Brain Imaging and Behavior (2020) 14:2771–2784
https://doi.org/10.1007/s11682-019-00226-0

ORIGINAL RESEARCH

Altered brain network organization in romantic love as measured with resting-state fMRI and graph theory

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Published online: 2 January 2020

Abstract

Romantic love is a complex state that has been seen as similar to addiction. Previous task-based functional magnetic resonance imaging (fMRI) studies have shown that being in love is closely associated with functional brain changes in the reward and motivation system. However, romantic love-related functional connectivity network organization in resting-state fMRI has yet to be elucidated. To that end, here we used resting-state fMRI and graph theory to compare whole-brain functional network topology between an "in-love" group ($n = 34$, 16 females, currently in love and in a romantic relationship) and a "single" group ($n = 32$, 14 females, never in love and not in a romantic relationship). Compared to the single group, we found lower network segregation in the love group (i.e., lower small-worldness, mean clustering coefficient, and modularity), and these metrics were negatively associated with scores on the Passionate Love Scale (PLS) (an index of intense passionate/romantic love). Additionally, the love group displayed altered connectivity degree (reflecting the importance of a node): decreased degree in left angular gyrus and left medial orbitofrontal cortex, but increased degree in left fusiform gyrus. Furthermore, local efficiency or degree of these regions was significantly correlated to PLS scores. Taken together, results showed decreased overall brain functional segregation but enhanced emotional-social processing in romantic lovers. These findings provide the first evidence of love-related brain network organization changes and suggest similar but different brain network alterations between romantic love and addiction, providing new insights on the neural systems underlying romantic love.

Keywords Romantic love · Resting-state fMRI · Graph theory · Angular gyrus · Fusiform

Introduction

Romantic love is generally regarded as one of the deepest and most meaningful human sentiments – one that has played an important role in the reproduction, development, survival and evolution of our species. Romantic love is a complex state of emotion dominated by a strong desire to be with the loved individual, a state known to affect feelings, behaviors and cognition (Hazan and Shaver 1987; Sternberg 1986).

Reduced cognitive control has been reported in romantic lovers. Lovers display worse performance in Stroop and flanker tasks [two tasks measuring the ability of individuals to ignore irrelevant information while focusing on the information they need, see (Steenbergen et al. 2014)], and can demonstrate an almost obsessive focus toward their special others (Fisher 1998). As such, love is accompanied by significant changes in resource prioritization and deployment (Reis and Aron 2008). At the same time however, studies have shown an increased capacity for social cognition in romantic lovers. For example, lovers are better at interpreting emotional states of

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others (i.e., mentalizing abilities) after being primed with a love-related stimulus than with a neutral prime (Wlodarski and Dunbar 2014). Increased inhibitory control capacity in an emotional stop-signal task has also been shown in people who report being in love (Song et al. 2016). These behavioral findings suggest very specific changes in cognition related to romantic love, with a depletion of general cognitive resources but enhanced social-emotional processing.

Previous task-related fMRI studies in romantic lovers provide evidence for the hypothesis that romantic love is associated with functional changes in the reward and motivation system. For example, compared with photos or name stimuli of a familiar other, photographs or names of a romantic partner have been consistently shown to be related to greater activation of the reward and motivation system [e.g., ventral tegmental area (VTA), caudate, anterior cingulate cortex (ACC), nucleus accumbens, medial insula] (Acevedo et al. 2012; Aron et al. 2005; Bartels and Zeki 2000; Ortigue et al. 2007; Xu et al. 2011; Zeki and Romaya 2010). Based on these findings, some researchers have proposed that romantic love is very similar to, and even could be seen as, a form of addiction (Burkett and Young 2012; Fisher et al. 2016).

Neuroimaging studies in romantic lovers have also demonstrated greater activation of Default Mode Network (DMN) regions in a variety of behavioral tasks. For example, a study by Acevedo et al. (2012) found higher activation in the anterior and posterior cingulate when lovers viewed their partner's photo, an effect found even when interspersed with a distraction-attention task. Others, have found higher activation in the left inferior temporal gyrus, parahippocampal gyri, angular gyrus and bilateral fusiform regions when individuals view their partner's name in a lexical decision task (Ortigue et al. 2007). Involvement of DMN regions is important for social-emotional processing such as in emotional stop-signal tasks (Song et al. 2016) or the 'reading of the mind in the eyes' task (Wlodarski and Dunbar 2014). Interestingly, activity in these DMN regions can differentiate individuals in love from individuals with drug addiction who also demonstrate impaired social cognition (Baler and Volkow 2006; Barrós-Loscertales et al. 2006; Zou et al. 2016). In contrast to romantic love, social cognition in drug addicted individuals is characterized by a shift away from social-emotional processing and towards drug-cue related processing (Heilig et al. 2016; Zilverstand et al. 2018). Romantic love may hence diverge from human drug addiction in its effects on social-emotional cognition.

Changes in brain function associated with being in love have also been investigated using resting-state fMRI (rs-fMRI), free from constraints of having to perform a task in the MR-scanner. Our team previously found that resting-state functional connectivity (FC) in the reward and social cognition network, was significantly increased in an "in-love" group relative to a group of "single" individuals (Song et al. 2015). Patterns of resting-state FC can also be further used to construct a network (i.e., graph) of brain regions which can then be implemented to study functional network organization across large scale cortical networks (Bassett et al. 2011; Bullmore and Sporns 2012; He and Evans 2010; Stam and Reijneveld 2007). Such an endeavor, however, remains to be undertaken. In particular, the application of graph theory-based analyses allows for a system-level quantification of brain network architecture that provides rich and novel information about brain function (Bullmore and Sporns 2012).

The most common network metrics used in graph theory include small-worldness, modularity, degree, etc. (Guimerà and Amaral 2005; Heuvel et al. 2011; Rubinov and Sporns 2010) (defined in the Materials and Methods). In the current study, we aimed to characterize the functional topology of romantic lovers using these graph metrics.

While no previous study in romantic lovers has yet explored network topology using graph theoretical methods, studies investigating addiction using graph theory models have provided intriguing insights. Research on human drug addiction has found significantly lower small-worldness in chronic heroin users as compared to non-drug users, in addition to greater degree in large scale networks including the reward network [e.g., orbital part of the inferior frontal gyrus, anterior cingulate gyrus, putamen, pallidum, and caudate] (Liu et al. 2009). A second study also found lower small-worldness and increased degree of the reward and other networks (e.g., orbitofrontal, dorsolateral prefrontal cortex, rostral anterior cingulate gyrus, parahippocampal gyrus, caudate, putamen, and medial prefrontal cortex) in a heroin-dependent group compared to controls (Yuan et al. 2010). Most recently, a study in cocaine-addicted individuals found increased global functional density (similar to degree) in the DMN network (e.g., ventromedial prefrontal cortex, posterior cingulate/precuneus, and putamen/amygdala) (Konova et al. 2015). Together, these studies suggest altered functional topology in the reward and social cognition networks in human drug addiction and reveal potential functional network markers that can be studied in romantic lovers using graph theoretical analysis techniques.

Based on these previous studies showing similarity in reward processing, but differences in social cognition between love and drug addiction, we hypothesized that changes in the reward network topology in romantic love as compared to single individuals would be similar to those seen in addiction, while opposite effects would be observed in other brain networks such as the social cognition networks.

