum volume leads to a greater capacity to experience psychological need satisfaction or whether psychological need satisfaction leads to greater striatum volume. It is also not clear why some individuals possess greater (or lesser) ventral striatum volume than do others in the first place.

Fifth, the VBM method also has limitations in localization and detection accuracy (Mechelli et al. 2005). Therefore, the complementary use of other methods (e.g., tensor-based morphometry) also need to be considered for future studies.

Conclusion

Even while recognizing the limitations, the present study found that, among the gray matter volumes of the brain areas functionally related to reward processing and self-related processing, only ventral striatum gray matter volume showed a positive association with general psychological need satisfaction. These neuroanatomic findings suggest a possibility that there only exist inter-individual differences in the primitive hedonic reactions to stimuli or situations (but not inter-individual differences in conscious processes such as hedonic information utilization and self-related processing) in the neuroanatomic system of psychological need satisfaction.

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Compliance with ethical standards

Conflict of interest None of the authors on this paper has any conflict of interest to report.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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