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ORIGINAL RESEARCH

Common and distinct neural substrates of the compassionate and uncompassionate self-responding dimensions of self-compassion

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Abstract

Self-compassion is beneficial for individuals' emotional health, but debates regarding its conceptualization are increasing. The present study aimed to explore the neural basis of self-compassion and its compassionate and uncompassionate dimensions and the indirect path from neural basis to emotional health. Structural MRI and Resting-state fMRI data were used to measure the gray matter volume (GMV) and the amplitude of low-frequency fluctuation (ALFF) in 88 healthy college students. We found that individuals with higher self-compassion had decreased GMV in the prefrontal cortex, cerebellum as well as lower ALFF in the occipital lobe. The compassionate and uncompassionate dimensions of self-compassion shared some similarities (e.g., common correlation with GMV in the medial prefrontal cortex, ALFF in the occipital lobe) but also had some differences (e.g., only uncompassionate dimensions correlated with GMV in the lateral prefrontal cortex, ALFF in medial temporal lobe/striatum). The indirect path analyses revealed that corresponding brain characteristics could have associations with emotional health through self-compassion, as well as its uncompassionate dimension, but not compassionate dimension. This exploratory whole-brain study showed some preliminary findings that compassionate and uncompassionate dimensions of self-compassion were related to distinct brain regions, which are both important to the current conceptualization of self-compassion and intervention study.

Keywords Self-compassion · Gray matter volume · Amplitude of low-frequency fluctuation · Positive and negative affect · Depression

Introduction

Over the past two decades, the research interest in self-compassion has greatly increased (Neff, 2016). As a potential protective factor and healthier self-attitude, accumulated empirical studies have been conducted and have supported the positive effect of self-compassion on alleviating mental health problems (MacBeth & Gumley, 2012; Pinto-Gouveia et al., 2014) and promoting well-being (Neff & Germer, 2017; Zessin et al., 2015). Self-compassion was also an important internal psychological resource that can help individuals find hope and strength in the face of difficulties in life (Macbeth & Gumley, 2012; Pinto-Gouveia et al., 2014). Bedsides, low level of self-compassion could also be a predictor of mental disease (e.g., depression, Krieger et al., 2016). Although interest in compassion toward the self has emerged since the beginning of this century, Neff was the first to provide the operational definition of self-compassion (Neff, 2003a), which was defined as being open and non-judgmental toward one's own suffering, inadequacies and failure, and having the desire to alleviate one's own pain with kindness. As such, this concept involves three components with two opposite ends: (1) being kind or judgmental to oneself when facing suffering, (2) recognizing that suffering is a common part of the human experience or feeling it is unique to oneself and feeling isolated from other people, and (3) maintaining moment-to-moment awareness of personal suffering or becoming fully absorbed.

According to this conceptualization, the Self-Compassion Scale (SCS) was developed, which consists of six subscales (self-kindness vs. self-judgment, common humanity vs. isolation, and mindfulness vs. over-identification) (Neff,

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2003b). This scale has been the most widely used measure in self-compassion research (Muris & Otgaar, 2020). However, researchers have raised questions about the validity of conceptualization about self-compassion in recent years, which would make the research efforts on self-compassion built on a biased, or even flawed, scientific foundation (Muris & Otgaar, 2020). The main argument was about the definition and assessment of the negative half of self-compassion attribute (Muris & Otgaar, 2020; Muris et al., 2018). While the developer of the concept of self-compassion contends its original definition and assessment (Neff, 2016, 2019), some researchers were skeptical about the inclusion of the negative aspect (Muris & Otgaar, 2020) and found a better fit using a two-factor structure of the SCS (Brenner et al., 2017; Costa et al., 2016; López et al., 2015; Muris & Petrocchi, 2017; Williams et al., 2014). The subscales reflecting a compassionate response toward the self (self-kindness, common humanity, and mindfulness) were grouped together, whereas the uncompassionate counterparts (self-judgment, isolation, and over-identification) constituted a separate factor (Brenner et al., 2017; Costa et al., 2016; López et al., 2015; Muris et al., 2018; Williams et al., 2014). Considering the potential influences from self-compassion to mental health, researchers further investigated the relationship between the two parts of the SCS and mental health, which showed a divergent pattern. Specifically, the compassionate dimension was more prone to associate with variables reflecting well-being, whereas the uncompassionate dimension was more likely to be related to symptoms (Brenner et al., 2017, 2018; Chan et al., 2020; López et al., 2015; Muris et al., 2018). These results further questioned the rationale of combining the compassionate and uncompassionate dimensions into one concept. The potential drawbacks of doing so have been elaborated by Muris and Otgaar (2020). Therefore, it is of great theoretical and empirical importance to further examine the association and distinction of the two dimensions.

Neuroscience studies can contribute to this research question. Advancements in neuroimaging technology can capture both structural and functional findings about the neural bases of individual differences in various psychological characteristics. Structural magnetic resonance imaging (sMRI) captures brain morphology features [e.g., gray matter volume (GMV) and gray matter thickness], which can be used to explore the anatomical structure of individual differences in a variety of personal characteristics, such as well-being (Lewis et al., 2014; Sato et al., 2015), personality (Bjørnebekk et al., 2013), dispositional mindfulness (Murakami et al., 2012; Taren et al., 2013), and dispositional rumination (Kühn et al., 2012). To our knowledge, there is only one recent study using sMRI to investigate the GMV of self-compassion (Guan et al., 2021). They found that self-compassion was a negative correlation with GMV in the dorsolateral prefrontal cortex. Additionally, four of six subscales (i.e., mindfulness, self-judgment, isolation, and over-identification) are correlated with GMV in different brain regions. Resting-state functional MRI (R-fMRI) captures the spontaneous neural activity of the brain without any specific tasks, which can be measure by amplitude of low-frequency fluctuation (ALFF). ALFF reflects the intensity of low-frequency fluctuation in local brain regions and has been used to examine brain functional mechanisms with individual behavior performance, including well-being (Kong et al., 2015), personality (Kunisato et al., 2011), dispositional mindfulness (Kong et al., 2016), and dispositional rumination (Kühn et al., 2012). A recent task-based fMRI study suggested that self-compassion was negatively associated with activation of the right dorsolateral prefrontal cortex during self-processing in depressed adolescents (Liu et al., 2022). However, to the best of our knowledge, no study has investigated the neural basis of compassionate and uncompassionate responses toward the self from brain structure and function simultaneously. Interestingly, one task-based fMRI study has investigated the neural substrates of self-criticism and self-reassurance (Longe et al., 2010), which may be related to the two dimensions of self-compassion. They found that the temporal pole and insula were activated when individuals engaged in self-reassuring process. Meanwhile, the lateral prefrontal gyrus, medial prefrontal gyrus, dorsal anterior cingulate gyrus, and occipital gyrus were activated during self-criticism process. The insula is associated with the monitoring of internal states (Damasio, 1999; Phan et al., 2002) and the self-referential process (Modinos et al., 2009; Northoff et al., 2006). Lateral prefrontal gyrus activity is associated with self-criticism (N. Doerig et al., 2014; Longe et al., 2010), error monitoring and inhibition of inappropriate behavior (Miller & Cohen, 2001). Anderson et al. (2010) found that functional connections between the medial temporal and lateral prefrontal gyrus were associated with inhibition of unnecessary memories. Therefore, we speculate that the compassionate dimension may be involved in the neural basis related to self-referential processes, such as the prefrontal gyrus, temporal gyrus and insula. The uncompassionate dimension may be involved in the neural basis related with processes of self-reference, error-monitoring, problem solving, and behavior inhibition, such as the prefrontal gyrus, dorsal anterior cingulate gyrus, the medial temporal gyrus, and the occipital gyrus. Both dimensions may be jointly related to the neural basis related with self-referential function.