Materials and methods

Participants

Sixty-six healthy (hetero-sexual) college students were enrolled in the study. All participants were recruited from

Southwest University(Chongqing,China) by flyer or Internet advertisement. All were interviewed at the beginning of the study regarding previous romantic relationships and personal demographic characteristics. Participants were divided into two groups according to their romantic relationship status: (1) an "in-love" group (LG, $n = 34$), consisting of individuals currently intensely falling in love and in a romantic relationship; and (2) a "single" group (SG, $n = 32$), consisting of individuals who had never been in love and not in a romantic relationship. Table 1 describes demographics and sample characteristics of subjects. There were no significant differences in family income, personal monthly expenses, age, or years of education ($p > 0.7$) between the two groups.

This study was approved by the Ethics Committee of Southwest University (Chongqing, China). Written informed consent was obtained from all participants prior to participation in the study. All participants were informed that their participation was completely voluntary and that they could withdraw from the study at any point. All participants were over 18 years of age.

Behavioral assessment

To measure current status of passionate/romantic love in the LG, we used the Passionate Love Scale (PLS) (Hatfield and Sprecher 1986), a construct previously used for the study of romantic love (Song et al. 2015; Yin et al. 2013). Length of time in love for LG individuals was between 8 to 17 months (mean = 12.23, SD = 2.95).

Neuroimaging protocol

Rs-fMRI was performed on all participants using a 3-T Siemens MAGNETOM Tim Trio whole-body magnetic resonance scanner (Siemens AG, Erlangen, Germany) equipped with a 16-channel head coil at the Southwest University Brain Imaging Research Center. Eligible participants underwent a sequence consisting of 242 T2*-weighted echo-planar images, with slice thickness 3 mm, 32 slices, repetition time 2000 milliseconds, echo time 30 milliseconds, flip angle 90°, field of view 220 mm × 220 mm, resolution matrix 64 × 64, axial view descending, voxel size 3.4 × 3.4 × 3 mm, duration 6 min, 242 volumes. Participants were instructed to lie in the scanner with eyes closed while not thinking of anything and remaining still, relaxed, and awake throughout the scanning session (Hao et al. 2013).

Resting state image analysis

Image preprocessing was conducted using Statistical Parametric Mapping software (SPM8; http://www.fil.ion.ucl.ac.uk/spm/software/spm8/) and DPARSF (Yan and Zang 2010). The following procedures were performed: removing the first ten time points; slice-timing correction; functional realignment excluding subjects with head motion more than 2 mm or 2°; reorientation of functional and T1 images; T1 coregistration; using DARTEL for segmentation; normalization to standard stereotaxic space [Montreal Neurological Institute (MNI)]; spatial smoothing with a 8-mm full-width-at-half-maximum (FWHM) Gaussian kernel; nuisance covariates using regression for extracting mean time series from white matter and CSF; detrending; scrubbing using Framewise Displacement (FD) (Jenkinson et al. 2002) method to set an FD threshold for "bad" volumes as 0.2 and to cut one time point preceding the "bad" timepoint and two time points after the "bad" timepoint; temporal band-pass filtering between 0.01 and 0.08 Hz.

Network topology analysis

The large-scale whole brain network was built based on the collection of nodes (AAL regions) and links (FC between nodes). First, a whole-brain parcellation was conducted in native space using the anatomical automatic labeling (AAL) atlas (Tzourio-Mazoyer et al. 2002), which parcellated the brain into 90 cortical and subcortical (45 per hemisphere) regions of interest. Adjacency matrices were constructed using GRETNA (https://www.nitrc.org/projects/gretna), computing bivariate (z-transformed) correlations between the mean time-series (i.e. , average signal across voxels) for each pair of nodes (Fox et al.

Table 1 Demographics and sample characteristics

	SG (single-group) $n = 32$, 14 females		LG (in-love group) $n = 34$, 16 females		SG vs LG t-scores, p values
	Mean	SD	Mean	SD	
Family income (RMB/month)	4.04×10^3	6.82×10^2	4.10×10^3	7.04×10^2	$t_{(64)} = -0.37$, $p = 0.72$
Monthly expenses (RMB/months)	7.41×10^2	86.7	7.35×10^2	78.32	$t_{(64)} = 0.28$, $p = 0.78$
Age (years)	21.41	1.92	21.21	2.42	$t_{(64)} = 0.37$, $p = 0.71$
Years of education(years)	13.41	1.92	13.24	2.45	$t_{(64)} = 0.314$, $p = 0.75$
Intensity of love (PLS score)			104.21	10.58	
Duration of love (months)			12.23	2.95	

SG, participants who have never been in love and not in a romantic relationship; LG, participants who fell in love and were in a romantic relationship; RMB, renminbi; PLS, Passionate Love Scale

2005), for each participant. This resulted in a 90 × 90 undirected and unweighted correlation matrix.

Then, using GRETNA, adjacency matrices were binarized over a series of cost thresholds, which fixed the total number of edges to a particular connection density (Achard and Bullmore 2007). Network analysis (including brain network measures and nodal measures) was conducted across a range of connection densities (0.050, 0.075, 0.100, 0.125, 0.150, 0.175, 0.200, 0.225, 0.250 and 0.275), ranging from 0.05 to 0.275 in increments of 0.025, to reduce the impact of threshold selection on results. These values are within the ideal cost range (approximately 0.01–0.30) where the sparsity of a graph is considered optimal because within this range many graph theory metrics, including small-worldness, are maximal (Achard and Bullmore 2007; Bassett et al. 2008; Bullmore and Bassett 2011). To verify that the selection of the threshold range was not too wide, which may produce disconnected nodes and networks without small-worldness features (Zhang X, et al. 2011, Zhang J,et al.2011), we ensured that all participants showed network properties of small-worldness with $\sigma > 1$ for all threshold values.

All above network measures and nodal measures are calculated for individual subjects, then group comparisons were conducted using GRETNA. All results were corrected for multiple comparisons using a false positive correction: Bonferroni ($p < 0.05$). BrainNet Viewer (Xia et al. 2013) was used to visualize the brain network.

Brain network measures and nodal measures

Brain network measures

Brain network measures are used to estimate the functional segregation and integration of the brain network. We choose several common measures, including: *Small-worldness* (segregation and integration)*, Mean clustering coefficient* (segregation)*, Characteristic path length* (integration) and *Global Efficiency* (integration) (Rubinov and Sporns 2010).

Small-worldness describes the degrees of small-world organization, which is the optimal balance of functional integration and segregation. A small-world organization (e.g., national railway network) usually has sub-modules (e.g., provincial railway networks) that perform specific functions (separation), and each sub-module is connected to each other (e.g., through some hub cities) to perform more advanced functions (high integration). The calculation of small-worldness is based on the clustering coefficient and the characteristic path length (see below) of the tested network and random networks (Humphries and Gurney 2008).

Mean clustering coefficient is the mean value of the clustering coefficients of all nodes (for the description of the clustering coefficient, see below). Characteristic path length describes the average shortest path length between all pairs of nodes. Global Efficiency (GE) is inversely proportional to the characteristic path length. For the case of isolated nodes, the characteristic path length is infinite, while GE is zero. Therefore, GE has been taken as a superior measure of integration, reflecting the efficiency of information processing (Rubinov and Sporns 2010).

To evaluate the topology of brain networks, these network metrics must be compared with their corresponding values from randomly generated networks composed of the same number of nodes, edges, and degree distribution as the network of interest (Maslov and Sneppen 2002; Milo et al. 2002). Thus, we obtained these corresponding mean values from randomly generated graphs (2000 random networks generated) with the same number of nodes, total edges, and degree distribution.

Nodal measures

Nodal measures are calculated with each individual node (region), reflecting local differences in the brain network. The basic and important measures that were used widely included *Degree, Clustering coefficient, Modularity, Local efficiency, Within-module degree z-score* and *Participant coefficient* (Rubinov and Sporns 2010).

