

Neurostructural correlates of dispositional self-compassion

Fang Guan^{a,1}, Guanmin Liu^{a,1,*}, Walker S. Pedersen^b, Outong Chen^c, Sasa Zhao^d, Jie Sui^e, Kaiping Peng^{a,**}

^a Department of Psychology, Tsinghua University, Beijing, China

^b Department of Psychiatry, Massachusetts General Hospital, Harvard Medical School, Charlestown, MA, USA

^c Normal College & School of Education, Qingdao University, Qingdao, China

^d UMR 5229, Institut des Sciences Cognitives Marc Jeannerod, CNRS, Université Claude Bernard Lyon 1, Lyon, France

^e School of Psychology, University of Aberdeen, Aberdeen, UK

ARTICLE INFO

Keywords:

Self-compassion
Self-judgment
Mindfulness
Emotion regulation
Voxel-based morphometry

ABSTRACT

Self-compassion is an important emotion regulation strategy predicting positive psychological health and fewer psychopathological problems, but little is known about its structural neural basis. In the current study, we investigated the neurostructural correlates of dispositional self-compassion and its components using voxel-based morphometry (VBM). We found that self-compassion was inversely correlated with gray matter volume (GMV) in the left dorsolateral prefrontal cortex (DLPFC), which was primarily driven by the reduced self-judgment component. We also found that the mindfulness component was associated with greater GMV in the dorsomedial prefrontal cortex/anterior cingulate cortex and the left supplementary motor area, while the isolation and the over-identification components were both correlated with greater GMV in the right inferior temporal gyrus, and over-identification additionally related to less GMV in visual areas. Our findings suggest that dispositional self-compassion and its components are associated with brain structure in regions involved in emotion regulation, self-referential and emotion processing, with implications for the cognitive and neural mechanisms of self-compassion as well as those underlying the effects of self-compassion on its health outcomes.

1. Introduction

Self-compassion is an emotionally positive self-attitude in the face of one's suffering (Neff, 2003b), which entails three positive components (i.e., self-kindness, recognition of common humanity, and mindfulness) and three negative components (i.e., [reduced] self-judgment, isolation, and over-identification) (Neff, 2003a). Previous studies have established that self-compassion is an effective emotion regulation strategy (Die-drich et al., 2014; Neff, 2003b; Trompeter et al., 2017), which significantly predicts positive psychological health and fewer psychopathological problems (Muris and Petrocchi, 2017; Neff et al., 2018). Despite the important protective roles of self-compassion, the structural neural basis of this trait remains unclear. The present study aimed to address the issue using voxel-based morphometry (VBM).

No study has hitherto examined the neurostructural correlates of dispositional self-compassion, but VBM studies have examined similar constructs. First, self-compassion and self-esteem are both positive self-

attitude and they are highly correlated ($r = 0.59$) (Neff, 2003a). Second, the definition of self-compassion is closely related to the more general construct of compassion (Neff, 2003b). Based on these similarities, VBM studies of self-esteem and compassion may provide insight into the neurostructural correlates of self-compassion. It has been found that both self-esteem and compassion (or its practice) are linked to increased gray matter volume (GMV) in the anterior cingulate cortex (ACC) and the right dorsolateral prefrontal cortex (DLPFC) (Agroskin et al., 2014; Hou et al., 2017), as well as insula (Hou et al., 2017) or the right temporo-parietal junction (TPJ) (Agroskin et al., 2014; Leung et al., 2013). These regions were thought to be associated with emotion regulation or empathic processes (Agroskin et al., 2014; Hou et al., 2017). In addition to VBM studies of similar constructs, functional magnetic resonance imaging (fMRI) studies of dispositional self-compassion may reveal candidates for neural regions supporting this trait and may inform hypotheses about regions whose morphology may correlate with it. So far, most of these fMRI studies (Berry et al.,

* Corresponding author.

** Corresponding author.

E-mail addresses: guanmin.liu@gmail.com (G. Liu), pengkp@mail.tsinghua.edu.cn (K. Peng).

¹ Co-first authors.

2020; Liu et al., 2020b; Williams et al., 2020) have found that dispositional self-compassion or self-kindness was associated with activation in DLPFC, dorsal ACC and/or posterior cingulate cortex (PCC)/precuneus, regions thought to be associated with emotion regulation and self-referential processing (Sui and Gu, 2017; Yankouskaya and Sui, 2021). These studies suggest that dispositional self-compassion may be correlated with regions associated with emotion regulation and self-referential processing (e.g., DLPFC, ACC, PCC/precuneus) as well as those associated with empathy/theory of mind (e.g., insula, TPJ).

As for the components of self-compassion, VBM studies of similar constructs have also provided insight into their neurostructural correlates. The most studied construct similar to certain component of self-compassion is mindfulness, which refers to a process of openly attending, with awareness, to one's present moment experience (Creswell, 2017). The difference between the mindfulness component of self-compassion and mindfulness more generally is that the former refers to mindfulness only in face of one's personal suffering. It has been found that trait mindfulness was linked to greater GMV in ACC and hippocampus/amygdala, and less GMV in PCC and orbito-frontal cortex (Lu et al., 2014). Another construct similar to certain component of self-compassion whose neurostructural correlates have been examined is brooding. Brooding is a subcomponent of rumination, referring to self-critical moody pondering (Raes, 2010; Treynor et al., 2003), and thus is closely associated with self-criticism or the self-judgment component of self-compassion (Neff et al., 2018). Brooding has been found positively correlated with GMV in ACC and the left DLPFC (Sin et al., 2018). Because self-compassion correlates inversely with brooding (Raes, 2010), it might show an opposite relationship (i.e., negative correlations) with GMV in these regions.