Numerous studies have supported that self-compassion was closely linked to individual's emotional well-being, showing positive correlations with positive affect and negative correlations with negative affect (Krieger et al., 2015; Neff et al., 2007; Zessin et al., 2015), since self-compassion encourages adaptive coping strategies and positive automatic thoughts when facing setbacks. In addition to affective outcomes, meta-analyses found that self-compassion was strongly negatively associated with depressive symptoms (MacBeth & Gumley, 2012; Muris & Petrocchi, 2017). Moreover, the uncompassionate dimension outperformed compassionate dimension in predicting depressive symptoms over a 12-month interval (López et al., 2018a, b), which highlighted the role of the uncompassionate dimension of self-compassion in the experience of depressive symptoms. Self-compassion is an influential emotion regulation strategy predicting more emotional health and fewer depressive symptom, however little is known about the structural and functional neural substrates underlying this relationship.

Here, the aims of the present study are three-fold. First, the neural basis of self-compassion, as well as the compassionate and uncompassionate self-responding dimensions, was explored. Second, the relations of self-compassion and the two dimensions with mental health variables were examined. Third, further explored whether self-compassion-related brain regions could indirectly correlate with mental health variables through self-compassion. Three corresponding hypotheses are proposed: (1) We hypothesized that the neural basis of compassionate and uncompassionate dimensions of self-compassion would be different. Specifically, the compassionate dimension may be related to neural basis involved in self-referential processes (e.g., medial prefrontal gyrus), while the uncompassionate dimension may be related to neural basis involved in processes of self-reference, error-monitoring and behavior inhibition (e.g., medial and lateral prefrontal gyrus, medial temporal gyrus). To avoid missing any neural involvement, whole-brain association analyses were conducted by correlating participants' trait scores with the gray matter volume (GMV) from structural MRI and the amplitude of low-frequency fluctuation (ALFF) value from R-fMRI separately for each gray matter voxel. More importantly, the relations with brain characteristics were evaluated separately for the compassionate and uncompassionate self-responding dimensions so that the findings could be compared to examine the associations and distinctions between them. These results may have implications for the conceptualization of self-compassion. (2) According to previous studies (MacBeth & Gumley, 2012; Muris & Petrocchi, 2017; Zessin et al., 2015), we hypothesized that there would be differential associations of compassionate and uncompassionate self-compassion with three mental health variables ranging from affect to symptom (i.e., positive affect, negative affect, and depression). Specifically, self-compassion and compassionate dimension would positively correlate with positive affect but negatively correlate with negative affect and depression, which would positively correlate with the uncompassionate dimension. (3) The self-compassion-related brain regions could indirectly correlate with mental health variables through self-compassion. It could imply that the specific brain region could have an impact on the individual trait of self-compassion and in turn, benefit the individual's well-being. In line with the above two goals, the results of two dimensions were calculated separately and compared to further provide evidence for the conceptualization argument.

Method

Participants

To estimate a priori sample size for correlation analysis, we firstly expected this study could detect a medium-sized effect (i.e., absolute correlation r-value ranging from 0.30 to 0.50) based on the findings of previous relevant studies (Guan et al., 2021; Longe et al., 2010; Parrish et al., 2018). Then, we employed the G*Power analysis program to calculate the sample size to ensure adequate power to detect a medium-size effect (Faul et al., 2009). The input parameters were as follows: effect size $|\rho| = 0.30$; type I error $\alpha = 0.05$; and power $(1-\beta) = 0.80$. As a result, a minimum sample size of 84 was calculated for a medium-size effect at an alpha level of 0.05 and with a power of 0.8. Here, ninety-three healthy right-handed Chinese participants were recruited and received payment for attending this study. All participants had no history of neurological or psychiatric disorders, sensorimotor or cognitive impairment, or other anatomical injuries of the brain. The present study was approved by the Institutional Review Board in the Department of Psychology, Sun Yat-sen University. Written informed consent was obtained from all participants. Five participants were excluded for excessive head motion (see "*Data Analyses*"). The data of the remaining 88 participants (mean age = 18.98 ± 1.09 years old, females = 60) were used for further analysis.

Measures

Self-compassion The 26-item Chinese version of the SCS (Chen et al., 2011; Neff, 2003b) was used to assess self-compassion. Participants responded from 1 (almost never) to 5 (almost always) for each item. The SCS consists of six subscales: self-kindness, self-judgment, common humanity, isolation, mindfulness, and over-identification. The total score of the SCS was used as the indicator of self-compassion. According to the two-factor model of the SCS (Brenner et al., 2017; Costa et al., 2016; López et al., 2015; Muris et al., 2018; Williams et al., 2014), a compassionate self-responding dimension (containing items from the original self-kindness, common humanity and mindfulness subscales) and an uncompassionate self-responding dimension (containing items from the self-judgment, isolation and over-identification subscales) were generated. The reliability of the self-compassion, compassionate and uncompassionate dimensions in this study was acceptable (Cronbach's $\alpha = 0.619$, 0.878, and 0.834, respectively). Before investigating neural substrates of the compassionate and uncompassionate dimensions of self-compassion, we first performed a confirmatory factor analysis (CFA) using M*plus* to examine the degree to which the theoretical two-factor model fits our data. First, the 26 items of the Self-Compassion Scale were loaded to two factors according to their corresponding dimension division. Second, we improved the model fit performance using modification indices (MI), which is a method that targets to increase model fit by removing model restrictions, such as allowing residuals of different items to be correlated. Meanwhile, we calculated the following fit indices to evaluate model fit: Confirmatory Fit Index (CFI), Tucker Lewis index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Mean Square Residual (SRMR).