The degree of a node is the overall number of edges (links) connected to that node, and is equal to the number of neighbors of the node. The value of degree reflects importance of a node in the network. Greater value of degree indicates an important role of the node (e.g., hub nodes). Clustering coefficient (CC) measures the proportion of neighbors of a node that are also neighbors each other. Mean CC of the three nodes in a triangle equals to 1, reflecting a strong clustering of these nodes.

Modularity is a more sophisticated measure, which is similar but different from clustering (clustering coefficient). It describes the presence of groups of regions (modules) and finds the size and composition of each group. Large value of modularity reflects the whole brain networks can be segregated into more sub-networks. We used a well-known modularity algorithm called spectral optimization to perform the modularity analysis (Newman 2006) to estimate the optimal modular structure of the brain network.

Local efficiency (LE) represents communication efficiency between one node and others (or within a module), which equals to average inverse shortest path length. Small LE reflects long distance for information transferring between nodes. For any two disconnected nodes or sub-networks, it is zero efficiency.

Within-module degree z-score and participation coefficient are calculated in order to identify different role of each node in a network. Within-module degree z-score (Zi) describes the connection between one node and other nodes in the same module. Participation coefficient (Pi) describes the connection between one node and other nodes in different modules

(Guimerà and Amaral 2005). We can partition nodes into four types based on Zi and Pi (Guimerà and Amaral 2005): connector hub ($P_i > 0.5$, and $Z_i > 1.0$), connector non-hub ($P_i > 0.5$, but $Zi \leq 1.0$), provincial hub ($P_i \leq 0.5$, and $Z_i > 1.0$) and provincial non-hub ($P_i \leq 0.5$, and $Zi \leq 1.0$).

Correlation analysis

To explore brain-behavior relationships, we conducted partial correlation analyses between PLS score and graph metrics, controlling for the impact of love duration as a confounder.

Results

Brain network measures

Figure 1 shows that small-worldness decreased with higher sparsity. Compared to the single group, the love group showed lower small-worldness at sparsity 0.075 to 0.275 (Bonferroni, $p < 0.005$). Figure 2 depicts that the mean clustering coefficient (CC) decreased with higher sparsity, and CC was lower in LG compared with SG at all sparsity levels (Bonferroni, $p < 0.005$). There was no significant difference in characteristic path length ($p > 0.05$), except at a sparsity of 0.05 ($p = 0.02$). There was no significant difference in network global efficiency ($p > 0.05$) between the two groups, except at a sparsity of 0.2 ($p = 0.045$).

Nodal measures

Nodal measures included *Degree, Clustering coefficient, Modularity, Local efficiency, Within-module degree z-score* and *Participant coefficient*.

Figure 3 shows the results of degree measure (area under the curve, AUC) of all 90 brain regions. Compared with the single group, the love group showed significantly decreased degree in the left angular gyrus, bilateral medial orbital part of superior frontal gyri (ORBsupmed) and right gyrus rectus, and increased degree in bilateral fusiform gyri, bilateral cuneus and bilateral lingual gyrus (Bonferroni, $p < 0.001$).

There was a significant difference in modularity between the two groups at sparsity 0.075 to 0.275 (Bonferroni, $p < 0.005$) (Fig. 4), indicating that lovers had overall fewer modules. Figure 5 (1A, 1B) and Table 2 illustrate module properties in SG at a sparsity of 0.15. Figure 5 (2A, 2B) and Table 3 illustrate module properties in LG at a sparsity of 0.15.

We detected predefined functional modules: the somatomotor, frontoparietal control, visual, default mode and limbic-ventral attention module (Yeo et al. 2011). Then we defined hubs in each module. There were fewer hubs in LG (12 Vs.19) in all, and the difference between two groups was driven by the limbic-ventral attention module (see Tables 2 and 3). The fusiform and parahippocampal gyrus were connector hubs in LG, while connector hubs in SG included the amygdala and putamen.

The fusiform was a connector hub in LG, with a significant difference in degree between two groups. We further investigated the connections in bilateral fusiform gyri with its neighboring nodes for both groups, based on the average connection matrix of each group at sparsity of 0.15. In SG, both the left

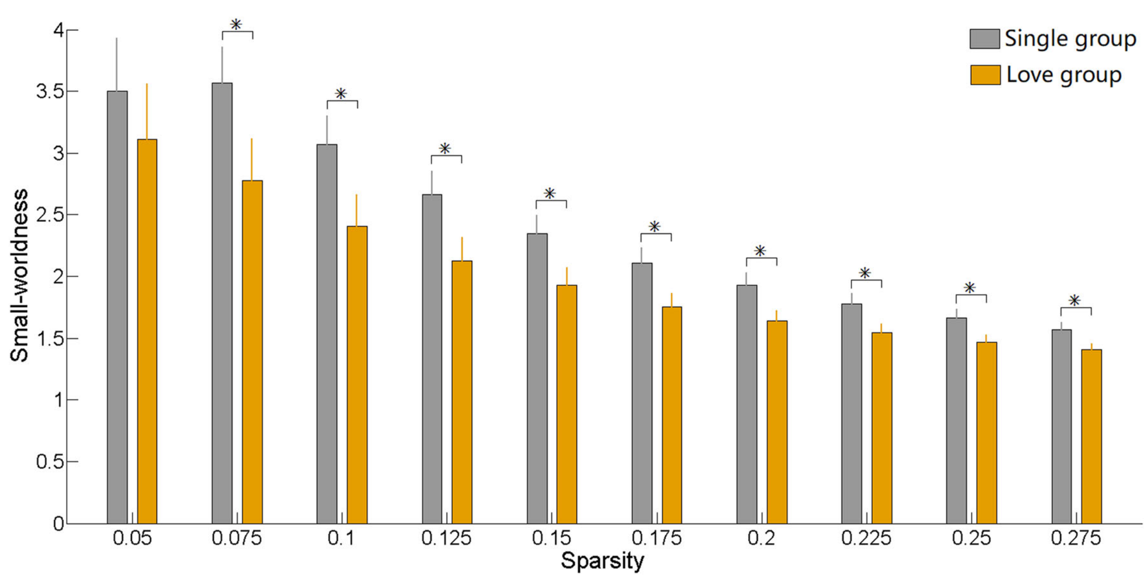

Fig. 1 Small-worldness of single group and love group. The small-worldness of the love group was lower than that of the single group (significant at sparsity 0.075 to 0.275). *$p < 0.005$; Bonferroni corrected

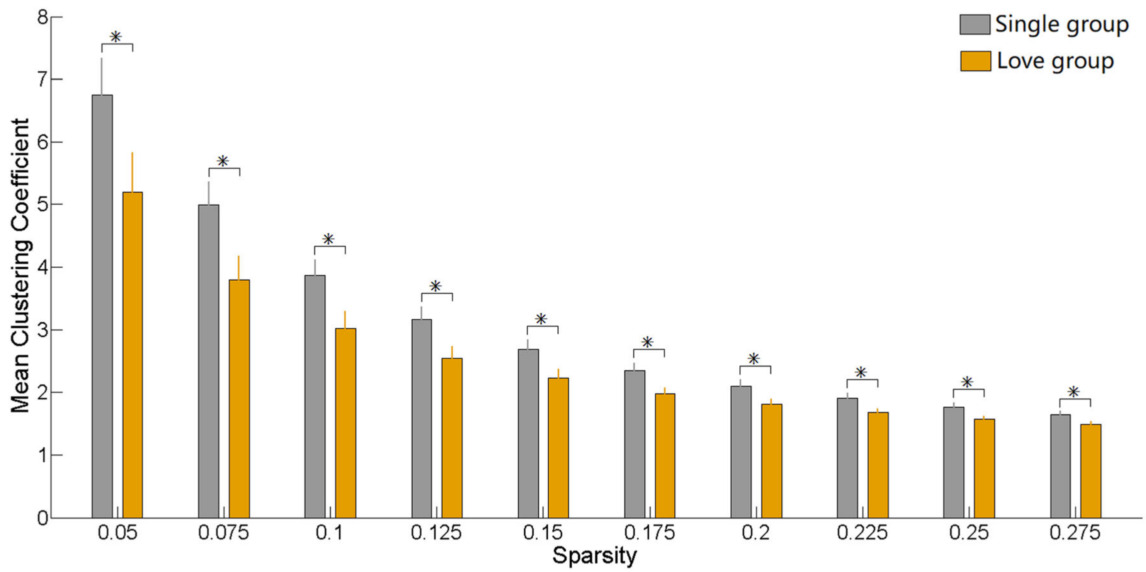

Fig. 2 Mean clustering coefficient of single group and love group. The mean clustering coefficient of the love group is lower than that of the single group at all levels of sparsity. $*p < 0.005$; Bonferroni corrected