The present study aimed to identify the neurostructural correlates of dispositional self-compassion and its components using exploratory analyses since no studies have hitherto investigated this issue. However, because VBM studies of constructs similar to self-compassion and its components as well as fMRI studies of self-compassion have convergently found the involvement of ACC and DLPFC, we expected that dispositional self-compassion and its components may be correlated with GMV in these regions (i.e., ACC and DLPFC). We did not have specific hypotheses regarding how the individual components of self-compassion may be differentially correlated with GMV in certain regions.

2. Methods

2.1. Participants

One hundred and nine healthy university students (70 females; mean age = 20.49 years, SD = 1.65), with no history of neurological, psychiatric, or physical abnormalities, were recruited from South China Normal University for the current study. All individuals were right-handed with normal or corrected-to-normal vision. The protocol was approved by the Brain Imaging Center Institutional Review Board of South China Normal University and carried out in accordance with its recommendations. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

2.2. Measures

The Self-Compassion Scale (SCS) developed by Neff (2003a) was used to measure dispositional self-compassion. It comprises 26 items that assess the degree of self-compassion across three positive (i.e., self-kindness, recognition of common humanity, and mindfulness) and three negative dimensions (i.e., self-judgment, isolation, and over-identification). Each item was scored on a 5-point Likert-type scale (from 1 = *almost never* to 5 = *almost always*). Average scores for each dimension were calculated by averaging scores of all corresponding items, with higher scores representing higher levels of each dimension.

An average score of dispositional self-compassion was calculated by averaging all items after those of the three negative dimensions were reverse coded. Higher scores thus represented higher levels of dispositional self-compassion.

2.3. Image acquisition

Structural MRI was performed on a Trio 3.0 T Tim scanner (Siemens, Erlangen, Germany) at the Brain Imaging Center at South China Normal University, Guangzhou, China. During imaging, the participants were asked to refrain from moving their head or closing their eyes and to remain awake. A three-dimensional magnetization-prepared rapid gradient-echo (3D MP-RAGE) sequence was used to obtain high-resolution T1-weighted anatomical images with the following parameters: repetition time (TR) = 1900 ms, echo time (TE) = 2.52 ms, flip angle = 9°, matrix = 256 × 256, slice thickness = 1.0 mm, field of view (FOV) = 230 × 230 mm², and voxel size = 1 × 1 × 1 mm³.

2.4. Image preprocessing

Images were preprocessed using the Statistical Parametric Mapping (SPM) software (SPM12; Wellcome Department of Cognitive Neurology, London, United Kingdom; www.fl.ion.ucl.ac.uk/spm), following the VBM protocol by Ashburner (2010). First, each image was displayed in SPM12 to screen for artifacts and gross anatomical abnormalities. For better registration, the manual method was used to reorient the images to the anterior commissure. Next, the T1-weighted anatomical images were segmented into Gray Matter (GM), White Matter (WM), and Cerebrospinal Fluid (CSF) using the segmentation procedure. The registration and normalization processes were conducted through Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra (DARTEL) in SPM12 (Ashburner, 2007). These probability maps were manually examined first, to ensure proper segmentation, and were then spatially normalized (Friston et al., 1995) to Montreal Neurologic Institute (MNI) space (resampling to 1.5 mm cubic isotropic voxels). Finally, the modulated GM images were spatially smoothed with an isotropic Gaussian kernel with full width at half maximum (FWHM) = 8 mm.

2.5. Statistical analyses

2.5.1. Neural correlates of dispositional self-compassion

To identify the neurostructural correlates of dispositional self-compassion, a voxel-wise multiple regression model (Model 1) was performed across the whole brain, with dispositional self-compassion as covariate of interest and age, gender, and total GMV as confounding covariates. Age and gender were set as confounding covariates because these variables affect brain structure (Smith et al., 2007) and are generally controlled for in VBM studies (Guan et al., 2018; Kanai et al., 2010, 2011; Liu et al., 2018). A gray matter mask was created by binarizing SPM's prior probability gray matter map at the threshold of 0.2 and was applied to the analysis (Liu et al., 2020a; Wang et al., 2017). The voxel-wise intensity threshold was set at $p_{\text{uncorr}} < 0.001$, and the cluster-extent threshold of $p_{\text{FWE}} < 0.05$ was calculated using Monte Carlo simulations with AFNI 18 (Cox, 1996). Clusters surviving the threshold of $p_{\text{FWE}} < 0.1$ were reported as trending results. Eigenvariate values of each significant cluster were extracted for visualization and partial correlation analyses.

2.5.2. Neural correlates of self-compassion components

To explore neurostructural correlates of self-compassion components, another six voxel-wise multiple regression models were performed across the whole brain, with self-kindness, self-judgment, recognition of common humanity, isolation, mindfulness and over-identification as the respective variable of interest, and age, gender, and total GMV as confounding covariates. The other details were the

same as those mentioned above in Model 1.

3. Results

3.1. Descriptive statistics of behavioral measures

Table 1 presents the minimum value, maximum value, mean, and SD for dispositional self-compassion and its components.

