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The neural basis of orienting independence vs. interdependence: A voxel-based morphometric analysis of brain volume

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running head: CULTURAL ORIETATIONS & BRAIN

Abstract

Social-cultural research has established *independence* and *interdependence* as two fundamental ways of thinking about oneself and the social world. Recent neuroscience studies further demonstrate that these orientations modulate brain activity in various self- and socially-related tasks. In the current study, we explored whether the traits of independence and interdependence are reflected in anatomical variations in brain structure. We carried out structural brain imaging on a large sample of healthy participants (n=265) who also completed self-report questionnaires of cultural orientations. Voxel-based morphometry (VBM) analysis demonstrated that a relative focus of independence (vs. interdependence) was associated with increased gray matter volume (GMV) in a number of self-related regions, including the ventro-medial prefrontal cortex (vmPFC), right dorsolateral prefrontal cortex (DLPFC), and right rostrolateral prefrontal cortex (RLPFC). These results provide novel insights into the biological basis of social-cultural orientations.

Keywords: independence orientation, interdependence orientation, gray matter volume, voxel-based morphometry

Introduction

People vary greatly in their ways of thinking about themselves and the social world around them. There is now a great deal of cross-cultural research indicating that the contrast between *independence* vs *interdependence* is an important dimension distinguishing behaviors in different cultures and social contexts (Kitayama et al., 2014; Markus & Kitayama, 1991)[1]. Independence, most prominent in Western cultures, is associated with an emphasis on personal agency and uniqueness from others. In contrast, interdependence, most prominent in Eastern cultures, is associated with an emphasis on the relations between people and with the maintenance of collectivist values, emphasizing social harmony. The overarching independence-interdependence dimension is linked to cultural differences in various domains, (e.g. Carpenter, 2000; S. Kitayama, Duffy, Kawamura, & Larsen, 2003). Furthermore, although the concept was initially developed from cross-cultural research, subsequent studies indicate that independent vs. interdependent orientations can also be treated as individual-level dispositional constructs within a single culture (e.g. Cross & Madson, 1997), and they can be temporally manipulated by priming (Gardner, Gabriel, & Lee, 1999).

With the emergence of social-cultural neuroscience in recent years, a growing literature shows that independent vs. interdependent orientations modulate neural activity in various tasks. For example, Zhu et al. (2007) found that, consistent with an interdependent orientation towards incorporating close others into one's own self-

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[1] In social psychology and cross-cultural psychology, various related terms has been used such as *independent-interdependent self-construals* or *individualism-collectivism*. In the current paper, following Kitayama et al. (2014), we use the term *independence-interdependence* to refer to these general orientations.

concept, Chinese participants showed greater overlap in their neural representations of themselves and their mother, compared with Western participants. This overlap was centered on the ventromedial prefrontal cortex (vmPFC), an area typically associated with self judgments (Northoff et al., 2006; Sui, Rotshtein, & Humphreys, 2013). Chiao et al. (2009) also found increased activity of the vmPFC during general vs. contextual self-judgments for those scored relatively higher on measures of independence vs. interdependence. Although these studies provide valuable insight into the interaction of social-culture and brain, they are all functional in nature. Previous research in voxel-based morphometry (VBM) has shown that experience shapes the structure of the brain, and proficiency in a certain domain of processing is typically associated with enlargement of relevant brain regions (May & Gaser, 2006). As suggested by Kitayama & Tompson (2010), repeated engagement with one's own culture may lead not only to functional changes in brain activity but also to anatomical changes in anatomical structure. To date, there have been several attempts to compare the brain structural characteristics of Easterners and Westerners. For example, Kochunov and colleagues (2003) have reported that, compared to English-speaking Caucasians, Chinese-speaking Asians had larger left middle frontal gyrus, inferior middle temporal gyrus and right superior parietal lobule, but smaller left superior parietal lobule. Chee and colleagues (2011) have also reported higher cortical thickness and gray matter density in young Chinese Singaporean than in young non-Asian Americans in a number of regions, including bilateral ventrolateral and anterior medial prefrontal cortex, right supramarginal gyrus, superior parietal lobule, and middle temporal gyrus. These studies shed new light on how culture may shape the structural characteristics of the brain. However, these results were obtained from cross-cultural comparisons and thus might be attributed to factors other than the independence-interdependence orientations, such as other cultural values and environmental factors.

Contrasting to prior work, in the present study we administrated two widely-used self-report measures of independent and interdependent orientations, namely Singelis's (1994) Self-Construal Scale (SCS) and Singelis et al.'s (1995) Individualism and Collectivism Scale (INDCOL), in a large sample of healthy Chinese participants, and performed voxel-based morphometry (VBM) analysis to examine its anatomical correlates of the profiles on these subjective measures. This study provided a direct examination of the relations between brain structure and independence-interdependence orientations.