and right fusiform gyri had 18 neighbors, with 15 neighbors located in the same module. In LG, the left fusiform gyrus had 35 neighbors (right fusiform gyrus: 30), of which only 13 belonged to the same module (right fusiform gyrus: 13).

Finally, we did not find any significant differences in clustering coefficient, or local efficiency AUC between the two groups ($p > 0.05$).

Correlations of PLS score with network measures

Partial correlation analysis (using "love duration" as a control variable) showed significant negative associations between PLS score and small-worldness, mean clustering coefficient and modularity (Bonferroni, $p < 0.05$) (see Table 4). Results also showed significant negative associations between PLS

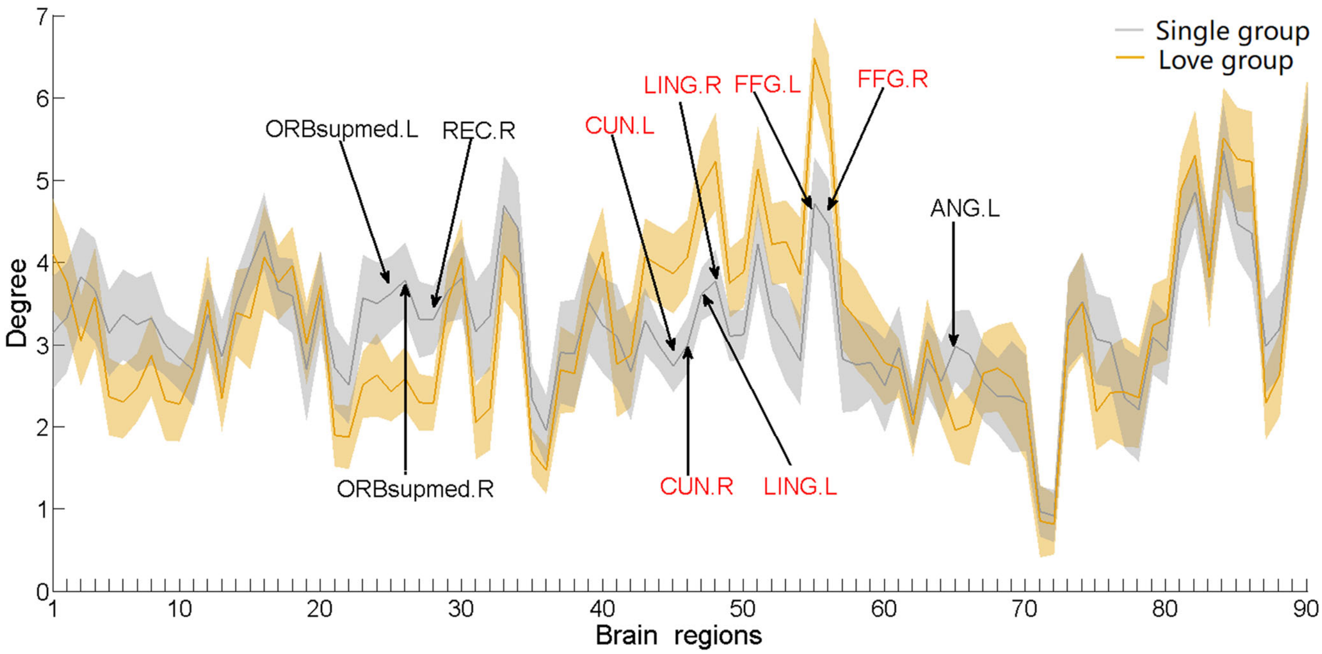

Fig. 3 Area under the curve in the single group (grey) and the love group (yellow) for nodal degree. Compared with the single group, the love group showed decreased degree in the left angular gyrus, bilateral medial orbital superior frontal gyri and right gyrus rectus; increased degree was found in the bilateral fusiform gyri, bilateral cuneus and bilateral lingual gyrus (Bonferroni, $p < 0.001$). Regions with increased degree are labled red, and regions with decreased degree are labled black. The gray shaded area represents the 95% confidence intervals in the single group and the yellow shaded area represents the 95% confidence intervals in the love group. Regions are listed as NAME.L/R. ORBsupmed, Medial orbital superior frontal gyrus; REC, Gyrus rectus; CUN, Cuneus; FFG, Fusiform gyrus; LING, Lingual gyrus; ANG, Angular gyrus. L, left; R, right

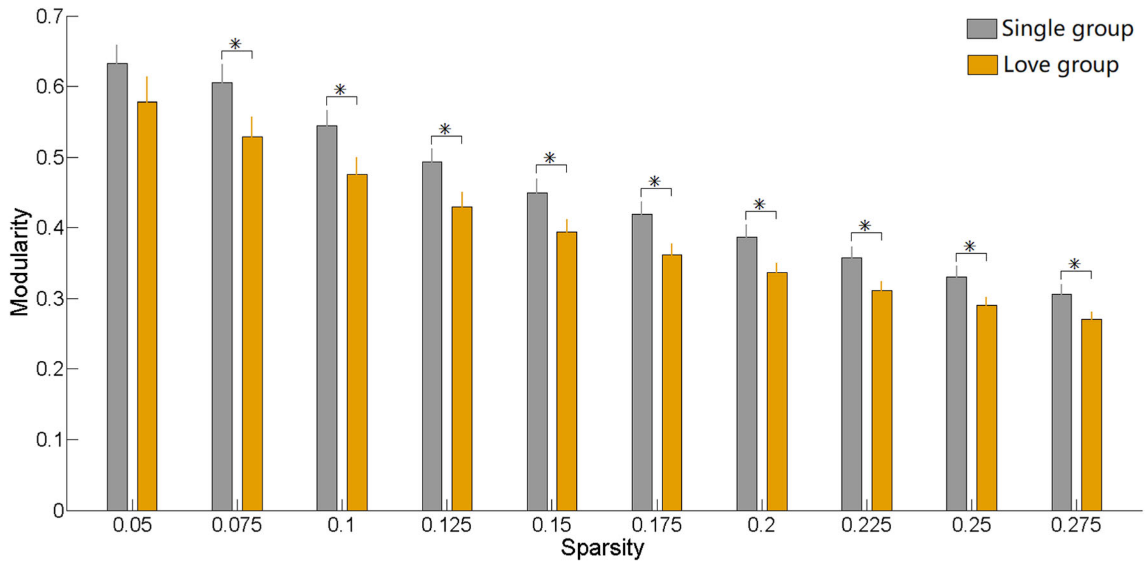

Fig. 4 Modularity of single group and love group. Modularity of the love group is significantly lower than that of the single group (significant at sparsities 0.075 to 0.275). The mean number of modules calculated per group based on the mean connectivity matrices were 6 (single group) and 5 (love group). $*p < 0.005$; Bonferroni corrected

score and local efficiency of left ORBsupmed gyrus, as well as trending negative associations between PLS score and degree of left angular gyrus. Furthermore, we found significant positive associations between PLS score and clustering coefficient (or local efficiency) of left fusiform gyrus with trending positive associations between PLS score and clustering coefficient (or local efficiency) of right fusiform gyrus (see Table 4). No other significant or trend-level correlation between PLS score and brain metrics was found.