Positive and negative affect The 18-item Chinese version of the Positive and Negative Affect Schedule (PANAS) (Qiu et al., 2008; Watson et al., 1988) was used to assess individuals' positive and negative affect. The Chinese version of the PANAS was translated from the original English version and two of the 20 items were removed because of low factor loading (Qiu et al., 2008). The PANAS consists of a word list describing two kinds of affect states (nine positive and nine negative words) (e.g., 'active' and 'afraid'). Participants were asked to rate the extent to which they experienced each specific affect in their daily life from 1 (very slightly or not at all) to 5 (very much). The reliability was acceptable for both positive affect and negative affect subscales in the current study (Cronbach's $\alpha = 0.873$ and 0.721, respectively).

Depression The depression subscale of the 21-item Chinese version of the Depression Anxiety Stress Scales (Gong et al., 2010; Lovibond & Lovibond, 1995) was used in the current study. It has 7 items (e.g., 'I felt down-hearted and blue') ranging from 1 (did not apply to me at all) to 5 (applied to me very much) and had acceptable reliability in the current study (Cronbach's $\alpha = 0.830$).

MRI Acquisition All participants were scanned using a Siemens 3.0 Tesla MRI scanner (Siemens, Erlangen, Germany) at South China Normal University (Guangzhou, China). Headphones and foam pads were used to avoid interference from scanner noise and reduce participants' head motion while scanning. The participants were instructed to close their eyes, stay awake without thinking anything and keep awake during the scanning. Structural T1-weighted images were obtained in a sagittal orientation by employing a magnetization-prepared rapid gradient-echo sequence: repetition time (TR) = 1900 ms, echo time (TE) = 2.52 ms, flip angle (FA) = 9°, field of view (FOV) = 256×256 mm^2, inversion time = 900 ms, matrix = 256×256, slices = 176, slice thickness = 1 mm and voxel size = $1 \times 1 \times 1$ mm^3. R-fMRI data were collected using an echo-planar imaging sequence: TR = 2000 ms, TE = 30 ms, FA = 9°, FOV = 224×224 mm^2, slices = 32, matrix = 64×64, slice thickness = 3.5 mm and voxel size = $3.5 \times 3.5 \times 3.5$ mm^3. The total number of collected functional volumes was 240 for each participant. After scanning, all participants confirmed that they had stayed awake during the scan and were asked to complete the following behavioral assessments: the Chinese version of the Self-Compassion Scale, Positive and Negative Affect Schedule and Depression Anxiety Stress Scales.

Image preprocessing

Voxel-based morphometric analysis of the structural MRI data was performed using the Data Processing Assistant for Resting-State fMRI (DPARSF, http://rfmri.org/DPARSF) (Yan et al., 2016) toolbox and Statistical Parametric Mapping (SPM8, https://www.fil.ion.ucl.ac.uk/spm) based on the MATLAB platform. Briefly, the structural images were first segmented into gray matter (GM), white matter (WM), and cerebrospinal fluid (CSF) by using the "New Segment" feature in SPM8 (Ashburner & Friston, 2005). Next, to increase the accuracy of brain registration between participants (Ashburner, 2007), a custom, study-specific GM template was obtained from the whole image data using the Diffeomorphic Anatomic Registration Through Exponentiated Lie Algebra (DARTEL) algorithm. Later, each participant's GM density (GMD) image of native space was warped to the GM DARTEL template. The resultant image was registered to MNI space, and the GMD map was obtained in MNI space. Then, an individual's gray matter volume map was generated by multiplying the resulting GMD map with the Jacobian determinant. The resulting maps were smoothed with an 8 mm full-width at half-maximum Gaussian kernel and then resampled to 3-mm isotropic voxels.

The preprocessing of R-fMRI data was also implemented using DPARSF and SPM8. First, to stabilize the signal that may be influenced by factors related to scanning machines and participants' adaption, we removed the first 10 functional volumes for each participant. These remaining functional images were corrected for acquisition time delay between slices. Then, the volumes were realigned to the first volume to correct for head motion. The head motion of each participant was checked, and five participants were excluded under the threshold criteria of 2 mm or 2 degrees. Considering that age has a significant influence on brain structure and function (Bethlehem et al., 2022), the data excluding one adolescent participant (age 17 years old) were also used to conduct the complete analyses and the results were substantively unchanged (for details, see Fig. S1, Fig. S2 and Table S7 in the Supplemental

Materials). Next, T1-weighted images were co-registered to the motion-corrected functional images by linear transformation (Collignon et al., 1995). These structural images were then segmented into GM, WM and CSF maps by using a unified segmentation algorithm (Ashburner & Friston, 2005). After that, we spatially normalized motion-corrected functional images into MNI space using the normalization parameters estimated during unified segmentation and then resampled the images into 3-mm isotropic voxels. Next, we smoothed the normalized functional images using a Gaussian kernel (FWHM = 4 mm × 4 mm × 4 mm). Finally, we removed the linear trends and regressed out the nuisance variables (Friston 24 head motion parameters, WM and CSF signals) from the original signal of each voxel. After preprocessing, we calculated the amplitude of regional spontaneous neural activity presented with the ALFF value (Zang et al., 2007) for each participant. Briefly, the time series of each voxel was transformed to the frequency domain using a fast Fourier transform. Next, the averaged square root (i.e., the ALFF value) of the power spectrum ranging from 0.01 to 0.08 Hz was calculated. Finally, ALFF values for each participant were transformed to Z scores for normalization at the voxel level. A higher ALFF value reflected greater intrinsic neural activity.

Correlation analysis

Voxel-wise correlation analysis was conducted to explore how the structural and functional brain regions were related to self-compassion, the compassionate dimension and the uncompassionate dimension separately. Partial correlation between a specific trait score and the GMV or ALFF value was calculated in a voxel-wise manner within the GM mask, which was generated by thresholding the a priori GM probability map at 0.2 in SPM, with setting age and sex as two covariates; prior studies have revealed stable age and sex differences existing both in the structural brain and functional brain (Barnes et al., 2010). To control the false positive rate caused by multiple statistical comparisons, the AFNI AlphaSim program (http://afni.nimh.nih.gov/pub/dist/doc/manual/AlphaSim.pdf) was used. Given the exploratory nature of the current study, we used a rather lenient voxel-level p threshold to identify significant voxels (Bender & Lange, 2001; Cao & Zhang, 2014). Specifically, the statistically significant threshold for GMV/ALFF correlation analysis was set at voxel-level $p_{uncorr} < 0.05$ in line with previous neuroimaging studies (Qi et al., 2019; Yuan et al., 2020; Zhao et al., 2017), with cluster size greater than 1016/250, 1017/259 and 1032/260 voxels for the self-compassion, compassionate and uncompassionate dimensions respectively, which corresponded to cluster-level family-wise error (FWE) corrected $p_{FWE} < 0.05$.