3.2. Neuroimaging results

3.2.1. Neural correlates of dispositional self-compassion

The results of the whole-brain VBM analysis of dispositional self-compassion revealed a negative correlation between self-compassion and GMV in the left DLPFC (MNI coordinates: $-32, 59, 18$; $r_p = -0.37$; Table 2 and Fig. 1) after controlling for age, gender and total GMV.

3.2.2. Neural correlates of self-compassion components

Self-judgment showed a correlation with greater GMV in the left DLPFC (MNI coordinates: $-47, 53, 14$; $r_p = -0.37$; Table 2 and Fig. 2a), which was the same region where GMV correlated with dispositional self-compassion, suggesting that the link between dispositional self-compassion and less GMV in the DLPFC was primarily driven by (reduced) self-judgment. In addition, isolation showed a correlation with greater GMV in the right inferior temporal region (ITG)/temporal pole (MNI coordinates: $51, 5, -45$; $r_p = 0.38$; Table 2 and Fig. 2b), mindfulness showed a correlation with greater GMV in dorsomedial prefrontal cortex (DMPFC)/ACC (MNI coordinates: $-9, 39, 38$; $r_p = 0.42$) and the left supplementary motor area (SMA) (MNI coordinates: $-9, -8, 57$; $r_p = 0.37$; Table 2 and Fig. 2c), and over-identification showed a correlation with greater GMV in the right ITG (MNI coordinates: $51, 5, -45$; $r_p = 0.36$) and less GMV in the right superior occipital gyrus (SOG)/middle occipital gyrus (MOG) (MNI coordinates: $26, -92, 32$; $r_p = -0.39$; Table 2 and Fig. 2d). On the other hand, self-kindness and recognition of common humanity only showed positive trends with GMV in calcarine/precuneus and cerebellum/fusiform, respectively.

4. Discussion

The current study investigated the neurostructural correlates of dispositional self-compassion and its components, using VBM in healthy adults. The results revealed that dispositional self-compassion was negatively correlated with GMV in the left DLPFC while self-judgment was positively correlated with GMV in the same region. Furthermore, we found that mindfulness was positively correlated with GMV in DMPFC/ACC and the left SMA, while both isolation and over-identification were positively correlated with GMV in the right ITG, and over-identification was additionally negatively correlated with GMV in visual areas (i.e., the right SOG/IOG).

We found that dispositional self-compassion was negatively correlated with GMV in the left DLPFC. It has been suggested that DLPFC is associated with executive control (Diamond, 2013; Miller and Cohen, 2001; Sui et al., 2013) and emotion regulation (Golkar et al., 2012).

Table 1
Descriptive statistics of the self-report measures.

	Min	Max	Mean	SD
Dispositional Self-compassion	1.65	4.46	3.14	0.50
Self-kindness	1.60	5.00	3.51	0.62
Self-judgment	1.80	4.60	3.08	0.60
Recognition of common humanity	1.75	5.00	3.51	0.68
Isolation	1.00	5.00	3.18	0.85
Mindfulness	1.75	5.00	3.55	0.61
Over-identification	1.50	5.00	3.49	0.76

Correspondingly, self-compassion has been established as an effective emotion regulation strategy (Diedrich et al., 2014; Neff, 2003b; Trompetter et al., 2017) and previous research has consistently found that dispositional self-compassion is correlated with DLPFC activity (Berry et al., 2020; Liu et al., 2020b; Williams et al., 2020). For example, Liu et al. (2020b) reported that higher self-compassion was associated with lower activity in the right DLPFC during sad self-face recognition among depressed adolescents, which might indicate lower engagement of cognitive control or emotion regulatory processes for dampening negative emotions induced by sad self-face. Moreover, we found that the self-judgment component was positively correlated with GMV in the same region, suggesting that the relationship between self-compassion and smaller DLPFC was primarily driven by reduced self-judgment. Likewise, Longe et al. (2010) found that self-criticism activated the left DLPFC, suggesting the engagement of inhibitory processes. Together with previous findings on the link between self-compassion and typical circuit connectivity (i.e., VMPFC-amygdala) engaging in emotion regulation during negative social feedback (Parrish et al., 2018), the present results in the DLPFC volume might specifically reflect the role of DLPFC in emotion regulation.

The direction of the link between self-compassion and the left DLPFC volume deserves further discussion. On the one hand, the negative correlation between self-compassion and the left DLPFC volume is different from the past findings of a positive relationship between self-esteem/compassion practice and the right DLPFC volume (Agroskin et al., 2014; Leung et al., 2013). On the other hand, the positive correlation between self-judgment and the left DLPFC volume is consistent with that between brooding and the left DLPFC volume (Sin et al., 2018). Though the negative link between self-compassion and the left DLPFC volume is somewhat unexpected, some previous studies have shown that the premise of “the larger the volume, the better the function” is not always true (Liu et al., 2016). Specifically for the left DLPFC volume, it has been found to be negatively correlated with positive constructs such as social well-being (Kong et al., 2015) and trait elevation (a positive emotion induced by witnessing moral beauty) (Liu et al., 2018), and positively with negative constructs such as brooding (Sin et al., 2018) and permissive attitudes toward suicide (Liu et al., 2016). It has been reported that young adults exhibit growth in executive control function but reduced gray matter density because of events such as increased myelination and synaptic pruning in dorsal frontal cortex (Sowell et al., 2001). According to this account, a smaller left DLPFC among self-compassionate individuals might be reflective of more efficient myelination or synaptic pruning and thus better ability in emotion regulation, which might further contribute to lower level of brooding and permissive attitudes toward suicide. The potential relationship between self-compassion, a smaller left DLPFC and brooding/permissive attitudes toward suicide deserves further investigation.