Discussion

In this study, we used rs-fMRI and graph theory to investigate the brain network topology of lovers (LG, people who fell in love and were in a romantic relationship) compared with those who have never been in love and not in a romantic relationship (SG). Data revealed significant differences in brain network metrics between groups: compared to the SG, the brain network of lovers showed lower small-worldness, mean clustering coefficient and modularity properties, which were negatively correlated to Passionate Love Scale scores. Results also showed significant differences in nodal metrics: the degree of the left angular gyrus, bilateral ORBsupmed and right gyrus rectus was decreased; the degree of bilateral fusiform gyrus, bilateral cuneus and bilateral lingual gyrus was increased in the brain network of lovers. Partial correlation analysis revealed a significant negative correlation between PLS score and local efficiency of the left ORBsupmed gyrus and a trending negative correlation between PLS score and degree of the left angular gyrus; positive correlation between PLS score and clustering coefficient (or local efficiency) of left fusiform gyrus in LG (trending significant for right gyrus). This study, for the first time, found that love may be related to functional topology changes in the resting state of the brain, both on a large-scale brain network and nodal level.

Brain network changes in lovers

There are three kinds of network topology: random networks, small-world networks and regular networks (Stam and Reijneveld 2007). Small-world networks are optimized for information exchange, as they have shorter characteristic path length as compared to random networks, but higher clustering coefficients as compared to regular networks. Because of this, both the extent of segregation and integration in small-world networks is higher than in other networks, leading to increased communication efficiency. In Graph Theory analysis, small-worldness is a measure that reflects the degree of small-world organization.

Previous researchers have found lower small-worldness in addicted individuals (Liu et al. 2009; Yuan et al. 2010) and also patients diagnosed with dementia due to Alzheimer's disease (Haan et al. 2009). Mean clustering coefficient is a measure of network segregation, and is a good indicator of efficient exchange of information. For example, a study showed that performance on an intelligence test was positively associated with higher network clustering coefficient (Langer et al. 2012). Another study reported lower mean clustering coefficient in patients with Alzheimer (Haan et al. 2009). Our results found that the mean clustering coefficient was decreased in the brain network of lovers, and that small-

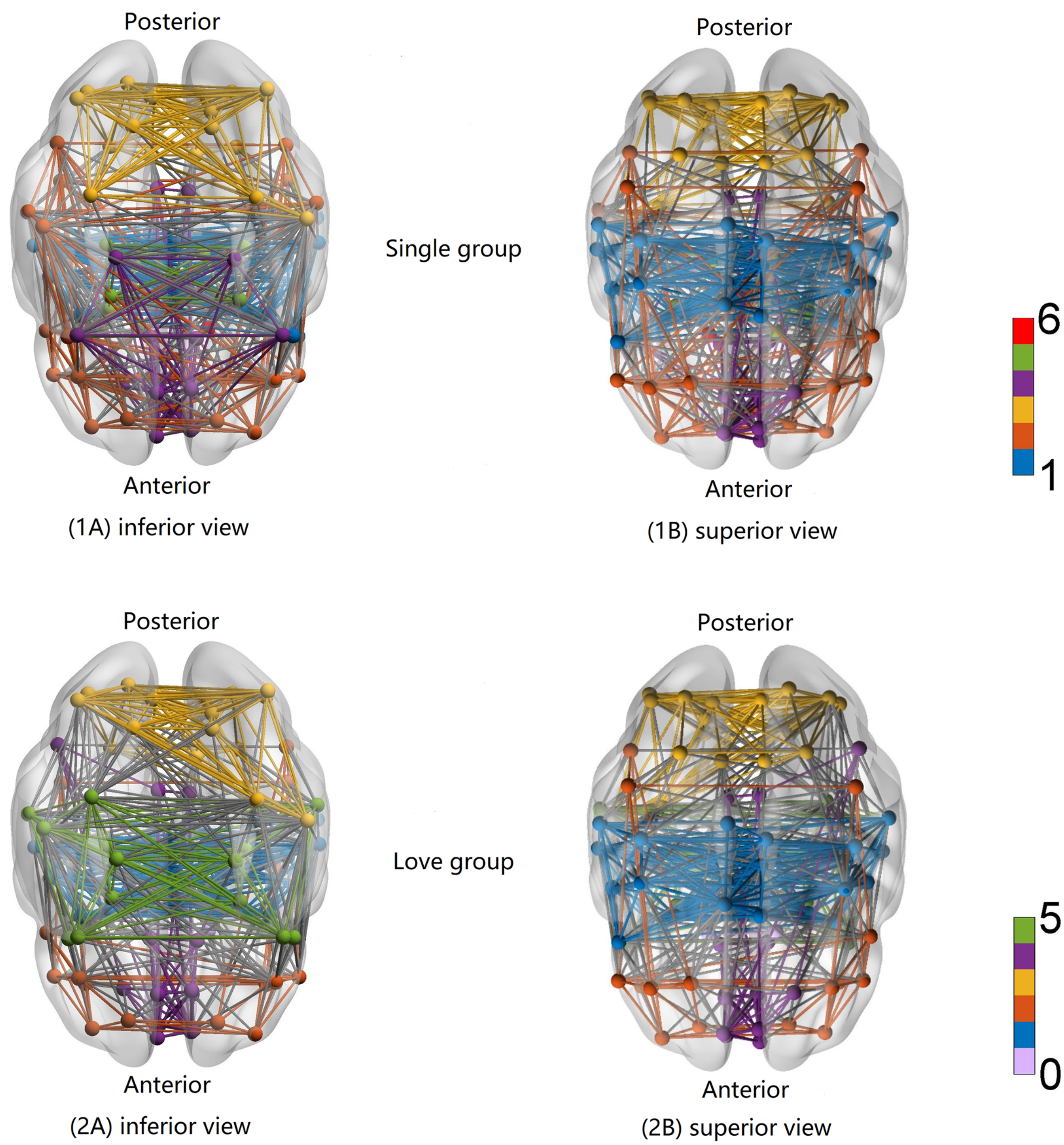

Fig. 5 Modular brain network (based on the average connection matrix) of the single group and the love group at a sparsity of 0.15. There were six modules (1A, 1B) in the single group and five modules in the love group (2A, 2B). The vertical color bar represents the color coding of the modules (number 0 is assigned to isolated nodes). Node connections within each module are represented in the module's color, while connections between different modules are indicated in gray

worldness was also decreased in LG, suggesting decreased functional segregation in LG.

A more direct manifestation of the segregation extent of a network is the number of modules in a network, that is, the extent of modularity, a measure of functional segregation (Rubinov and Sporns 2010). The current study showed a decrease in brain modularity in lovers, suggesting decreased functional segregation.

Furthermore, results found that the small-worldness, mean clustering coefficient, and modularity were negatively correlated with PLS scores, demonstrating that lower segregation was associated with greater intensity of romantic love.