Converging existing evidence from VBM and fMRI studies, we expect that individuals showing a relative focus of independence would have enhanced brain volume in the vmPFC. This hypothesis is in line with Chee et al.’s study (2011) showing increased cortical thickness in the frontal regions in Americans than in Singaporeans. However, it should be noted that cortical thickness and gray matter volume are highly-correlated but separated measures (Hutton, Draganski, Ashburner, & Weiskopf, 2009). This idea is also consistent with previous studies showing increased activity in the vmPFC associated with stronger self-bias in cognition (Sui et al., 2013). It has been argued that the vmPFC plays a central role in processing of stimuli relevant to personal self (Northoff et al., 2006; Sui, 2016). Additional evidence comes from neuropsychological studies demonstrating that the lesions in the vmPFC result in impairments in self-referential memory (Philippi, Duff, Denburg, Tranel, & Rudrauf, 2012) and in self matching where participants match shapes to labels referring to the self and others (Sui, Enock, Ralph, & Humphreys, 2015). This neuropsychological evidence suggests that the vmPFC may play a necessary role in establishing and maintaining self-bias.

Methods

Participants

Data were obtained from two-hundred and sixty-five young and healthy Chinese participants (128 females, age mean ± SD = 23.01 ± 2.69), all of whom were undergraduate and graduate students recruited from nearby universities through online advertisement. The participants were taking part in various neuroimaging studies, and anatomical images of their brains were acquired as part of the scanning protocols. Informed consent was obtained from all participants prior to the experiment according to procedures approved by the local ethics committee. Data were accumulated during December, 2011 to July, 2015, after which we decided that the sample size was adequate for the research problem (approximately 90% statistical power for an effect size of r=.20 at p<.005).

Image Acquisition

Participants were scanned via a 3.0T Philips Achieva 3.0T TX system with a SENSE 8-channel head coil. A High-resolution T1-weighted image was acquired for each participant with 160 contiguous sagittal slices of 1 mm thickness and 8° flip angle. SENSE factor was 2/1.5 for AP/RL. Time of repetition was 8.2 ms and time of echo was 3.8 ms. The acquisition matrix was 256 × 256 × 160 with voxel size of 0.938 mm × 0.938 mm × 1 mm.

Measurement of Independence-interdependence Orientations

After the scanning session, participants completed the following two widely-used measures of trait independence-interdependence:

Self-Construal Scale. The Self-Construal Scale (SCS; Singelis, 1994) consists of 30 items, half of which measure independent self-construals (e.g. "*I do my own thing, regardless of what others think*"), while the other half measure interdependent self-construals (e.g. "*I will sacrifice my self interest for the benefit of the group I am in*"). Participants rated the extent to which they agreed with each item using a 7-posint Likert-like scale from 1= *strongly disagree* to 7=*strongly agree*. In this study, the alpha coefficient for the independence and interdependence subscales were .75 and .75, respectively.

Individualism and Collectivism Scale. The Individualism and Collectivism Scale (INDCOL; Singelis et al., 1995) consists of 32 items belong to four dimensions: vertical individualism (VI, e.g. *"Winning is everything"*), horizontal individualism (HI, e.g. *"I often do 'my own thing'"*), vertical collectivism (VC, e.g. *"I hate to disagree with others in my group"*), horizontal collectivism (HC, e.g. *"I like sharing little things with my neighbors"*). Participants rated the extent to which they agreed with each item using a 7-posint Likert-like scale from 1= *strongly disagree* to 7=*strongly agree*. In this study, the alpha coefficient for VI, HI, VC, HC were .69, .66, .65 and .70, respectively.

Scores of Independence-Interdependence. The independence and interdependence orientations was initially proposed as a contrast between Eastern and Western cultures. Later, there have been debates regarding whether they should be treated as a bipolar dimension or two separate dimensions (Brewer & Chen, 2007; Oyserman, Coon, & Kemmelmeier, 2002). In the field of cultural neuroscience, however, a great many of the existing studies took the unidimensional approach by making contrast between either Easterners and Westerners (e.g. Zhu et al., 2007) or participants primed with different cultural mindset (e.g. Sui & Han, 2007), or by administrating self-reported measures and computing a composite score (e.g. Chiao et al., 2009).

Following Kitayama et al.'s (2014) recent work, we combine the unidimensional approach with a factor analysis approach, calculating a composite score of independence-interdependence through following steps. Firstly, we computed the mean ratings of each subscale (independent self-construal, interdependent self-construal, VI, HI, VC, HC) based on the two questionnaires. These six indexes were then submitted to a factor analysis, extracting factors with the Principal Axis Factoring (PAF) method and Oblimin rotation with Kaiser Normalization. Based on Kaiser's rule (dropping all components with eigenvalues under 1.0) and visual inspection of the scree plot, we decided that a 2-factor solution was most appropriate. As shown in Table 1, in this solution, factor 1 represented an interdependent orientation and factor 2 represented an independent orientation. Loadings of all indexes, with the exception of VI, were greater than .6 on the expected factor and lower than .3 on the other. VI's loadings on both factors were lower than .3. The regression-based factor score was computed for each factor. Finally, a composite factor score was derived by subtracting the score for factor 1 (the interdependence factor) from the score for factor 2 (the independence factor), such that higher score indicated more inclination towards independence relative to interdependence. This approach would allow us to control for the response bias to affirm cultural values (Kitayama et al., 2009). Furthermmore, scores derived from factor analysis accounted for measurement errors and differentiated item weights, which helps to tackle the lingering issue of the poor validity of self-reported measures in the field of independence-interdependence (Brewer & Chen, 2007; Oyserman et al., 2002), thus providing an edge over raw scale scores. In addition, results using separate factors of independence-interdependence were also reported, and analyses using raw scores of independence-interdependence are shown in the Supplementary Materials.