Considering that the link between self-compassion and smaller left DLPFC volume was primarily driven by the (reduced) self-judgment component, an alternative interpretation of the negative link between self-compassion and the left DLPFC volume is that larger left DLPFC may correspond to more frequent spontaneous compensatory emotion regulation processes evoked by self-judgment/criticism. Previous research has found that self-criticism activated the left DLPFC (Longe et al., 2010), and that brooding, a construct closely associated with self-judgment/criticism, showed positive correlation with the left DLPFC volume (Sin et al., 2018). It is possible that a larger left DLPFC among less self-compassionate individuals might be reflective of more frequent spontaneous regulation of negative emotions induced by perceived self-discrepancies from self-judgment/criticism. Consistent with this account, negative affect has been found to be positively correlated with cortical density in the left DLPFC (Zhu et al., 2020). Together with the findings that healthy and unhealthy emotion regulation strategies (i.e., reappraisal and suppression, respectively) both activated DLPFC (Etkin et al., 2015; Goldin et al., 2008), it is possible that a single index of GMV in DLPFC cannot be an indicator of how good

Table 2Structural neural correlates of dispositional self-compassion and its components ($p_{uncorr} < 0.001$ at voxel level, cluster-level $p_{FWE} < 0.05$).

Region	Direction	Hemisphere	Cluster Size (K)	MNI coordinates			Z
				X	y	z	
Dispositional self-compassion							
DLPFC (MFG), BA10/46	Negative	Left	228	-32	59	18	4.06
Self-kindness							
Calcarine/precuneus, BA23	Positive	Right	162 ^a	8	-59	14	3.78
Self-judgment							
DLPFC (MFG/IFG), BA10/46	Positive	Left	286	-47	53	14	4.71
Recognition of common humanity							
Cerebellum/fusiform, BA18/19	Positive	Left	167 ^a	-39	-83	-20	4.37
Isolation							
ITG/temporal pole, BA21/38/20	Positive	Right	369	51	5	-45	4.57
Mindfulness							
SMA, BA6	Positive	Left	251	-9	-8	57	4.34
DMPFC (SFG)/ACC, BA9/32/10/6	Positive	Left/Right	782	-9	39	38	4.33
Over-identification							
ITG, BA21/20/38	Positive	Right	232	51	5	-45	4.12
SOG/MOG, BA19/7	Negative	Right	276	26	-92	32	3.94

DLPFC, dorsolateral prefrontal cortex; MFG, middle frontal gyrus; IFG, inferior frontal gyrus; ITG, inferior temporal gyrus; SMA, supplementary motor area; DMPFC, dorsomedial prefrontal cortex; SFG, superior frontal gyrus; ACC, anterior cingulate cortex; SOG, superior occipital gyrus; MOG, middle occipital gyrus.

^a Trending results ($p_{uncorr} < 0.001$ at voxel level, cluster-level $p_{FWE} < 0.1$).

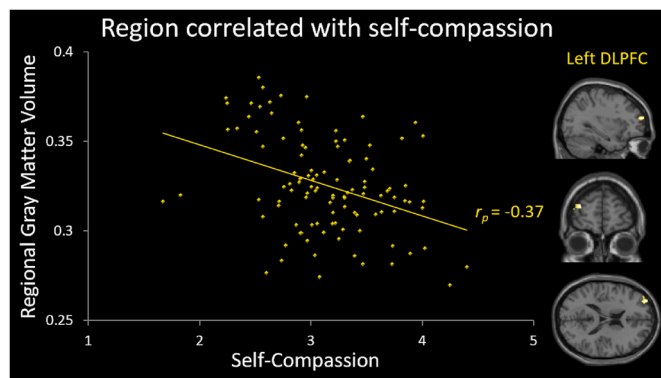


Fig. 1. Neurostructural correlates of dispositional self-compassion. Self-compassion was negatively correlated with GMV in the left dorsolateral prefrontal cortex (DLPFC).

one is at regulating emotions, without more information about what strategies they frequently use.

In addition to the negative link between self-compassion and the left DLPFC volume, the opposite direction with that between self-esteem/compassion and the right DLPFC volume observed in previous studies (Agroskin et al., 2014; Leung et al., 2013) also suggests the hemispheric lateralization of DLPFC (Rêgo et al., 2015; Shi et al., 2021). It has been shown that the left and the right DLPFC have distinct roles in emotion regulation, with the left DLPFC involved in meaning reinterpretation of affective responses and the right DLPFC mediating psychological distancing from affective stimuli (Ochsner et al., 2012; Rêgo et al., 2015). In addition, a recent study reported that the left DLPFC was dominant in inhibiting ipsilateral primary motor cortex (Y. Wang et al., 2020). According to these findings, self-compassion and self-esteem may facilitate positive self-attitudes through distinct emotion regulation mechanisms. Specifically, self-compassion may do so by reducing self-judgment and inhibitory processes (disengaging the left DLPFC), while self-esteem by encouraging distancing from negative stimuli (engaging the right DLPFC). Nevertheless, this hypothesis requires further investigation.