This reduced network segregation in the brain networks of lovers is consistent with lower performance in general cognitive tasks (Steenbergen et al. 2014), and is consistent with findings in human drug addiction (Liu et al. 2009; Yuan et al. 2010). Early-phase romantic love (i.e., "falling in love") is characterized by euphoria, intensely focused attention on the preferred individual, obsessive thinking about the person, and emotional dependency on and craving for emotional union with the beloved (Aron et al. 2005; Fisher 1998). Thus, those who are in love may be subject to being preoccupied with their beloved and not focus on cognitive processing, a hypothesis concordant with cognitive deficits in addicted individuals (Zou et al. 2016).

Table 2 Summary of module properties for single subjects (at a sparsity of 0.15)

Module	Nodes	Connectors	Hubs	Key regions
Fronto-parietal-temporal (Somatomotor)	23	6 (26%)	Provincials = 6	ROL.L
				ROL.R
				INS.L
				INS.R
				STG.L
				STG.R
			Connectors = 0	
Prefronto-temporal-parietal (Frontoparietal control)	20	14 (70%)	Provincials = 3	MFG.L
				ORBmid.L
				ORBmid.R
			Connectors = 2	ORBinf.L
				ITG.L
Occipital-parietal-temporal (Visual)	19	4 (21%)	Provincials = 1	MOG.L
			Connectors = 0	
Prefronto-parietal-temporal (Default mode)	17	11 (65%)	Provincials = 4	ORBsupmed.L
				ORBsupmed.R
				REC.L
				REC.R
			Connectors = 0	
Temporal-subcortical (Limbic & Ventral Attention)	10	7 (70%)	Provincials = 1	PAL.L
			Connectors = 2	AMYG.L
				PUT.L
Subcortical (Limbic)	1	0	Provincials = 0	
			Connectors = 0	

Regions are listed as NAME.L/R

MFG, Middle frontal gyrus; ORBmid, Middle frontal gyrus, orbital part; ORBinf, Inferior frontal gyrus, orbital part; ROL, Rolandic operculum; ORBsupmed, Medial orbital part of superior frontal gyrus; REC, Gyrus rectus; INS, Insula; AMYG, Amygdala; MOG, Middle occipital gyrus; CAU, caudate nucleus; PUT, Lenticular nucleus, putamen; PAL, Lenticular nucleus, pallidum; STG, Superior temporal gyrus; ITG, Inferior temporal gyrus. L, left; R, right

Nodal changes in lovers

The most basic nodal measure is degree, which shows the importance of a node within a network. Significant differences of nodal metrics between groups was found mainly in the 'degree' coefficient. Decreased degree was found in LG in the left angular gyrus, bilateral ORBsupmed and right gyrus rectus, while increased degree was found in bilateral fusiform gyri, bilateral cuneus and bilateral lingual gyrus. However, correlation analysis showed that only four nodes among these regions were probably related to romantic love. The local efficiency or degree of these nodes was significantly associated (or trending toward significance) with PLS scores: left angular gyrus (negative correlation), left ORBsupmed gyrus (negative correlation) and bilateral (especially left) fusiform gyrus (positive correlation). These findings suggest that passionate love may be associated with an enhanced role of the fusiform cortex in brain network topology, as well as attenuated contributions from the left angular and ORBsupmed gyri.

The fusiform gyrus, a part of the temporal lobe and occipital lobe, has been known to play an important role for emotional-social processing. It is critical in face and body recognition (Rypma et al. 2015), object identification and integration of abstract representations (Arzy et al. 2006; Blanke et al. 2002). Research shows that dopamine receptor binding potential, indicative of the reward value of a stimulus, are related to neural activity in the fusiform gyrus during face recognition (Rypma et al. 2015). The subliminal presentation of a beloved's name, as compared to a control stimulus, recruits the bilateral fusiform regions (Ortigue et al. 2007). Recently, Yin et al. (2018) found higher activation of bilateral fusiform gyrus when performing romantic appraisal. In the current study, the fusiform gyrus was found to have increased degree and became a connector hub in LG (not in SG), suggesting its pivotal role in love. The enhanced role of the fusiform gyrus may contribute to performance of lovers in social-emotional cognitive processing in daily life, such as reading facial emotions from their beloved.

Table 3 Summary of module properties for love subjects (at a sparsity of 0.15)

Module	Nodes	Connectors	Hubs	Key regions
Fronto-subcortical-parietal (Somatomotor)	27	9 (33%)	Provincials = 2	SMA.R
				PUT.R
			Connectors = 2	STG.L
				STG.R
Prefrontal-parietal (Frontoparietal control)	15	13 (87%)	Provincials = 1	ORBmid.L
			Connectors = 0	
Occipital-parietal-temporal (Visual)	18	8 (44%)	Provincials = 0	
			Connectors = 1	MOG.L
Prefrontal-parietal (Default mode)	14	9 (64%)	Provincials = 3	mSFG.L
				ORBsupmed.L
				ORBsupmed.R
			Connectors = 0	
Temporal (Limbic & Ventral Attention)	14	8 (57%)	Provincials = 0	
			Connectors = 3	PHG.L
				PHG.R
				FFG.L

Regions are listed as NAME.L/R

ORBmid, Middle frontal gyrus, orbital part; SMA, Supplementary motor area; mSFG, Superior frontal gyrus, medial; ORBsupmed, Medial orbital part of superior frontal gyrus; PHG, Parahippocampal gyrus; MOG, Middle occipital gyrus; FFG, Fusiform gyrus; PUT, Lenticular nucleus, putamen; STG, Superior temporal gyrus. L, left; R, right

The angular gyrus is a part of the DMN (Buckner et al. 2008), and has also been shown to play a key role in love. In a previous task-based fMRI study, a subliminal prime of a loved-one was related to activation of the angular gyrus (Ortigue et al. 2007). Functional activity in this area has also been shown to be critical to episodic memory retrieval (Thakral et al. 2017), which in turn may help consolidate positive emotional attachment towards a preferred other (Sutin and Gillath 2009). Furthermore, the angular gyrus has also been shown to be vital in the monitoring of one's own actions via self-awareness (Farrer et al. 2008), as well as in the abstract representation of the self (Arzy et al. 2006; Blanke et al. 2002).

We speculate that changes in functional network organization related to this region in romantic lovers may indicate alterations in the processing of abstract representations of the self. In fact, there is evidence to suggest that lovers' abstract representations of the 'self' are adapted to include their significant other (A. Aron and Aron 1986; Aron and Aron 1996; Jackson et al. 2006). From an evolutionary perspective, changes in network organization may be less aberrant and more naturally-occurring, as previous studies suggest that intense lifetime achievements, including falling in love and finding an intimate partner, are central in human motivation for 'expanding the self' (Aron and Aron 1986; Aron and Aron 1996).

Table 4 Partial correlations between brain network and nodal metrics with PLS score in the love group (n = 34)

	Partial correlation	p value
Brain network metrics		
Small-worldness	−0.430*	0.012
Mean clustering coefficient	−0.451*	0.008
Nodal metrics		
Modularity	−0.370*	0.034
Degree of left angular gyrus	−0.329	0.062
Clustering coefficient of left fusiform gyrus	0.381*	0.029
Local efficiency of left fusiform gyrus	0.378*	0.030
Clustering coefficient of right fusiform gyrus	0.323	0.067
Local efficiency of right fusiform gyrus	0.338	0.055
Local efficiency of left ORBsupmed gyrus	−0.412*	0.017

PLS, Passionate Love Scale; *$p < 0.05$; Bonferroni corrected

The ORBsupmed gyrus, a part of the medial orbitofrontal cortex (mOFC), is also a part of the DMN, and plays an important role in social cognition. The mOFC is also involved in monitoring of reward values (Kringelbach 2005; Kringelbach and Rolls 2004). Across a range of studies, the OFC has been associated with valuation of positive stimuli, such as pleasant foods (e.g., Rolls et al. 2003; Small et al. 2003), attractive faces (e.g., O'Doherty et al. 2003), and monetary rewards (e.g., Knutson et al. 2001). In addicts, increased activation in the mOFC has been reported during exposure to drug cues (Baler and Volkow 2006; Volkow et al. 2003). Increased degree between the mOFC (or OFC) and other areas has also been reported in resting state studies in addicted individuals (Yuan et al. 2010).