Table 1. Factor Loadings for six measures extracted from the Self-construal Scale and Individualism-collectivism Scale.

	Factor 1	Factor 2
Interdependent Self-Construal	**.88**	-.02
Vertical Collectivism	**.78**	-.20
Horizontal Collectivism	**.68**	.18

Vertical Individualism	.24	.13
Independent Self-Construal	.09	**.79**
Horizontal Individualism	-.05	**.63**

Image Pre-processing

Images were pre-processed using SPM8 (Wellcome Department of Cognitive Neurology, London, United Kingdom; www.fil.ion.ucl.ac.uk/spm). Participants' T-1 weighted images were examined individually, and the orientation and origin point were manually adjusted to match the template for better registration. The adjusted images were segmented into different tissue types, including gray matter, white matter, and cerebrospinal fluid, using SPM8's 'New Segmentation' module. A study-specific template of gray matter was created using the Diffeomorphic Anatomical Registration through Exponential Lie (DARTEL) algorithm (Ashburner, 2007) implemented in SPM8, and then affine-registered to the Montreal Neurological Institute (MNI) space. Individual segmented gray matter images were non-linearly warpped to match the space of DARTEL template and were modulated to preserve gray matter volumes. Finally, the modulated images were smoothed with a Gaussian kernel of FWHM = 4mm.

Statistical Analysis

Statistical analyses were performed on pre-processed gray matter images using SPM8.

ROI analysis. An anatomical-defined mask of vmPFC was created using WFU

Pickaltas Toolbox by combining the IBASPM71 labels of the bilateral medial frontal gyrus, cingulate region, and medial orbital-frontal gyrus, and then cropping to -15<X<15, Y>3s0 & Z<10.

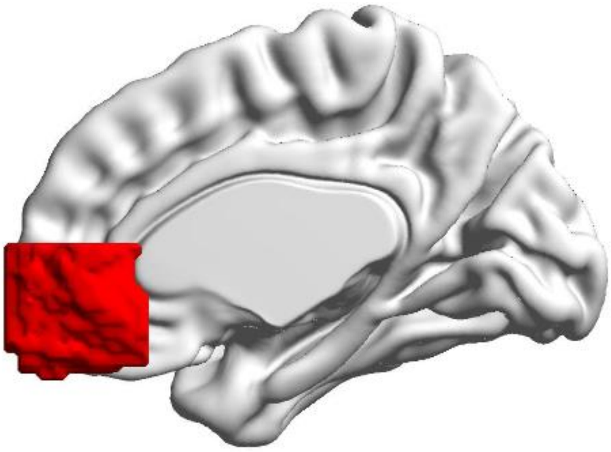

Figure 1. Illustration of the anatomical mask of vmPFC, visualized with BrainNet Viwer (Xia, Wang, & He, 2013)**.**

A voxel-wise generalized linear modeling (GLM) was performed within the mask to identify regions whose GMV was significantly correlated with the composite score of independence-interdependence, controlling for global GMV, gender and age. A dichotomous covariate representing pre- and post-update was also included due to a major update of the MRI scanner during the collection of the data. Statistical maps were thresholded at p_{ucorr}<.005 and clusters were considered as significant if passing a cluster-level threshold of p<.05 after familywise error correction using small-volume correction (SVC). Furthermore, clusters passing a more liberal cluster-level threshold of p_{uncorr}<.05 were considered as trending results, which were reported in detail in the Supplementary Materials. Non-stationary extent correction (Hayasaka, Phan, Liberzon, Worsley, & Nichols, 2004) was applied during calculation of the cluster-level p-value to address the issue of non-isotropic smoothness in the VBM data.

Whole brain analyses. To identify other regions where GMV correlated with the independence-interdependence scores, a similar GLM was performed across the whole-brain. A sample-specific gray matter mask was created using the automatic optimal-thresholding method implemented in the masking toolbox in SPM8 (http://www0.cs.ucl.ac.uk/staff/g.ridgway/masking/). This approach has been shown to be superior in reducing the risk of false negatives relative to other commonly used approaches such as absolute or relative threshold masking (Ridgway et al., 2009). Statistical maps were again thresholded at p_{ucorr}<.005 and clusters were considered as significant if passing a cluster-level threshold of p<.05 after familywise error correction. Furthermore, clusters passing a more liberal cluster-level threshold of p_{uncorr}<.05 were reported as trending results, which were reported in detail in the Supplementary Materials. Non-stationary extent correction was applied during calculation of the cluster-level p-value.

Scatter plots were also created for each significant cluster for demonstrating purpose, in which correlation coefficients were calculated using the independence-interdependence scores and the peak GMW of the clusters adjusted for global GMW, gender and age.

The above analyses were performed again using the independence and interdependence factors as separate predictors in the GLMs. Contrasts for the two factors were examined separately.