To further evaluate the specificity of brain regions associated with each single dimension, we put compassionate and uncompassionate dimensions into the same model. Specifically, for GMV correlation analyses, we first obtained the shared brain region map of compassionate and uncompassionate dimensions by spatially overlapping their significant brain region map. Then, to determine the range of brain regions that were uniquely related to a certain dimension (i.e., unique brain region), we removed the shared brain region from each significant cluster. Third, we calculated the partial Pearson correlation between the mean GMV values of each unique brain region and the scores of corresponding self-compassion dimensions (e.g., compassionate dimension), controlling for another dimension (e.g., uncompassionate dimension), age and sex as three covariates. Brain regions with significant r values were considered to be unique for corresponding self-compassion dimension. Following the same procedure, we also conducted brain region specificity analyses for the significant brain regions derived from ALFF correlation analysis.

To evaluate the association between GMV/ALFF and self-compassion was well as its two dimensions, and locate the region of interest (ROI) independent of the present data, we further employed ROIs derived from related previous research (Guan et al., 2021) of exploring the neurostructural basis of self-compassion [MNI coordinates: dorsolateral prefrontal cortex (DLPFC): x/y/z = -32/59/18; DLPFC2: x/y/z = -47/53/14; Calcarine (CAL): x/y/z = 8/-59/14; Cerebellum: x/y/z = -39/-83/-20; inferior temporal gyrus (ITG): x/y/z = 51/5/-45; supplementary motor area (SMA): x/y/z = -9/-8/57; dorsomedial prefrontal cortex (DMPFC): x/y/z = -9/39/38; superior occipital gyrus (SOG): x/y/z = 26/-92/32]. The ROIs were defined as spheres with radii of 6 mm centered at the peak voxel of significant clusters. Then, a partial correlation between GMV/ALFF of these ROIs and self-compassion total scores or its dimensional scores was performed with age and sex as two covariates.

The correlations between three self-compassion-related variables and mental health variables were also calculated. We collected daily positive and negative affect as a measurement of mental health. Besides, considering the different relationships between depression and two dimensions of SCS, we also collected scores of depression. To investigate the differences among correlation coefficients, a statistical comparison of correlations was applied to test whether the r values were statistically different in magnitude (Diedenhofen & Musch, 2015; Meng et al., 1992). Notably, when calculating the correlations between the compassionate dimension and mental health variables, partial correlation was conducted with the uncompassionate dimension controlled for, and vice versa.

Indirect effect analyses

After finding the specific brain regions related to self-compassion and its two dimensions, a series of indirect effect analyses was conducted to explore the potential indirect effect from a neural basis to mental health variables through self-compassion-related variables. All path analyses were conducted in SPSS 22.0. Five thousand bootstrap samples were used to examine the indirect effect (Preacher & Hayes, 2008). If the 95% bias-corrected confidence intervals did not include zero, the indirect effects were deemed statistically significant.

Results

Model fit

A confirmatory factor analysis (CFA) was conducted to examine the degree to which the theoretical two-factor model fits our data. The results of our CFA analysis were as follows: CFI = 0.943, TLI = 0.936, RMSEA = 0.040, SRMR = 0.071. According to previous studies (Hox et al., 2017; Hu & Bentler, 1999), RMSEA below 0.06, SRMR below 0.08, and CFI and TLI estimate greater than 0.90 are indicative of acceptable model-data fit, hence the theoretical two-factor model showed adequate and acceptable fit to our data.

self-compassion related brain regions

Brain structural regions Correlation analyses for GMV revealed 3 self-compassion-related regions, including the left cerebellum (MNI coordinates of the peak voxel: [-27, -87, -51] mm), right cerebellum (MNI coordinates of the peak voxel: [9, -30, -42] mm) and prefrontal cortex (PFC)/temporal lobe (MNI coordinates of the peak voxel: [18, 39, 36] mm) (Table 1, Fig. 1A). The mean GM volumes of these three clusters were negatively correlated with self-compassion (r = -0.331, p = 0.002; r = -0.357, p = 0.001; and r = -0.368, $p < 0.001$, respectively). Further examining the two dimensions of self-compassion, the medial PFC (MNI coordinates of the peak voxel: [18, 60, 12] mm) and cerebellum (MNI coordinates of the peak voxel: [9, -30, -42] mm) were identified as compassionate dimension-related regions (Table 1, Fig. 1B), and the lateral and medial PFC (MNI coordinates of the peak voxel: [-12, 12, 69] mm) were identified as uncompassionate dimension-related regions (Table 1, Fig. 1C). Mean GM volumes of the medial PFC and cerebellum were negatively correlated with the compassionate dimension (r = -0.301, p = 0.005 for the PFC and r = -0.397, $p < 0.001$ for the cerebellum). The mean GM volume of the lateral and medial PFC was positively correlated with the uncompassionate dimension (r = 0.395, $p < 0.001$). The mean GMV values of the medial PFC, which was the overlapping brain regions, were significantly associated with both compassionate and uncompassionate dimensions simultaneously (r = -0.290, p = 0.007 for compassionate dimension and r = 0.322, p = 0.003 for uncompassionate dimension, Table 2). Moreover, the brain region specificity analyses for GMV correlation analysis showed that the correlations between the mean GM volumes of dimension-specific regions and corresponding dimension scores were significant after controlling for the effects of another dimension, age and sex (Table S1).

Table 1 Structural and functional neural correlates of self-compassion and its compassionate and uncompassionate dimension (voxel-level $p_{uncorr} < 0.05$, cluster-level $p_{FWE} < 0.05$)

Region	Hemisphere	Cluster size (number of voxel)	MNI coordinate			*r* value
			x	y	z	
Self-compassion						
CBL (GMV)	left	1055	-27	-87	-51	-0.378
CBR (GMV)	right	2015	9	-30	-42	-0.429
PFC (GMV)	right	4584	18	39	36	-0.391
OC (ALFF)	right	758	27	-99	3	-0.436
Compassionate self-responding dimension						
PFC (GMV)	right	1035	18	60	12	-0.338
CB (GMV)	right	4236	9	-30	-42	-0.415
OC (ALFF)	right	348	18	-69	45	0.346
Uncompassionate self-responding dimension						
PFC (GMV)	left	4608	-12	12	69	0.400
OCL (ALFF)	left	334	-18	-84	24	0.366
OCR (ALFF)	right	310	27	-99	3	0.410
MTL/STR (ALFF)	left	725	-51	-27	-33	-0.460