In addition to self-judgment, we also found that the mindfulness component was positively correlated with regions associated with emotion regulation, i.e., DMPFC/ACC and the left SMA. The positive link between mindfulness and ACC volume is especially consistent with

previous findings (Fox et al., 2014; Lu et al., 2014). The mindfulness component of self-compassion indicates that one's failings are seen clearly rather than being ignored or disregarded (Neff, 2003a). Consistent with this, ACC has been associated with error detection (Bush et al., 2000) and emotional awareness (Lane et al., 1998). These are also functions that mindful individuals are good at (Fox et al., 2014). It may be that larger ACC enables stronger error detection/emotional awareness and thus higher level of mindfulness. In addition to ACC, a meta-analysis has shown that SMA is involved in the process of emotion regulation (Kohn et al., 2014). Etkin et al. (2015) proposed that ACC and SMA are involved in two different types of emotion regulation, i.e., model-free and model-based. While model-free emotion regulation proceeds based on prediction error feedback, model-based emotion regulation relies on the application of rule-based decision making. The positive correlation between mindfulness and GMV in both ACC and SMA may indicate that those with higher level of the mindfulness component are good at both types of emotion regulation. On the other hand, both DMPFC and ACC are part of the cortical midline structures, which have been proposed to enable self-referential processing (Northoff and Bermpohl, 2004; Northoff et al., 2006). It is possible that larger DMPFC and ACC in more mindful individuals reflects increased capacity for self-awareness.

The present study showed that both the isolation and the over-identification components were correlated with greater GMV in the right ITG. Longe et al. (2010) has found that self-criticism (similar to self-judgment) activated ITG/MTG and interpreted the association in terms of ITG's role in enhanced emotional salience during self-criticism (Narumoto et al., 2000). However, a meta-analysis (Fox et al., 2014) found that meditation (including mindfulness) practitioners showed significantly greater GMV in ITG, which has been interpreted as the tendency to feel deep pleasure and experience of insight into the unity of all reality. This interpretation is at odds with the positive link between isolation/over-identification and the right ITG volume. A more parsimonious interpretation is that a larger right ITG may reflect stronger tendency to experience salient emotions, irrespective of positive or negative. Consistent with this interpretation, it has been found that dispositional gratitude was positively correlated with GMV in the right ITG (Zahn et al., 2013). Taken together, it is possible that a larger right ITG among those with higher level of isolation and over-identification may reflect stronger tendency to experience salient emotions in face of personal failure or setback.

Finally, we found a negative association between over-identification and GMV in visual areas. Although the visual cortex is traditionally