For lovers, the mOFC may reflect social evaluations of a romantic partner and others (Hughes and Beer 2012). Researchers found activation of the mOFC when people viewed pictures of their beloved (Takahashi et al. 2015). However, deactivations in the mOFC have been reported to be associated with greater relationship satisfaction in long-term relationships (Acevedo et al. 2012; Xu et al. 2012). We found decreased degree of mOFC, which may suggest detachment from individuals other than the loved one in lovers. This process may be helpful for enhancing commitment strength in intimate relationships.

Finally, we found significant differences in degree properties of several nodes (e.g., right gyrus rectus, bilateral cuneus, bilateral lingual gyrus) in LG. However, no significant correlations were found between degree (or any other nodal metrics) and PLS scores. This result implies that these differences may have already existed between groups before falling in love and are perhaps not love-dependent. Thus, future longitudinal research should consider investigating the causal consequences of 'falling in love' in brain network functional organization properties.

However, we should interpret differences in topology with caution. In the present study, we chose the single group (never been in love and not in a relationship) as a control group, resulting in possibly large differences between the two groups and therefore maximizing differences in the brain. This is a common issue found in studies comparing different groups, such as comparing healthy individuals with addicted individuals (Kelly et al. 2011; Liu et al. 2009; Yuan et al. 2010), individuals with depression (Fitzgerald et al. 2008; Forbes et al. 2006), or individuals with pathological aggression (Gan et al. 2018). In this study, pre-existing good communication abilities may be an important factor in increasing the likelihood of someone finding a partner and fall in love in LG. Thus, in a recent study from our group (not published) we used the Interpersonal Relationship Comprehensive Diagnostic Scale (Richang 1999) to compare strength of interpersonal relationships in both groups. Data showed that there were no significant differences in interpersonal relationship scores between the two groups [$t_{(82)} = 1.105$, $p = 0.273$, 95% confidence interval (−1.082, 3.783)]. Therefore, although we cannot definitely ensure that the brain connectivity changes observed here arose from falling in love, it seems likely that they are indeed love-related.

In conclusion, our findings of network and nodal changes suggest that the resting-state brain network topology in lovers is different from single individuals, with an overall decrease in brain functional segregation but enhanced emotional-social processing.

Comparison between romantic love and addiction

As discussed above, our results confirm love-related changes in brain networks. Some of these changes parallel the effects observed in addiction, while others differ from addiction.

Romantic love is a state of intense longing for union with another. The early stage of romantic love is reminiscent of addiction, with behavioral changes that include euphoria, intense focused attention on the preferred individual, and obsessive thoughts about the person (Aron et al. 2005; Hatfield and Rapson 1987). Previous fMRI studies have found that lovers show significant activation when viewing pictures of their partner, including the limbic-reward system and other networks: ventral tegmental area (VTA), nucleus accumbens (NAC), caudate, insula, dorsal anterior cingulate cortex (dACC), dorsolateral prefrontal cortex (dlPFC), hippocampus, posterior cingulate cortex (PCC), precuneus, temporo-parietal junction (TPJ), and hypothalamus (Acevedo et al. 2012; Aron et al. 2005; Bartels and Zeki 2000; Ortigue et al. 2007; Xu et al. 2011). Similarly, when addicted individuals are exposed to drug cues, they show significant activations in the VTA, NAC, caudate, insula, dACC, dlPFC, mPFC, ventral anterior cingulate cortex (vACC), medial orbitofrontal cortex (mOFC), inferior frontal gyrus (IFG), and amygdala (Baler and Volkow 2006; Volkow et al. 2003; Zhang et al. 2009; Zhang X, et al. 2011; Zhang J, et al. 2011). Zhang et al. (2016) reviewed addiction-related cue-induced neural changes and found that addicts have high activations in right orbitofrontal cortex (OFC), right NAC, bilateral anterior cingulate (ACC), mPFC, right dlPFC, right caudate nucleus, left parahippocampus when exposed to addiction-related cues. In our recent article, we highlighted that brain regions related to romantic love overlap with those implicated in drug addiction such as the VTA, NAC, caudate, insula, dACC, mPFC, and dlPFC, all which share membership with the reward network (Zou et al. 2016).

Consistent with findings from behavioral and fMRI task paradigms, our results here provide complementary evidence for the partial similarity between love and addiction. The decreased small-worldness, mean clustering coefficient and modularity properties observed in this study parallel reports from previous studies in human drug addiction (Liu et al.

2009; Yuan et al. 2010) and may hence underlie an inherent similarity of behavioral and task-related neural activity.

However, it is worthwhile to note that we found differences from addiction studies when it came to nodal metrics. Research in addiction shows higher activation in right orbitofrontal cortex (OFC) when drug users are exposed to drug stimuli (Zhang et al. 2016), yet here we found that the OFC had a decreased functional role in lovers (decreased degree in mOFC). Second, while previous studies in addiction have reported enhanced functional connectivity between the left angular gyrus and other cortical regions (e.g., left anterior cingulate cortex) in cocaine users (Ray et al. 2015), here we found lower degree of the angular gyrus in lovers. Third, while changes in the fusiform gyrus have rarely been reported in studies of addiction, here we found a significantly altered functional role of the fusiform gyrus in lovers (being a connector hub in LG but not in SG).

In fact, within the context of strong involvement of the fusiform gyrus in face processing and the angular gyrus' involvement in monitoring of self-action and self-awareness, as well as the mOFC's association with social evaluation, all nodal love-related changes in the present study were found within the emotional-social processing system. Considering reported socio-emotional differences between lovers and drug users (social avoidance in addicts vs. enhanced social performance in lovers), these network changes may reflect the neural mechanism underlying different social behaviors in addicts and lovers.

Taken together, our findings provide evidence that romantic love is both similar and different from addiction in several respects. These two populations share similar overall network properties (less functional integration and segregation), in addition to possible underlying general cognitive deficits; yet, lovers show opposite nodular properties from addicts, particularly in the social processing system, supporting the hypothesis that lovers may have improved emotional-social processing compared to addicts.

Limitations

Though our research provides insights into the nature of romantic love, some limitations should be mentioned. First, the cross-sectional nature of the study design prevents us from observing any causal inferences. We cannot know if differences between groups existed before or after falling in love, or whether differences we found may be confounded by other potential characteristics of the participants (e.g., personality, interpersonal relationship). Thus, future longitudinal studies that track brain functional connectivity in parallel with love progression, intensity, and status, would greatly help to better understand the topological changes in functional connectivity associated with intensity of romantic love. Second, the behavioral markers used in this study were limited, and future research in romantic lovers should combine resting-state scans with cognitive tasks or psychological tests to better explain how observed effects in network topology relate to behavioral changes. Third, although we reminded participants to keep their eyes closed while awake, and think of nothing during the resting-state scan, we cannot know exactly what they were thinking during the scan. Fourth, the anatomical identification was done automatically by AAL, which is commonly used in the field, but has limited spatial resolution. Future improvements in scanning processing control and data processing would be very helpful.