Results

Demographics and Self-report Measures

Table 2 presents descriptive statistics of demographics and self-report measures. There was no significant gender difference for the independence-interdependence scores, $t(263) = -0.43$, $p = .66$.

Table 2. Descriptive statistics of demographics and self-report data

	Total (n=265)	Male (n=137)	Female (n=128)
Age	23.01 ±2.69	23.57 ±2.45	22.41 ±2.82
Independence-Interdependence Score	0.00 ±1.04	-0.001 ±0.91	0.001 ±0.89

VBM Results – Composite Score

ROI analysis. Within the vmPFC mask, a cluster was identified as having GMV significantly positively correlated with trait independence, $k = 195$, BA10, $p_{FWE} = .04$ at a cluster level; peaking at [6 69 -18], $Z = 3.82$ (**Figure 2**). The stronger the orientation to independence, the larger the size of GMV in the vmPFC.

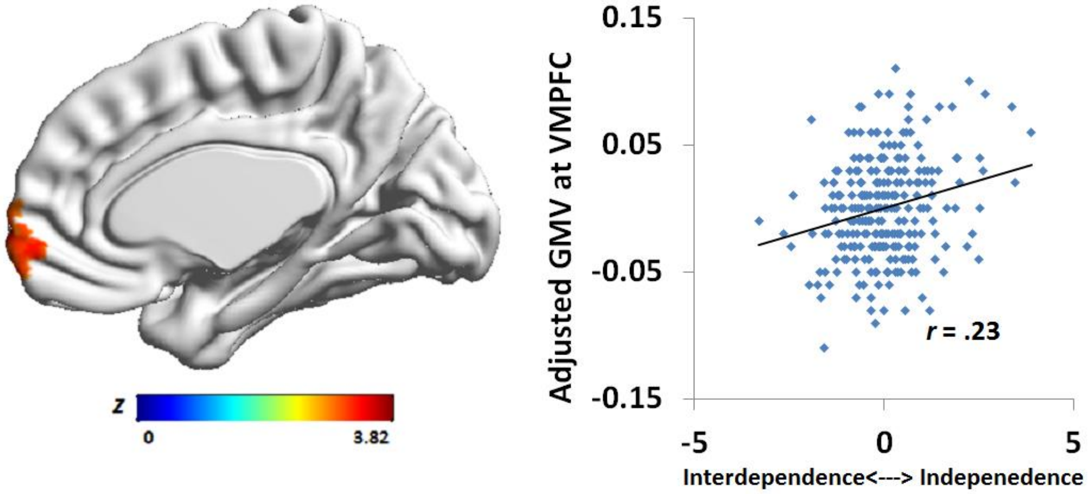

Figure 2. A clusters within the VMPFC mask showing significant positive correlations between gray matter volume (GMV) and trait independence (independence-interdependence) (p_{FWE}<.05 at a cluster level after small volume correction). (Statistical map was thresholded at p_{uncorr}<.005 voxel-wise).

Whole brain analyses. Whole-brain VBM results are presented in **Table 3-5** and **Figure 3 & 4**. The analysis showed that the independence-interdependence score was positively correlated with the GMV in the right DLPFC (k = 427, BA 9/10/46, p_{FWE} = .02 at cluster level; peaking at [48 42 21], Z = 4.66) and right rostrolateral prefrontal cortex (RLPFC, k = 351, BA 10, p_{FWE} = .02 at cluster level; peaking at [31.5 63 -3], Z = 4.64) (**Figure 3, Table 3**). More the greater trait independence, the larger the GMV found in the right DLPFC and RLPFC. In addition, five clusters showed trends for positive correlations (**Figure S1, Panel A; Table S3**): left DLPFC, right fusiform and inferior temporal gyrus, VMPFC, left temporoparietal junction (TPJ) including superior, middle temporal and postcentral gyrus, and another cluster at right DLPFC.

For trait interdependence, two clusters were found covering the bilateral calcarine sulcus extending to the lingual gyrus and precuneus (**Figure S1, Panel B; Table S4**), and these both showed trends for negative correlations with the independence-interdependence score.

Table 3. Regions with gray matter volume (GMV) significantly correlated with trait independence (independence-interdependence) in a whole-brain analysis.

Regions	**Side**	**BA**	**Cluster**		**Peak**			
			k	***Volume(*** mm^3***)***	**x**	**y**	**z**	***Z*-value**
(+) DLPFC	**R**	**9/10/46**	**427**	1441 mm^3	**48**	**42**	**21**	**4.66**
(+) RLPFC	**R**	**10**	**351**	1185 mm^3	**31.5**	**63**	**-3**	**4.64**

Note. + represents positive correlations between GMV and independence orientation (independence-interdependence); DLPFC=dorsolateral prefrontal cortex; RLPFC=rostrolateral prefrontal cortex. Statistical maps were thresholded at p_{uncorr}<.005; all clusters were p_{FWE}<.05 at cluster level.