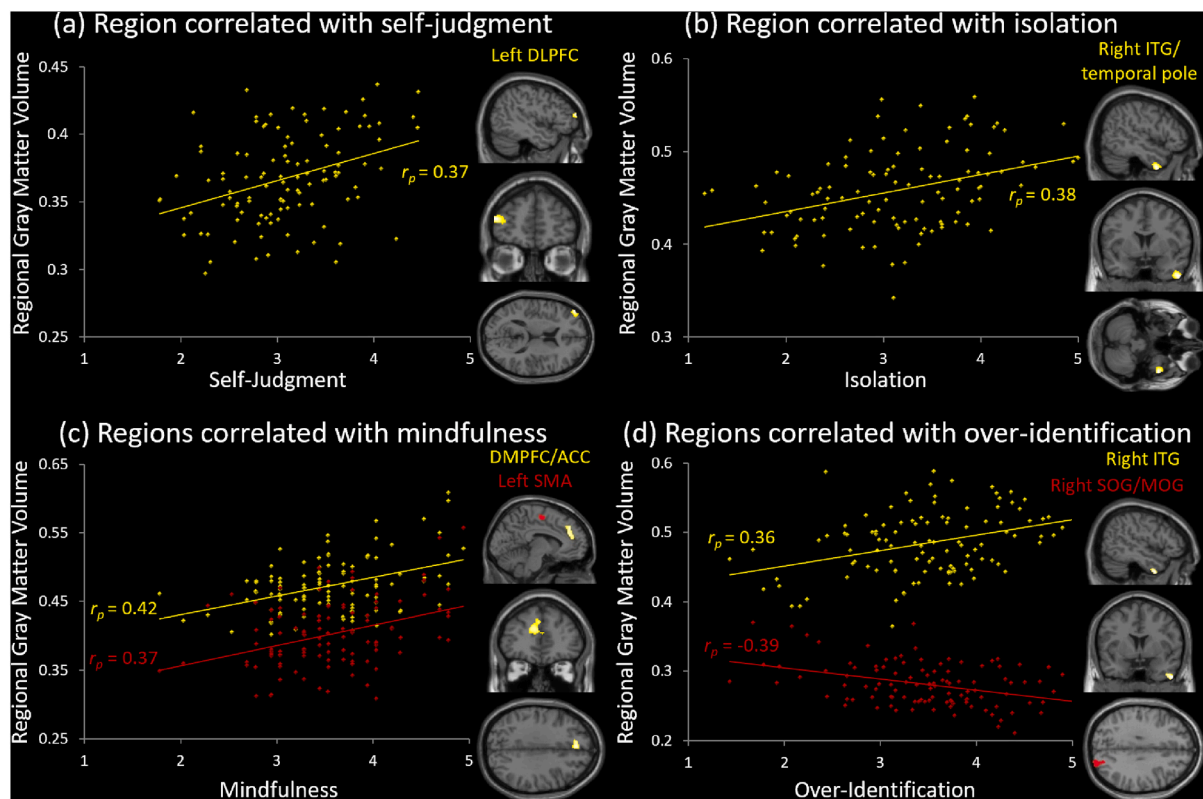


Fig. 2. Neurostructural correlates of self-compassion's components. (a) Self-judgment was associated with greater GMV in the left dorsolateral prefrontal cortex (DLPFC). (b) Isolation was associated with greater GMV in the right inferior temporal gyrus (ITG)/temporal pole. (c) Mindfulness was associated with greater GMV in the left supplementary motor area (SMA) and dorsomedial prefrontal cortex (DMPFC)/anterior cingulate cortex (ACC). (d) Over-identification was associated with greater GMV in the right ITG and less GMV in the right superior occipital gyrus (SOG)/middle occipital gyrus (MOG).

thought to be involved in visual processing, it has recently been found that patterns of human visual cortex activity encode emotion category (Bo et al., 2021; Kragel et al., 2019), consistent with the theory of emotions as adapted canonical responses to situations linked to survival in evolutionary terms (Tooby and Cosmides, 2008). Therefore, a smaller visual cortex in individuals with higher level of over-identification may represent a weaker ability in generating emotions corresponding to the current situations and thus a tendency to be stuck in the negative emotions in the face of failure or setback. This assumption, however, needs further examination.

There are some limitations to this study. First, because it is an exploratory study, the present findings require further validation. Second, it is correlational, and thus cannot establish the causal relationship between dispositional self-compassion and brain structure. Future studies should examine their causal relationship with experimental designs. Third, participants in the present study were all in their early adulthood. Considering the special brain growth of increased myelination and synaptic pruning during this stage (Sowell et al., 2001), it may be necessary to examine the neurostructural correlates of self-compassion and its components in a sample with a broader age range in the future.

5. Conclusion

We investigated the neurostructural correlates of dispositional self-compassion and its components using VBM in a sample of young adults. We showed that dispositional self-compassion was correlated with less GMV in the left DLPFC, which was primarily driven by the reduced self-judgment component. We also found that the mindfulness component was correlated with greater GMV in DMPFC/ACC and the left SMA, while both the isolation and the over-identification component

were correlated positively with GMV in the right ITG, and over-identification additionally correlated with smaller GMV in visual areas. Our findings suggest that a lack of self-compassion is associated with brain structure in regions involved in emotion regulation, self-referential and emotion processing, which may not only have implications for the cognitive and neural mechanisms of self-compassion but also those underlying the effects of self-compassion on its health outcomes.

Credit author statement

Fang Guan: Conceptualization, Investigation, Formal analysis, Writing - Original draft. **Guanmin Liu:** Conceptualization, Formal analysis, Writing - Original draft, Writing - Review & Editing. **Walker S. Pedersen:** Writing - Review & Editing. **Outong Chen:** Investigation, Formal analysis. **Sasa Zhao:** Investigation. **Jie Sui:** Writing - Review & Editing. **Kaiping Peng:** Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

Conflict of interest

The authors declared no conflicts of interest.

Acknowledgments

This work was supported by the Cultural Science Research Fund, School of Social Sciences, Tsinghua University (070202052).

References

- Agroskin, D., Klackl, J., Jonas, E., 2014. The self-liking brain: a VBM study on the structural substrate of self-esteem. *PLoS One* 9, e86430.