Age and sex were controlled for in all whole-brain correlation analyses. *CBL* left cerebellum, *CBR* right cerebellum, *PFC* prefrontal cortex, *OC* occipital lobe, *CB* cerebellum, *OCL* left occipital lobe, *OCR* right occipital lobe, *MTL/STR* medial temporal lobe/striatum, *GMV* gray matter volume, *ALFF* amplitude of low-frequency fluctuation

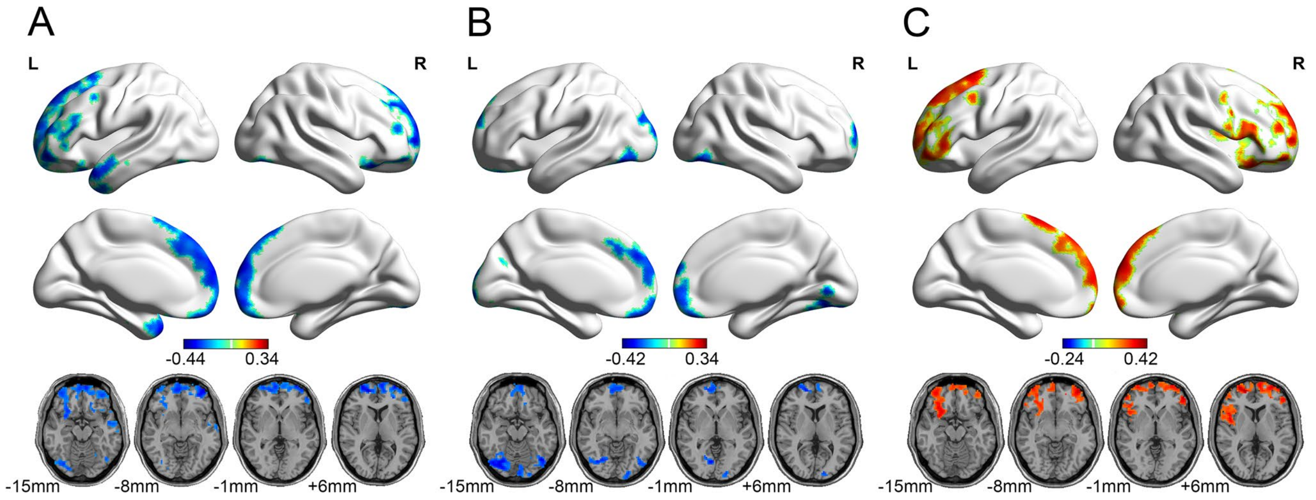

Fig. 1 Results of voxel-based morphometry (VBM) analyses. Colder or warmer indicates higher correlation coefficients. **A** Self-compassion-related brain regions including left and right cerebellum and prefrontal cortex. **B** Compassionate-dimension-related brain regions including cerebellum and prefrontal cortex. **C** Uncompassionate-dimension-related brain region including prefrontal cortex. The visualization was provided by with BrainNet Viewer (Xia et al., 2013)

Table 2 Partial Pearson correlation between single dimension scores and the mean GMV or ALFF values of overlapping brain regions across both two dimensions

Overlapping Region	Partial Pearson *r* value	*p* value
Compassionate self-responding dimension		
PFC (GMV)	-0.290**	0.007
OC (ALFF)	-0.339***	<0.001
Uncompassionate self-responding dimension		
PFC (GMV)	0.322**	0.003
OC (ALFF)	0.349***	<0.001

PFC prefrontal cortex, *OC* occipital lobe, *GMV* gray matter volume, *ALFF* amplitude of low-frequency fluctuation

$^{**}p<0.01$; $^{***}p<0.001$

Brain functional regions For ALFF analyses of self-compassion, the occipital lobe (MNI coordinates of the peak voxel: [27, -99, 3] mm) was identified. The mean GM volume of this cluster was negatively correlated with self-compassion ($r=-0.430$, $p<0.001$) (Table 1, Fig. 2A). Further examining the two dimensions, the results showed that the ALFF value in the occipital lobe (MNI coordinates of the peak voxel: [18, -69, 45] mm) was correlated with the compassionate dimension (Table 1, Fig. 2B). The mean ALFF value of this cluster was negatively correlated with the compassionate dimension score, $r=-0.275$, $p=0.010$. For the uncompassionate dimension, ALFF values in three brain clusters were significantly correlated with the uncompassionate dimension score; the brain clusters included left superior and middle occipital lobe (MNI coordinates of the peak voxel: [-18, -84, 24] mm), right superior and middle occipital lobe (MNI coordinates of the peak voxel: [27, -99, 3] mm), and medial temporal lobe (MTL)/striatum (STR) (MNI coordinates of the peak voxel: [-51, -27, -33] mm) (Table 1, Fig. 2C). The mean ALFF values of these clusters were significantly positively correlated with the uncompassionate dimension score ($r=0.420$, $p<0.001$ for the left occipital lobe; $r=0.464$, $p<0.001$ for the right occipital lobe; and $r=-0.505$, $p<0.001$ for the temporal pole). The mean ALFF values of the occipital lobe, which was the overlapping brain regions, were significantly associated with both compassionate and uncompassionate dimensions simultaneously ($r=-0.339$, $p<0.001$ for compassionate dimension and $r=0.349$, $p<0.001$ for uncompassionate dimension, Table 2). Moreover, the brain region specificity analyses for ALFF correlation analysis showed that the correlations between the mean ALFF values of most dimension-specific regions and corresponding dimension scores were significant after controlling for the effects of another dimension, age and sex (Table S2), except for the occipital lobe cluster associated with the compassionate dimension.

Moreover, we calculated the association between GMV/ALFF of eight priori ROIs, which were defined independently based on the results of previous studies (Guan et al., 2021). For GMV correlation analysis, we found that the GMV value in the (1) DLPFC and DMPFC were significantly negatively related with self-compassion [$p<0.05$; false discovery rate (FDR) corrected]; (2) DMPFC, ITG and cerebellum were marginally significantly negatively correlated with compassionate dimension ($p<0.1$, FDR corrected); (3) DLPFC and DMPFC were significantly