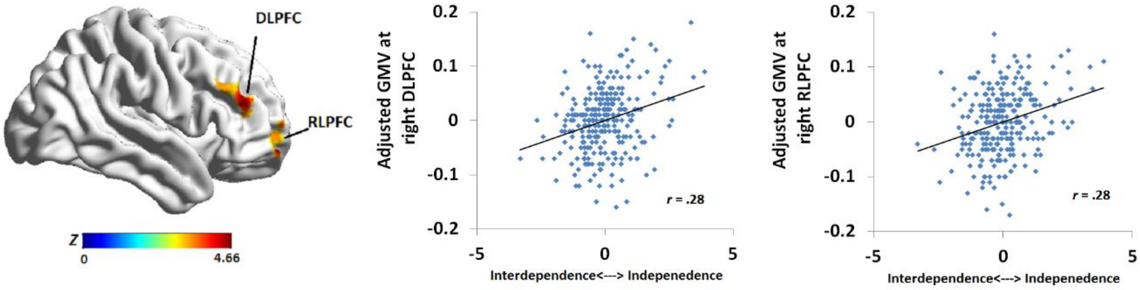

Figure 3. Two clusters within right DLPFC and RPLFC showed significant positive correlations between gray matter volume (GMV) and trait independence

(independence-interdependence) (p_{FWE}<.05 at cluster level) (Statistical maps were thresholded at p_{uncorr}<.005, k>300).

VBM Results – Separate Factor Scores

ROI analysis. No cluster was found with significant or trending positive or negative correlation with regional GMV for either the independence or interdependence factor score.

Whole brain analysis. For the independence factor score, no cluster was found with significant positive or negative correlation with regional GMV, but four clusters showed trending positive correlations: a cluster covering middle occipital gyrus, a cluster covering left TPJ including the superior temporal and postcentral gyrus, a cluster covering right fusiform gyrus, and a cluster covering left DLPFC (see Supplementary Materials for details). Furthermore, a cluster at right posterior superior frontal gyrus showed trending negative correlation. For the interdependence factor score, a cluster covering left calcarine sulcus extending to the lingual gyrus and precuneus showed significantly positive correlation (k = 893, BA 18/30, p_{FWE}=.04 at cluster level; peaking at [-10.5 -63 6], Z = 4.37). Additionally, a cluster covering right calcarine sulcus, a cluster covering right cerebellum, and a cluster covering left supramarginal gyrus showed trending positive correlations. Three clusters showed significant negative correlations: two clusters covering bilateral DLPFC (right: k = 404, BA 9/10/46, p_{FWE} = .02 at cluster level; peaking at [52.5 27 27], Z = 4.86; left: k = 390, BA 10/46, p_{uncorr}=.01 at cluster level; peaking at [-46.5 36 18], Z = 4.71) and one cluster covering right RLPFC (k = 393, BA 10, p_{FWE} = .01 at cluster level; peaking at [28.5 60 -9], Z = 4.61). Two additional clusters were identified as showing trending negative correlations: a cluster covering left medial frontal gyrus, middle cingulate cortex, and supplementary motor area, and a cluster covering left DLPFC.

Inter-correlations of regional GMVs between the vmPFC and other regions, and the mediating role of independence-interdependence.

Table 4 presents the partial inter-correlations among GMVs at peak coordinates of the vmPFC and other clusters, controlling for global GMV, gender and age. GMV of the vmPFC was positively correlated with bilateral DLPFC, right RLPFC and right fusiform gyrus, and negatively correlated with left Calcarine, $|r|$s>.12, ps<.05.

Table 4. Inter-correlations among regional GMVs (controlling for global GMV, gender, age, and wave).

	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1.vmPFC	.13*	.25**	.19**	.13*	.05	.04	-.17**	-.08
2.Right DLPFC		.26**	.30**	.06	-.05	.25**	-.09	-.02
3.Right RLPFC			.22**	.10	-.01	.20**	-.04	-.07
4.Left DLPFC				.05	-.04	.23**	.02	-.02
5.Right fusiform					*.11*	.10	-.08	-.09
6.Left postcentral						-.07	-.09	-.17**
7.Right DLPFC 2							-.14*	-.15*
8.Left Calcarine								.51**

9.Right Calcarine

Note. **=$p<.01$; *=$p<.05$; italic represents marginally significance ($p<.10$).

Discussion

As predicted, individuals expressing greater relative focus of independence was associated with greater GMV in the vmPFC. Enlargement of a brain region is usually linked to proficiency in the relevant processing domain (May & Gaser, 2006). For the vmPFC, previous functional neuroimaging studies have shown that it serves a critical role in self-related processing in a range of tasks (Sui, 2016), including perceptual matching (Sui et al., 2013), self-referential thinking and memory (Northoff et al., 2006), and that the activity in the vmPFC evoked by self-related processing is enhanced in individuals from independence-focused cultures relative to those from interdependent-focused cultures (e.g. Chiao et al., 2009, 2010; Sui & Han, 2007; Zhu et al., 2007). Therefore, our result is consistent with the theoretical view that trait independence (v.s. interdependence) focuses more on personal self (Markus & Kitayama, 1991) and provided novel evidence showing that such broad social-cultural orientations are also reflected in anatomical features of the brain.