- Ashburner, J., 2007. A fast diffeomorphic image registration algorithm. *Neuroimage* 38, 95–113.
- Ashburner, J., 2010. VBM Tutorial. Tech. repWellcome Trust Centre for Neuroimaging, London, UK.
- Berry, M.P., Lutz, J., Schuman-Olivier, Z., Germer, C., Pollak, S., Edwards, R.R., Gardiner, P., Desbordes, G., Napadow, V., 2020. Brief self-compassion training alters neural responses to evoked pain for chronic low back pain: a pilot study. *Pain Med.* 21, 2172–2185.
- Bo, K., Yin, S., Liu, Y., Hu, Z., Meyyappan, S., Kim, S., Keil, A., Ding, M., 2021. Decoding neural representations of affective scenes in retinotopic visual cortex. *Cerebr. Cortex* 31, 3047–3063.
- Bush, G., Luu, P., Posner, M.I., 2000. Cognitive and emotional influences in anterior cingulate cortex. *Trends Cognit. Sci.* 4, 215–222.
- Cox, R.W., 1996. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Comput. Biomed. Res.* 29, 162–173.
- Creswell, J.D., 2017. Mindfulness interventions. *Annu. Rev. Psychol.* 68, 491–516.
- Diamond, A., 2013. Executive functions. *Annu. Rev. Psychol.* 64, 135–168.
- Diedrich, A., Grant, M., Hofmann, S.G., Hiller, W., Berking, M., 2014. Self-compassion as an emotion regulation strategy in major depressive disorder. *Behav. Res. Ther.* 58, 43–51.
- Etkin, A., Büchel, C., Gross, J.J., 2015. The neural bases of emotion regulation. *Nat. Rev. Neurosci.* 16, 693–700.
- Fox, K.C., Nijeboer, S., Dixon, M.L., Floman, J.L., Ellamil, M., Rumak, S.P., Sedlmeier, P., Christoff, K., 2014. Is meditation associated with altered brain structure? A systematic review and meta-analysis of morphometric neuroimaging in meditation practitioners. *Neurosci. Biobehav. Rev.* 43, 48–73.
- Friston, K.J., Ashburner, J., Frith, C.D., Poline, J.B., Heather, J.D., Frackowiak, R.S., 1995. Spatial registration and normalization of images. *Hum. Brain Mapp.* 3, 165–189.
- Goldin, P.R., McRae, K., Ramel, W., Gross, J.J., 2008. The neural bases of emotion regulation: reappraisal and suppression of negative emotion. *Biol. Psychiatr.* 63, 577–586.
- Golkar, A., Lonsdorf, T.B., Olsson, A., Lindstrom, K.M., Berrebi, J., Fransson, P., Schalling, M., Ingvar, M., Öhman, A., 2012. Distinct contributions of the dorsolateral prefrontal and orbitofrontal cortex during emotion regulation. *PLoS One* 7, e48107.
- Guan, F., Xiang, Y., Chen, O., Wang, W., Chen, J., 2018. Neural basis of dispositional awe. *Front. Behav. Neurosci.* 12, 209.
- Hou, X., Allen, T.A., Wei, D., Huang, H., Wang, K., DeYoung, C.G., Qiu, J., 2017. Trait compassion is associated with the neural substrate of empathy. *Cognit. Affect Behav. Neurosci.* 17, 1018–1027.
- Kanai, R., Bahrami, B., Rees, G., 2010. Human parietal cortex structure predicts individual differences in perceptual rivalry. *Curr. Biol.* 20, 1626–1630.
- Kanai, R., Feilden, T., Firth, C., Rees, G., 2011. Political orientations are correlated with brain structure in young adults. *Curr. Biol.* 21, 677–680.
- Kohn, N., Eickhoff, S.B., Scheller, M., Laird, A.R., Fox, P.T., Habel, U.J.N., 2014. Neural network of cognitive emotion regulation—an ALE meta-analysis and MACM analysis. *Neuroimage* 87, 345–355.
- Kong, F., Hu, S., Xue, S., Song, Y., Liu, J., 2015. Extraversion mediates the relationship between structural variations in the dorsolateral prefrontal cortex and social well-being. *Neuroimage* 105, 269–275.
- Kragel, P.A., Reddan, M.C., LaBar, K.S., Wager, T.D., 2019. Emotion schemas are embedded in the human visual system. *Science Advances* 5, eaaw4358.
- Lane, R.D., Reiman, E.M., Axelrod, B., Yun, L.-S., Holmes, A., Schwartz, G.E., 1998. Neural correlates of levels of emotional awareness: evidence of an interaction between emotion and attention in the anterior cingulate cortex. *J. Cognit. Neurosci.* 10, 525–535.
- Leung, M.-K., Chan, C.C., Yin, J., Lee, C.-F., So, K.-F., Lee, T.M., 2013. Increased gray matter volume in the right angular and posterior parahippocampal gyri in loving-kindness meditators. *Soc. Cognit. Affect Neurosci.* 8, 34–39.
- Liu, H., Wang, Y., Liu, W., Wei, D., Yang, J., Du, X., Tian, X., Qiu, J., 2016. Neuroanatomical correlates of attitudes toward suicide in a large healthy sample: a voxel-based morphometric analysis. *Neuropsychologia* 80, 185–193.
- Liu, G., Zeng, G., Wang, F., Rotshtein, P., Peng, K., Sui, J., 2018. Praising others differently: neuroanatomical correlates to individual differences in trait gratitude and elevation. *Soc. Cognit. Affect Neurosci.* 13, 1225–1234.
- Liu, G., Cui, Z., Yu, H., Rotshtein, P., Zhao, F., Wang, H., Peng, K., Sui, J., 2020a. Neural responses to intention and benefit appraisal are critical in distinguishing gratitude and joy. *Sci. Rep.* 10, 1–12.
- Liu, G., Zhang, N., Teoh, J.Y., Egan, C., Zeffiro, T.A., Davidson, R.J., Quevedo, K., 2020b. Self-compassion and dorsolateral prefrontal cortex activity during sad self-face recognition in depressed adolescents. *Psychol. Med.* 1–10.
- Longe, O., Maratos, F.A., Gilbert, P., Evans, G., Volker, F., Rockliff, H., Rippon, G., 2010. Having a word with yourself: neural correlates of self-criticism and self-reassurance. *Neuroimage* 49, 1849–1856.
- Lu, H., Song, Y., Xu, M., Wang, X., Li, X., Liu, J., 2014. The brain structure correlates of individual differences in trait mindfulness: a voxel-based morphometry study. *Neuroscience* 272, 21–28.