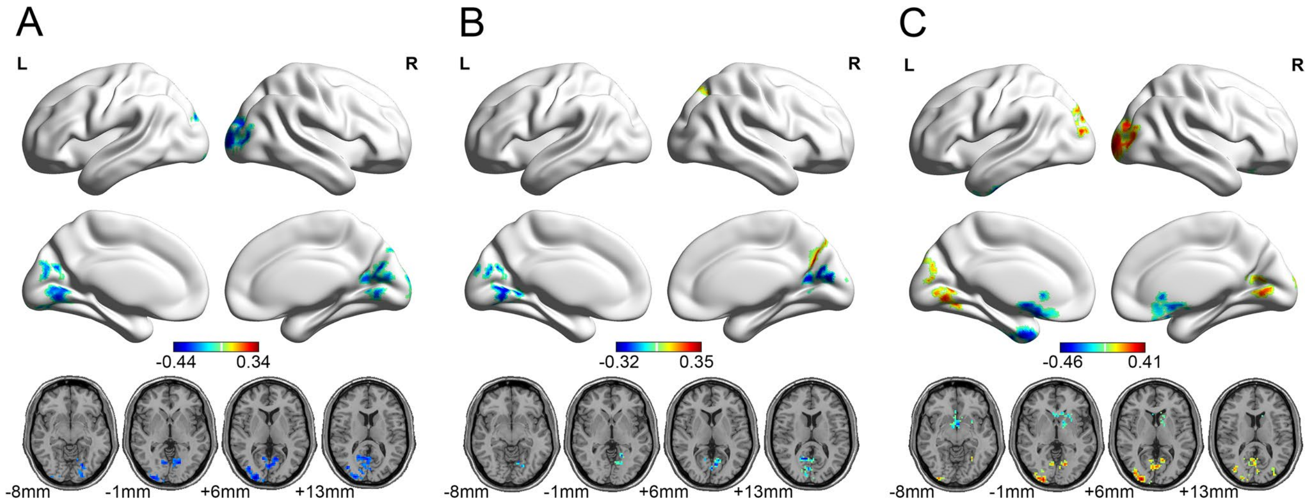

Fig. 2 Results of amplitude of low-frequency fluctuation (ALFF) analyses. The colder or warmer color indicates higher correlation coefficients. **A** Self-compassion-related brain regions including the occipital lobe. **B** Compassionate-dimension-related brain region including occipital lobe. **C** Uncompassionate-dimension-related brain regions including occipital lobe and temporal pole. The visualization was provided by with BrainNet Viewer (Xia et al., 2013)

positively correlated with uncompassionate dimension ($p < 0.05$, FDR corrected). Detailed results were presented in Table S3 of the Supplementary Material. These results suggested that there were some common brain regions relevant to both compassionate and uncompassionate dimensions such as the medial prefrontal cortex and some dimension-specific regions such as DLPFC. For ALFF correlation analysis, we found that the ALFF value in the (1) CAL was significantly negatively related with self-compassion ($p < 0.05$, FDR corrected) and the DLPFC was marginally significantly negatively correlated with self-compassion ($p < 0.1$, FDR corrected); (2) CAL was marginally significantly negatively related with compassionate dimension ($p < 0.1$, FDR corrected); (3) CAL and DLPFC were marginally positively significantly related with uncompassionate dimension ($p < 0.1$, FDR corrected). Detailed results were displayed in the Table S4 of Supplemental Materials. These results suggested that there were some common brain regions relevant to both compassionate and uncompassionate dimensions such as the calcarine located in the occipital lobe.

Correlations with mental health variables

The correlations between self-compassion and its dimensions and mental health variables are depicted in Table 3. Self-compassion was significantly correlated with positive affect, negative affect, and depression. Besides, compared to the compassionate dimension, the uncompassionate dimension were more related with depression ($z = 1.980$, $p = 0.048$). In further partial correlation analyses, the uncompassionate self-responding dimension was also significantly related to positive affect, negative affect, and depression with the compassionate dimension controlled for, whereas the compassionate self-responding dimension was only related to positive affect with the uncompassionate dimension controlled for.

Table 3 Correlations between self-compassion and external variables

	Positive affect	Negative affect	Depression
SC	0.499***	-0.370***	-0.546***
CSD	0.237*	-0.082	-0.146
UCSD	-0.325**	0.311**	0.469***

Correlation between compassionate (or uncompassionate) dimension and external variables were calculated by partial correlation analyses with the uncompassionate (or compassionate) dimension controlled for. *SC* self-compassion, *CSD* compassionate dimension, *UCSD* uncompassionate dimension

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Indirect effects

According to the correlation results, the indirect paths from corresponding structural/functional brain characteristics to mental health variables through self-compassion or its dimensions were examined. The detailed results are presented in Table 4. The results showed that corresponding brain characteristics could be associated with positive affect, negative affect, and depression through self-compassion or uncompassionate dimensions. However, corresponding brain characteristics did not have an association with positive affect, negative affect, or depression through the compassionate dimension. Moreover, we also examined the indirect paths from corresponding structural/functional brain