Besides the hypothesized vmPFC, we further found that independence-interdependence was significantly correlated with GMV in the right DLPFC and RLPFC. The DLPFC has been argued to play a crucial role in creating and maintaining a sense of self-agency (e.g. Fink et al., 1999). On this view then, increased GMV in the DLPFC linked to trait independence is consistent with more independent individuals having a greater drive for personal agency (Shinobu Kitayama & Uchida, 2005). The function of the RLPFC is even less well-understood (Gilbert et al., 2006); however, there are reports that the RLPFC is involved in processing self-generated information (Christoff, Ream, Geddes, & Gabrieli, 2003) and self-referential processing during retrieval from episodic memory (Sajonz et al., 2010). It is possible then that the tendency of independently oriented people to focus on the inner self (Markus & Kitayama, 1991) results in increased GMV in the RLPFC. In sum, the results in the whole-brain analysis can also be explained through the personal self account.

Interestingly, we also found that the GMV of the vmPFC was positively correlated with the GMV of the bilateral DLPFC. These results are in line with the theory of Self-Attention Network (Humphreys & Sui, 2015) which proposed that the functional coupling between the vmPFC and the DLPFC is linked to participants having to effect greater attentional control over biases to self-related stimuli compared with other stimuli. This idea is also supported by Northoff (2015), who suggests that these functional neural couplings reflect the interaction between internal self-specificity and external stimuli. Based on this theory, the current results can be interpreted as people with a relative focus of independence have strengthened self-attention network. Future work might focus on the relationship between independence-interdependence and the functional coupling between vmPFC and DLPFC using the resting-state network or self-related tasks.

Beyond these significant results, some regions further showed trending results. For example, we found increased GMV in relation to trait independence in the right fusiform gyrus, which is a key region in processing faces, and right fusiform is especially sensitive to self-face identity (Ma & Han, 2012). Furthermore, Sui, Chechlacz and Humphreys (2015) found that reduced GMV in the right fusiform cortex of neuropsychological patients was associated with reduced self-bias; these authors proposed that these regions contained self-related memories. In contrast, a relative focus of interdependence was associated with increased GMV bilaterally in the calcarine sulcus extending to lingual gyrus. As a visual region, the results of this area might be linked with previous studies showing that people with interdependence focus (e.g. East Asians) and independence focus (e.g. Westerners) are different in their scope of visual attention, such that East Asians are more likely to perceive visual scene as a whole and their attention is more evenly distributed between objects and background (Nisbett et al., 2001). However, it should be noted that these results were significant only at trending level. Future research may clarify these relationships by examining the relationship between independence-interdependence and the activity of these regions when performing the related behavioral tasks (e.g. a face processing task for the fusiform gyrus, or an attention task for the calcarine).

When the independence and interdependence orientations were examined separately, most of the significant results re-emerged for the interdependence score, and a cluster in the calcarine, which was a trending region in the unidimensional analysis, also reached significance, while the independence score only yielded trending results. The pattern of weaker results for the independence score has also been observed in Ray et al. (2009), in which only interdependent self-construal, but not independent self-construal, predicts MPFC and PCC's relative activations in self-referential vs. mother-referential judgment. One possibility is that the self-reported measures for independence may be noisier. For example, in Ray et al. (2009), the independent subscale had an alpha of .53, and in our study the VI subscale loaded poorly on both factors, leaving only two indicators for the independence factor. Although the independence-interdependence orientations were initially proposed as a contrast between Eastern and Western cultures, there have been debates on whether independence and interdependence should be treated as one bipolar dimension or two separate construals (Brewer & Chen, 2007; Oyserman et al., 2002). Nevertheless, our results are in line with previous cultural neuroscience studies which dominantly took a unidimensional approach and reported the links between the relative focus of independence and activities of self-related regions. Also, using relative score could control for the response bias artifacts of affirming cultural values, thus leading to a clearer result.

One limitation of the current study is that the analyses are correlational in nature, and a longitudinal design is needed to determine the causal direction between independent and interdependent traits and changes in brain structure. What's more, the results in the present study may also reflect the influences of environmental or genetic factors. Recently there is emerging evidence for the correlations between the independence-interdependence orientations and certain genotypes (e.g. Chiao & Blizinsky, 2010). Future research could pursue to establish the link of gene-brain-culture. Furthermore, our approach of treating independence-interdependence as individual difference variable within a single culture, while allowing us to control for confounds such as language, might also limit the range of distribution of the traits in our sample. Clearly a cross-cultural analysis would be helpful to test this. Actually, some of the regions reported here were also identified in Chee et al.'s (2011) comparison between young Easterners and Westerners. Nevertheless, our results provide novel evidence that there are anatomical variations of brain structure underlying the social-cultural orientations of independence-interdependence, even within a single culture.

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Author Contributions

F. Wang developed the study concept and design with K. Peng and J. Sui. Data collection were performed by teams from K. Peng and J. Sui's laboratory. F. Wang performed the data analysis and interpretation under the supervision of J. Sui. F. Wang drafted the manuscript. All authors contributed to discussion of the manuscript. J. Sui and G. Humphreys provided critical revisions. All authors approved the final version of the manuscript for submission.