- Miller, E.K., Cohen, J.D., 2001. An integrative theory of prefrontal cortex function. *Annu. Rev. Neurosci.* 24, 167–202.
- Muris, P., Petrocchi, N., 2017. Protection or vulnerability? A meta-analysis of the relations between the positive and negative components of self-compassion and psychopathology. *Clin. Psychol. Psychother.* 24, 373–383.
- Narumoto, J., Yamada, H., Iidaka, T., Sadato, N., Fukui, K., Itoh, H., Yonekura, Y., 2000. Brain regions involved in verbal or non-verbal aspects of facial emotion recognition. *Neuroreport* 11, 2571–2574.
- Neff, K.D., 2003a. The development and validation of a scale to measure self-compassion. *Self Ident.* 2, 223–250.
- Neff, K.D., 2003b. Self-compassion: an alternative conceptualization of a healthy attitude toward oneself. *Self Ident.* 2, 85–101.
- Neff, K.D., Long, P., Knox, M.C., Davidson, O., Kuchar, A., Costigan, A., Williamson, Z., Rohleder, N., Tóth-Király, I., Breines, J.G., 2018. The forest and the trees: examining the association of self-compassion and its positive and negative components with psychological functioning. *Self Ident.* 17, 627–645.
- Northoff, G., Bermpohl, F., 2004. Cortical midline structures and the self. *Trends Cognit. Sci.* 8, 102–107.
- 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, 440–457.
- Ochsner, K.N., Silvers, J.A., Buhle, J.T., 2012. Functional imaging studies of emotion regulation: a synthetic review and evolving model of the cognitive control of emotion. *Ann. N. Y. Acad. Sci.* 1251.
- Parrish, M.H., Inagaki, T.K., Muscatell, K.A., Haltom, K.E., Leary, M.R., Eisenberger, N.I., 2018. Self-compassion and responses to negative social feedback: the role of fronto-amygdala circuit connectivity. *Self Ident.* 17, 723–738.
- Raes, F., 2010. Rumination and worry as mediators of the relationship between self-compassion and depression and anxiety. *Pers. Individ. Differ.* 48, 757–761.
- Rêgo, G.G., Lapenta, O.M., Marques, L.M., Costa, T.L., Leite, J., Carvalho, S., Gonçalves, Ó.F., Brunoni, A.R., Fregni, F., Boggio, P.S., 2015. Hemispheric dorsolateral prefrontal cortex lateralization in the regulation of empathy for pain. *Neurosci. Lett.* 594, 12–16.
- Shi, G., Li, X., Zhu, Y., Shang, R., Sun, Y., Guo, H., Sui, J., 2021. The divided brain: functional brain asymmetry underlying self-construal. *Neuroimage* 118382.
- Sin, E.L., Shao, R., Geng, X., Cho, V., Lee, T., 2018. The neuroanatomical basis of two subcomponents of rumination: a VBM study. *Front. Hum. Neurosci.* 12, 324.
- Smith, C.D., Chebrolu, H., Wekstein, D.R., Schmitt, F.A., Markesbery, W.R., 2007. Age and gender effects on human brain anatomy: a voxel-based morphometric study in healthy elderly. *Neurobiol. Aging* 28, 1075–1087.
- Sowell, E.R., Thompson, P.M., Tessner, K.D., Toga, A.W., 2001. Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: inverse relationships during postadolescent brain maturation. *J. Neurosci.* 21, 8819–8829.
- Sui, J., Gu, X., 2017. Self as object: emerging trends in self research. *Trends Neurosci.* 40 (11), 643–653.
- Sui, J., Rotshtein, P., Humphreys, G.W., 2013. Coupling social attention to the self forms a network for personal significance. *Proc. Natl. Acad. Sci. Unit. States Am.* 110, 7607–7612.
- Tooby, J., Cosmides, L., 2008. The evolutionary psychology of the emotions and their relationship to internal regulatory variables. In: Lewis, M., Haviland-Jones, J.M., Barrett, L.F. (Eds.), *Handbook of Emotions*. The Guilford Press, New York, NY, pp. 114–137.
- Treynor, W., Gonzalez, R., Nolen-Hoeksema, S., 2003. Rumination reconsidered: a psychometric analysis. *Cognit. Ther. Res.* 27, 247–259.
- Trompetter, H.R., de Kleine, E., Bohlmeijer, E.T., 2017. Why does positive mental health buffer against psychopathology? An exploratory study on self-compassion as a resilience mechanism and adaptive emotion regulation strategy. *Cognit. Ther. Res.* 41, 459–468.
- Wang, F., Peng, K., Chechlac, M., Humphreys, G.W., Sui, J., 2017. The neural basis of independence versus interdependence orientations: a voxel-based morphometric analysis of brain volume. *Psychol. Sci.* 28, 519–529.
- Wang, Y., Cao, N., Lin, Y., Chen, R., Zhang, J., 2020. Hemispheric differences in functional interactions between the dorsal lateral prefrontal cortex and ipsilateral motor cortex. *Front. Hum. Neurosci.* 14, 202.
- Williams, K., Elliott, R., McKie, S., Zahn, R., Barnhofer, T., Anderson, I.M., 2020. Changes in the neural correlates of self-blame following mindfulness-based cognitive therapy in remitted depressed participants. *Psychiatr. Res. Neuroimaging* 304, 111152.
- Yankouskaya, A., Sui, J., 2021. Self-positivity or self-negativity as a function of the medial prefrontal cortex. *Brain Sci.* 11, 264.
- Zahn, R., Garrido, G., Moll, J., Grafman, J., 2013. Individual differences in posterior cortical volume correlate with proneness to pride and gratitude. *Soc. Cognit. Affect Neurosci.* 9, 1676–1683.
- Zhu, X., Wang, K., Cao, A., Zhang, Y., Qiu, J., 2020. Personality traits and negative affect mediate the relationship between cortical thickness of superior frontal cortex and aggressive behavior. *Neurosci. Lett.* 718, 134728.