Table 4 Indirect effects

	a	b	Direct effect	Indirect effect	95% CI
Self-compassion					
CBL(GMV)-SC-PA	**-0.382****	**0.492*****	-0.062	-0.188	**[-0.322, -0.075]**
CBR(GMV)-SC-PA	**-0.416*****	**0.479*****	-0.101	-0.199	**[-0.329, -0.092]**
PFC(GMV)-SC-PA	**-0.422*****	**0.492*****	-0.062	-0.188	**[-0.325, -0.076]**
OC(ALFF)-SC-PA	**-0.435*****	**0.474*****	-0.084	-0.207	**[-0.322, -0.106]**
CBL(GMV)-SC-NA	**-0.382****	**-0.356****	0.048	0.136	**[0.041, 0.267]**
CBR(GMV)-SC-NA	**-0.416*****	**-0.356****	0.044	0.148	**[0.048, 0.270]**
PFC(GMV)-SC-NA	**-0.422*****	**-0.381*****	-0.036	0.161	**[0.055, 0.291]**
OC(ALFF)-SC-NA	**-0.435*****	**-0.356****	0.032	0.155	**[0.058, 0.259]**
CBL(GMV)-SC-Dep	**-0.382****	**-0.552*****	-0.005	0.211	**[0.081, 0.362]**
CBR(GMV)-SC-Dep	**-0.416*****	**-0.537*****	0.042	0.224	**[0.106, 0.364]**
PFC(GMV)-SC-Dep	**-0.422*****	**-0.532*****	0.057	0.225	**[0.099, 0.370]**
OC(ALFF)-SC-Dep	**-0.435*****	**-0.555*****	-0.010	0.241	**[0.120, 0.397]**
Compassionate self-responding dimension					
PFC(GMV)-CSD-PA	-0.201	**0.239***	-0.013	-0.048	[-0.129, 0.007]
CB(GMV)-CSD-PA	**-0.371*****	0.212	-0.094	-0.079	[-0.187, 0.005]
OC(ALFF)-CSD-PA	-0.168	**0.217***	-0.121	-0.037	[-0.101, 0.012]
PFC(GMV)-CSD-NA	-0.201	-0.094	-0.015	0.019	[-0.027, 0.096]
CB(GMV)-CSD-NA	**-0.371*****	-0.071	0.065	0.026	[-0.061, 0.120]
OC(ALFF)-CSD-NA	-0.168	-0.085	0.029	0.014	[-0.021, 0.071]
PFC(GMV)-CSD-Dep	-0.201	-0.149	0.030	0.030	[-0.008, 0.093]
CB(GMV)-CSD-Dep	**-0.371*****	-0.124	0.098	0.046	[-0.019, 0.137]
OC(ALFF)-CSD-Dep	-0.168	-0.148	0.036	0.025	[-0.010, 0.092]
Uncompassionate self-responding dimension					
PFC(GMV)-UCSD-PA	**0.339****	**-0.324****	-0.081	-0.110	**[-0.218, -0.027]**
OCL(ALFF)-UCSD-PA	**0.313****	**-0.321****	-0.079	-0.101	**[-0.209, -0.019]**
OCR(ALFF)-UCSD-PA	**0.368*****	**-0.313****	-0.086	-0.115	**[-0.231, -0.021]**
MTL/STR(ALFF)-UCSD-PA	**-0.435*****	**-0.292***	0.104	0.127	**[0.008, 0.249]**
PFC(GMV)-UCSD-NA	**0.339****	**0.345****	-0.023	0.117	**[0.034, 0.217]**
OCL(ALFF)-UCSD-NA	**0.313****	**0.335****	0.009	0.105	**[0.016, 0.215]**
OCR(ALFF)-UCSD-NA	**0.368*****	**0.316***	0.051	0.116	**[0.023, 0.231]**
MTL/STR(ALFF)-UCSD-NA	**-0.435*****	**0.317***	-0.037	-0.138	**[-0.246, -0.026]**
PFC(GMV)-UCSD-Dep	**0.339****	**0.466*****	0.053	0.158	**[0.059, 0.277]**
OCL(ALFF)-UCSD-Dep	**0.313****	**0.495*****	-0.034	0.155	**[0.049, 0.269]**
OCR(ALFF)-UCSD-Dep	**0.368*****	**0.503*****	-0.046	0.185	**[0.067, 0.314]**
MTL/STR(ALFF)-UCSD-Dep	**-0.435*****	**0.466*****	-0.031	-0.203	**[-0.339, -0.075]**

Age and sex were controlled for in all mediation analyses above. Besides, when compassionate (or uncompassionate) dimension as mediator, uncompassionate (or compassionate) dimension score was also controlled. *CBL* left cerebellum, *CBR* right cerebellum, *PFC* prefrontal cortex, *OC* occipital lobe, *CB* cerebellum, *OCL* left occipital lobe, *OCR* right occipital lobe, *MTL/STR* medial temporal lobe/striatum, *GMV* gray matter volume, *ALFF* amplitude of low-frequency fluctuation, *SC* self-compassion, *CSD* compassionate dimension, *UCSD* uncompassionate dimension, *PA* positive affect, *NA* negative affect, *Dep* depression; 95% CI, 95% confidence interval. The results presented in boldface are significant

*$p \le 0.05$; **$p \le 0.01$; ***$p \le 0.001$

characteristics calculated based on priori independent ROIs derived from previous study (Guan et al., 2021) to mental health variables through self-compassion or its dimensions. The detailed results were presented in Table S5 and Table S6. The results also showed that corresponding brain characteristics could be linked to positive affect, negative affect, and depression through self-compassion or uncompassionate dimensions instead of compassionate dimension.

Discussion

The present study explored the neural bases of self-compassion and the potential differences in the neural substrates of its two dimensions—the compassionate and uncompassionate self-responding dimensions. The results revealed that the neural substrates underlying the compassionate and uncompassionate self-responding dimensions of self-compassion shared some similarities (e.g., common correlation of GMV in the medial PFC and ALFF in the occipital lobe) but also had some differences (e.g., only uncompassionate self-responding dimensions of self-compassion correlated with GMV in the lateral PFC and with ALFF values in medial temporal lobe/striatum). In addition to the neural substrate results, the associations with mental health variables (i.e., positive affect, negative affect, and depression) of compassionate and uncompassionate self-responding dimensions showed different patterns.

Given the scarcity of empirical studies that examined the neural substrates of self-compassion, in the current study, we investigated the neurostructural and neurofunctional correlates of self-compassion and its compassionate and uncompassionate dimensions simultaneously. The findings showed that individuals with higher levels of self-compassion were prone to have decreased gray matter volumes in the prefrontal cortex and cerebellum as well as lower spontaneous neural activity in the occipital lobe. These findings were consistent with previous studies (Guan et al., 2021; Parrish et al., 2018). Parrish et al. (2018) found a negative correlation between self-compassion and VMPFC-amygdala functional connectivity in responses to negative social feedback. Guan et al. (2021) found a negative correlation between self-compassion and GMV in the dorsolateral prefrontal cortex. The prefrontal cortex has been found to be associated with coping (Maier & Watkins, 2010), resilience (Davidson, 2000; Maier & Watkins, 2010), emotion regulation (Etkin et al., 2015), and well-being (Urry et al., 2004). In addition, the results revealed that individuals with a high level of self-compassion had less GMV in the cerebellum. Previous works have demonstrated that the cerebellum plays an important role in emotion regulation (Schutter & van Honk, 2009; Turner et al., 2007). Meanwhile, self-compassion has been regarded as an effective emotion regulation strategy in daily life (Diedrich et al., 2014). Negative correlations between self-compassion and GMV in the prefrontal cortex and cerebellum were found in the current study. These correlations are consistent with previous findings that showed negative correlations between GMV/GM density in the prefrontal cortex and individual behaviors and feelings, including well-being (Kong et al., 2019), emotional intelligence (Takeuchi et al., 2011), delay discounting (Wang et al., 2017), and extraversion (Coutinho et al., 2013). Moreover, previous task-based fMRI studies found that higher dorsolateral prefrontal cortex activity in response to negative (i.e., sad face or negative statement) vs. neutral events was correlated to lower self-compassion (Liu et al., 2022) and higher levels of self-criticism (Longe et al., 2010). And larger GMV in the dorsolateral prefrontal cortex was found to be related to higher levels of self-judgment (Guan et al., 2021), which may suggest that larger GMV in the dorsolateral prefrontal cortex may enable individual's higher tendency of self-criticism and thus induce lower self-compassion. Notably, a positive correlation between GMV in the cerebellum and affective losses was also found (Benetti et al., 2010). Therefore, the lower GMV may be attributed to synaptic pruning of excess neurons during development, which is beneficial for efficient cognitive processes (Kong et al., 2019; Takeuchi et al., 2011). In addition, we found that the brain activity of the occipital lobe region was found to be negatively related to self-compassion. Although no direct previous evidence supported the negative correlation between activity in the occipital lobe and positive individual traits, previous studies have reported increased activity in the occipital lobe in first-episode mental illness, including major depressive disorder (Wang et al., 2012), schizophrenia (Gong et al., 2020; Li et al., 2017), and a subtype of transdiagnostic major psychiatric disorders (Chang et al., 2021). Thus, the increased ALFF values may reflect a compensatory mechanism (Cabeza et al., 2002) for the weak cognitive performance and outcomes (e.g., visual recognition and detection of meaningful stimuli) induced by a reduction in self-compassion in people with low self-compassion.