References

Ashburner, J. (2007). A fast diffeomorphic image registration algorithm. *NeuroImage*, *38*(1), 95–113. http://doi.org/10.1016/j.neuroimage.2007.07.007

Brewer, M. B., & Chen, Y.-R. (2007). Where (who) are collectives in collectivism? Toward conceptual clarification of individualism and collectivism. *Psychological Review*, *114*(1), 133–51. http://doi.org/10.1037/0033-295X.114.1.133

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network: anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences*, *1124*, 1–38. http://doi.org/10.1196/annals.1440.011

Carpenter, S. (2000). Effects of Cultural Tightness and Collectivism on Self-Concept and Causal Attributions. *Cross-Cultural Research*, *34*(1), 38–56. http://doi.org/10.1177/106939710003400103

Chee, M. W. L., Zheng, H., Oon, J., Goh, S., Park, D., & Sutton, B. P. (2011). Brain Structure in Young and Old East Asians and Westerners : Comparisons of Structural Volume and Cortical Thickness. *Journal of Cognitive Neuroscience, 23*(5), 1065–1079. http://doi.org/10.1162/jocn.2010.21513

Chiao, J. Y., & Blizinsky, K. D. (2010). Culture-gene coevolution of individualism-collectivism and the serotonin transporter gene. *Proceedings. Biological Sciences / The Royal Society*, *277*(1681), 529–537. http://doi.org/10.1098/rspb.2009.1650

Chiao, J. Y., Harada, T., Komeda, H., Li, Z., Mano, Y., Saito, D., … Iidaka, T. (2009). Neural basis of individualistic and collectivistic views of self. *Human Brain Mapping*, *30*(9), 2813–20. http://doi.org/10.1002/hbm.20707

Chiao, J. Y., Harada, T., Komeda, H., Li, Z., Mano, Y., Saito, D., … Iidaka, T. (2010). Dynamic cultural influences on neural representations of the self. *Journal of Cognitive Neuroscience*, *22*(1), 1–11. http://doi.org/10.1162/jocn.2009.21192

Christoff, K., Ream, J. M., Geddes, L. P. T., & Gabrieli, J. D. E. (2003). Evaluating self-generated information: anterior prefrontal contributions to human cognition. *Behavioral Neuroscience*, *117*(6), 1161–8. http://doi.org/10.1037/0735-7044.117.6.1161

Cross, S. E., & Madson, L. (1997). Models of the self: self-construals and gender. *Psychological Bulletin*, *122*(1), 5–37. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9204777

Fink, G. R., Marshall, J. C., Halligan, P. W., Frith, C. D., Driver, J., Frackowiak, R. S., & Dolan, R. J. (1999). The neural consequences of conflict between intention and the senses. *Brain : A Journal of Neurology*, *122 (Pt 3*, 497–512. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10094258

Gardner, W. L., Gabriel, S., & Lee, A. Y. (1999). "I" Value Freedom, but "We" Value Relationships: Self-Construal Priming Mirrors Cultural Differences in Judgment. *Psychological Science*, *10*(4), 321–326. http://doi.org/10.1111/1467-9280.00162

Gilbert, S. J., Spengler, S., Simons, J. S., Steele, J. D., Lawrie, S. M., Frith, C. D., & Burgess, P. W. (2006). Functional specialization within rostral prefrontal cortex (area 10): a meta-analysis. *Journal of Cognitive Neuroscience*, *18*(6), 932–48. http://doi.org/10.1162/jocn.2006.18.6.932

Hayasaka, S., Phan, K. L., Liberzon, I., Worsley, K. J., & Nichols, T. E. (2004). Nonstationary cluster-size inference with random field and permutation methods. *NeuroImage*, *22*(2), 676–87. http://doi.org/10.1016/j.neuroimage.2004.01.041

Humphreys, G. W., & Sui, J. (2015). Attentional control and the self: The Self Attention Network (SAN). *Cognitive Neuroscience*, (June), 150506074704000. http://doi.org/10.1080/17588928.2015.1044427

Hutton, C., Draganski, B., Ashburner, J., & Weiskopf, N. (2009). A comparison between voxel-based cortical thickness and voxel-based morphometry in normal aging. *NeuroImage*, *48*(2), 371–380. http://doi.org/10.1016/j.neuroimage.2009.06.043

Kitayama, S., Duffy, S., Kawamura, T., & Larsen, J. T. (2003). Perceiving an Object and Its Context in Different Cultures: A Cultural Look at New Look. *Psychological Science*, *14*(3), 201–206. http://doi.org/10.1111/1467-9280.02432

Kitayama, S., King, A., Yoon, C., Tompson, S., Huff, S., & Liberzon, I. (2014). The dopamine D4 receptor gene (DRD4) moderates cultural difference in independent versus interdependent social orientation. *Psychological Science*, *25*(6), 1169–77. http://doi.org/10.1177/0956797614528338

Kitayama, S., & Tompson, S. (2010). Envisioning the future of cultural neuroscience. *Asian Journal of Social Psychology*, *13*, 92–101. http://doi.org/10.1111/j.1467-839X.2010.01304.x

Kitayama, S., & Uchida, Y. (2005). Interdependent Agency: An Alternative System for Action. In *Cultural and social behavior: The Ontario Symposium, Vol 10.* (pp. 137–164).