When examining compassionate and uncompassionate self-responding dimensions separately, the GMV of the cerebellar region was found to be correlated with the compassionate dimension exclusively. The cerebellum is known as a central region for functions including sensory perception, coordination, and motor control (Marr, 1969). Recently, crucial roles of the cerebellum in the processing of emotional stimuli and the regulation of emotion were also found (Gündel et al., 2003; Habel et al., 2005; Schutter & van Honk, 2009; Turner et al., 2007). Research has demonstrated that the cerebellum is involved in the process of social cognition and mentalizing (Van Overwalle et al., 2014), which consists of individuals perceiving and processing information from themselves and other people. For instance, the cerebellum has been found to play an important role in empathy and self-reassurance processes (Lutz et al., 2020; Preston, 2007). Studies also found that the brain structure in the cerebellum was changed after mindfulness training (Hölzel et al., 2011; Murakami et al., 2012). Therefore, the cerebellum may be an important region for being compassionate toward oneself.

On the other hand, the GMV of the lateral PFC and ALFF values of the medial temporal lobe (MTL)/striatum were found to be specifically correlated with the uncompassionate dimension instead of the compassionate dimension. Previous task-based fMRI studies have found that activity in the lateral PFC is associated with self-criticism (Doerig et al., 2014; Longe et al., 2010). The lateral PFC contributes to error detection and the inhibition of inappropriate behavior (Miller & Cohen, 2001). This may imply that people with a high level of uncompassionate thinking pay more attention to their mistakes, which may eventually result in these individuals displaying less kindness toward themselves. In addition, we found that ALFF values in the anterior medial temporal lobe (AT)/striatum were also related to an uncompassionate self-responding dimension. Previous studies have found that the medial temporal lobe was activated in response to self-critical material in healthy individuals (Doerig et al., 2014). Anderson et al. (2010) found that the functional connectivity between the medial temporal lobe and lateral frontal regions was associated with the inhibition of unwanted memories. Therefore, it could be possible that individuals who have difficulty suppressing their unwanted memories may more easily ruminate on these memories and be overinvolved in self-criticism. The striatum plays crucial roles in self-reward, self-punishment and responses to others' actions (Báez-Mendoza & Schultz, 2013; Robinson et al., 2012). Self-punishment was associated with the uncompassionate dimension of self-compassion (i.e., self-judgment) (Muris & Otgaar, 2020).

Overall, we found that the neural substrates of compassionate and uncompassionate dimensions of self-compassion were different. These findings supported the concept that the two counterparts of self-compassion have their own neural substrate. It would be beneficial for further studies investigating the effect of self-compassion to examine the two dimensions separately.

To further examine the importance of differentiating the two dimensions, the current study examined the relations between the two dimensions of self-compassion and the mental health variables from a neural perspective. The results revealed that the compassionate dimension only significantly correlated with positive emotion, whereas the uncompassionate dimension correlated with positive and negative affect and depression. Path analysis further revealed that only an uncompassionate dimension could show a mediation role similar to that of self-compassion to mediate the path from brain characteristics to mental health variables. These findings might imply that the uncompassionate dimension and its neural substrate may have been the main contributor in previous findings about self-compassion.

Several limitations of current study should be addressed. First, considering that our sample size is relatively small, which may lead to lower statistical power under the more stringent threshold, and our study is exploratory in nature, the current study used a rather lenient threshold (voxel-level $p_{uncorr} < 0.05$, cluster-level $p_{FWE} < 0.05$) to identify significant voxels (Bender & Lange, 2001; Cao & Zhang, 2014). We reanalyzed the data with stricter voxel-level p_{uncorr} thresholds (i.e., 0.005 and 0.001). Under the voxel-level $p_{uncorr} < 0.005$, we found that some dimension-specific regions still survived (e.g., lateral PFC for uncompassionate dimension, temporal cortex for compassionate dimension), but the neural basis shared by the two dimensions no longer existed (Table S8). However, no significant correlation between brain measures and self-compassion as well as its two dimensions with the voxel-level $p_{uncorr} < 0.001$. Additionally, performing multiple brain-behavior correlation analyses and subsequent path analyses in this study may induce serial test bias and increase false positive rates. Hence, the preliminary underlying neural substrates of self-compassion found in this exploratory study need to be further tested as a priori hypothesis (i.e., confirmatory study) in future large-sample studies. Second, the age range and sample size in this study were rather restricted, which may limit the generalizability of the results (Ellwardt et al., 2013). Future studies should investigate whether the relationships between the two dimensions of SCS and brain characteristics could be moderated by different ages and whether these results could be generalized to a larger sample. Third, all mediation analyses in our study were correlational, which did not allow us to assess the causal relationships. Further works should shed light on whether the functional and structural changes in brain regions (e.g., the PFC and occipital lobe) could alter compassionate or uncompassionate dispositions, which in turn lead to improved well-being in life.

Conclusion

In conclusion, the present study showed that the compassionate and uncompassionate dimensions of self-compassion were related to distinct brain regions. Specifically, the compassionate dimension was specifically related to the GMV of the cerebellum, and the uncompassionate dimension was specifically correlated with the GMV of the lateral prefrontal cortex region and brain activity of the MTL/striatum. The present study advanced our understanding of the distinction of the compassionate and uncompassionate self-responding dimensions of self-compassion, which are both important to the current conceptualization of self-compassion and intervention studies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11682-022-00723-9.

Author contributions YYW and ZJD designed the study. RZW, LFL, JJM, and ZJD analyzed the data. YYW, RZW, LFL and ZJD wrote the paper. LFL, JJM and WTY collaborated in writing the paper. All authors approved the final version of the manuscript for submission.

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Data availability In this study, the dataset we used is relevant to another larger ongoing project. Since we are still working on analyses of the dataset, data are not available at this time unless upon reasonable requests.

Declarations

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board of Department of Psychology, Sun Yat-sen University (201804160062) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate and consent for publication Written informed consents have been obtained from all participants.

Conflict of interest The authors declare that they have no conflict of interest.

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