Kochunov, P., Fox, P., Lancaster, J., Tan, L. H., Amunts, K., Zilles, K., … Gao, J. H. (2003). Localized morphological brain differences between English-speaking Caucasians and Chinese-speaking Asians: new evidence of anatomical plasticity. *Neuroreport*, *14*(7), 961–964. http://doi.org/10.1097/01.wnr.0000075417.59944.00

Markus, H. R., & Kitayama, S. (1991). Culture and the self: Implications for cognition, emotion, and motivation. *Psychological Review*, *98*(2), 224–253.

May, A., & Gaser, C. (2006). Magnetic resonance-based morphometry: a window into structural plasticity of the brain. *Curr Opin Neurol*, *19*(4), 407–411. http://doi.org/10.1097/01.wco.0000236622.91495.21

Northoff, G. (2015). Is the self a higher-order or fundamental function of the brain? The "basis model of self-specificity" and its encoding by the brain's spontaneous activity. *Cognitive Neuroscience*, *8928*(January 2016), 17588928.2015.1111868. http://doi.org/10.1080/17588928.2015.1111868

Northoff, G., Heinzel, A., de Greck, M., Bermpohl, F., Dobrowolny, H., & Panksepp, J. (2006). Self-referential processing in our brain--a meta-analysis of imaging studies on the self. *NeuroImage*, *31*(1), 440–57. http://doi.org/10.1016/j.neuroimage.2005.12.002

Oyserman, D., Coon, H. M., & Kemmelmeier, M. (2002). Rethinking individualism and collectivism: evaluation of theoretical assumptions and meta-analyses. *Psychological Bulletin*, *128*(1), 3–72. http://doi.org/10.1037/0033-2909.128.1.3

Philippi, C. L., Duff, M. C., Denburg, N. L., Tranel, D., & Rudrauf, D. (2012). Medial PFC damage abolishes the self-reference effect. *Journal of Cognitive Neuroscience*, *24*(2), 475–81. http://doi.org/10.1162/jocn_a_00138

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(2), 676–82. http://doi.org/10.1073/pnas.98.2.676

Ray, R. D., Shelton, A. L., Hollon, N. G., Matsumoto, D., Frankel, C. B., Gross, J. J., & Gabrieli, J. D. E. (2009). Interdependent self-construal and neural representations of self and mother. *Social Cognitive and Affective Neuroscience*, *5*(2-3), 318–323. http://doi.org/10.1093/scan/nsp039

Ridgway, G. R., Omar, R., Ourselin, S., Hill, D. L. G., Warren, J. D., & Fox, N. C. (2009). Issues with threshold masking in voxel-based morphometry of atrophied brains. *NeuroImage*, *44*(1), 99–111. http://doi.org/10.1016/j.neuroimage.2008.08.045

Sajonz, B., Kahnt, T., Margulies, D. S., Park, S. Q., Wittmann, A., Stoy, M., … Bermpohl, F. (2010). Delineating self-referential processing from episodic memory retrieval: common and dissociable networks. *NeuroImage*, *50*(4), 1606–17. http://doi.org/10.1016/j.neuroimage.2010.01.087

Singelis, T. M. (1994). The Measurement of Independent and Interdependent Self-Construals. *Personality and Social Psychology Bulletin*, *20*(5), 580–591. http://doi.org/10.1177/0146167294205014

Singelis, T. M., Triandis, H. C., Bhawuk, D. P. S., & Gelfand, M. J. (1995). Horizontal and Vertical Dimensions of Individualism and Collectivism: A Theoretical and Measurement Refinement. *Cross-Cultural Research*, *29*(3), 240–275. http://doi.org/10.1177/106939719502900302

Sui, J. (2016). Self-Reference Acts as a Golden Thread in Binding. *Trends in Cognitive Sciences*. http://doi.org/10.1016/j.tics.2016.04.005

Sui, J., Chechlacz, M., Rotshtein, P., & Humphreys, G. W. (2015). Lesion-Symptom Mapping of Self-Prioritization in Explicit Face Categorization: Distinguishing

Hypo- and Hyper-Self-Biases. *Cerebral Cortex*, *25*, 374–383. http://doi.org/10.1093/cercor/bht233

Sui, J., Enock, F., Ralph, J., & Humphreys, G. W. (2015). Dissociating hyper and hypoself biases to a core self-representation. *Cortex*. http://doi.org/10.1016/j.cortex.2015.04.024

Sui, J., & Han, S. (2007). Self-construal priming modulates neural substrates of self-awareness. *Psychological Science*, *18*(10), 861–6. Retrieved from http://pss.sagepub.com/content/18/10/861.full

Sui, J., Rotshtein, P., & Humphreys, G. W. (2013). Coupling social attention to the self forms a network for personal significance. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(19), 7607–12. http://doi.org/10.1073/pnas.1221862110

Xia, M., Wang, J., & He, Y. (2013). BrainNet Viewer: A Network Visualization Tool for Human Brain Connectomics. *PLoS ONE, 8*(7). http://doi.org/10.1371/journal.pone.0068910

Zhu, Y., Zhang, L., Fan, J., & Han, S. (2007). Neural basis of cultural influence on self-representation. *NeuroImage*, *34*(3), 1310–6. http://doi.org/10.1016/j.neuroimage.2006.08.047