Conclusions

In this study, we investigated brain network topology in an in-love group compared to a single group of individuals. Results showed decreased overall brain functional segregation (e.g., lower small-worldness, mean clustering coefficient and modularity properties) but enhanced emotional-social processing (e.g., decreased degree in left angular gyrus and left medial orbitofrontal gyrus, and increased degree in bilateral fusiform gyri) in romantic lovers. Our findings provided first evidence of love-related brain network organization changes, and suggest that romantic love is both similar and different from addiction.

Acknowledgements We thank Yun Tian for his help in data processing.

Funding sources This study was funded by the Fundamental Research Funds for the Central Universities (#SWU1809006) and the National Natural Science Foundation of China (31771237).

Author contributions Z.Z., and H.C. were responsible for the original study design. C.W., S.S. and H.S. collected the data. C.W. and F.d.U. performed data analysis. Z.Z., C.W., A.Z., and H.C. interpreted the findings. C.W., S.S. and F.d.U. wrote the manuscript. All authors contributed to the final version, approved the publication of the final version and agreed to be accountable for the integrity and accuracy of all aspects of the work.

Compliance with ethical standards

This study was approved by the Ethics Committee of Southwest University (Chongqing, China). Informed consent was obtained from all individual participants included in the study.

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

References

Acevedo, B. P., Aron, A., Fisher, H. E., & Brown, L. L. (2012). Neural correlates of long-term intense romantic love. *Social Cognitive and Affective Neuroscience, 7*(2), 145–159.

Achard, S., & Bullmore, E. (2007). Efficiency and cost of economical brain functional networks. *PLoS Computational Biology, 3*(2), e17.

Aron, A., & Aron, E. N. (1986). Love and the expansion of self: Understanding attraction and satisfaction. Hemisphere Publishing Corp/Harper & Row Publishers.

Aron, E. N., & Aron, A. (1996). Love and expansion of the self: The state of the model. *Pers Relatsh, 3*(1), 45–58.

Aron, A., Fisher, H., Mashek, D. J., Strong, G., Li, H., & Brown, L. L. (2005). Reward, motivation, and emotion systems associated with early-stage intense romantic love. *Journal of Neurophysiology, 94*(1), 327–337.

Arzy, S., Seeck, M., Ortigue, S., Spinelli, L., & Blanke, O. (2006). Induction of an illusory shadow person. *Nature, 443*(7109), 287–287.

Baler, R. D., & Volkow, N. D. (2006). Drug addiction: The neurobiology of disrupted self-control. *Trends in Molecular Medicine, 12*(12), 559–566.

Barrós-Loscertales, A., Meseguer, V., Sanjuán, A., Belloch, V., Parcet, M. A., Torrubia, R., & Avila, C. (2006). Striatum gray matter reduction in males with an overactive behavioral activation system. *The European Journal of Neuroscience, 24*(7), 2071–2074.

Bartels, A., & Zeki, S. (2000). The neural basis of romantic love. *Neuroreport, 11*(17), 3829–3834.

Bassett, D. S., Bullmore, E., Verchinski, B. A., Mattay, V. S., Weinberger, D. R., & Meyer-Lindenberg, A. (2008). Hierarchical organization of human cortical networks in health and schizophrenia. *The Journal of Neuroscience, 28*(37), 9239–9248.

Bassett, D. S., Wymbs, N. F., Porter, M. A., Mucha, P. J., Carlson, J. M., & Grafton, S. T. (2011). Dynamic reconfiguration of human brain networks during learning. *Proceedings of the National Academy of Sciences of the United States of America, 108*(18), 7641–7646.

Blanke, O., Ortigue, S., Landis, T., & Seeck, M. (2002). Neuropsychology: Stimulating illusory own-body perceptions. *Nature, 419*(6904), 269–270.

Buckner, R., Andrews-Hanna, J., & Schacter, D. (2008). The brain's default network: Anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences, 1124*, 1–38.

Bullmore, E. T., & Bassett, D. S. (2011). Brain graphs: Graphical models of the human brain connectome. *Annual Review of Clinical Psychology, 7*, 113–140.

Bullmore, E., & Sporns, O. (2012). The economy of brain network organization. *Nature Reviews. Neuroscience, 13*(5), 336–349.

Burkett, J. P., & Young, L. J. (2012). The behavioral, anatomical and pharmacological parallels between social attachment, love and addiction. *Psychopharmacology, 224*(1), 1–26.

Farrer, C., Frey, S. H., Horn, J. D. V., Tunik, E., Turk, D., Inati, S., & Grafton, S. T. (2008). The angular gyrus computes action awareness representations. *Cerebral Cortex, 18*(2), 254–261.

Fisher, H. E. (1998). Lust, attraction, and attachment in mammalian reproduction. *Human Nature, 9*(1), 23–52.

Fisher, H. E., Xu, X., Aron, A., & Brown, L. L. (2016). Intense, passionate, romantic love: A natural addiction? How the fields that investigate romance and substance abuse can inform each other. *Frontiers in Psychology, 7*(40), 687.

Fitzgerald, P. B., Srithiran, A., Benitez, J., Daskalakis, Z. Z., Oxley, T. J., Kulkarni, J., & Egan, G. F. (2008). An fMRI study of prefrontal brain activation during multiple tasks in patients with major depressive disorder. *Human Brain Mapping, 29*(4), 490–501.

Forbes, E. E., Christopher May, J., Siegle, G. J., Ladouceur, C. D., Ryan, N. D., Carter, C. S., ... & Dahl, R. E. (2006). Reward-related decision-making in pediatric major depressive disorder: An fMRI study. *Journal of Child Psychology and Psychiatry, 47*(10), 1031–1040.

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America, 102*(27), 9673–9678.

Gan, G., Zilverstand, A., Parvaz, M. A., Preston-Campbell, R. N., Uquillas, F. D. O., Moeller, S. J., ... & Alia-Klein, N. (2018). Habenula-prefrontal resting-state connectivity in reactive aggressive men–A pilot study. Neuropharmacology.

Guimerà, R., & Amaral, L. A. N. (2005). Cartography of complex networks: Modules and universal roles. *J Stat Mech, 2005*(02), P02001.

Haan, W. D., Pijnenburg, Y. A., Strijers, R. L., Made, Y. V. D., Flier, W. M. V. D., Scheltens, P., & Stam, C. J. (2009). Functional neural network analysis in frontotemporal dementia and Alzheimer's disease using EEG and graph theory. *BMC Neuroscience, 10*(1), 101.

Hao, X., Wang, K., Li, W., Yang, W., Wei, D., Qiu, J., & Zhang, Q. (2013). Individual differences in brain structure and resting brain function underlie cognitive styles: Evidence from the embedded figures test. *PLoS One, 8*(12), e78089.

Hatfield, E., & Rapson, R. L. (1987). Passionate love/sexual desire: Can the same paradigm explain both? *Archives of Sexual Behavior, 16*(3), 259–278.

Hatfield, E., & Sprecher, S. (1986). Measuring passionate love in intimate relationships. *Journal of Adolescence, 9*(4), 383–410.

Hazan, C., & Shaver, P. (1987). Romantic love conceptualized as an attachment process. *Journal of Personality and Social Psychology, 52*(3), 511–524.

He, Y., & Evans, A. (2010). Graph theoretical modeling of brain connectivity. *Current Opinion in Neurology, 23*(4), 341–350.

Heilig, M., Epstein, D. H., Nader, M. A., & Shaham, Y. (2016). Time to connect: Bringing social context into addiction neuroscience. *Nature Reviews. Neuroscience, 17*(9), 592.

Heuvel, M. P., Den, V., & Olaf, S. (2011). Rich-club organization of the human connectome. *The Journal of Neuroscience, 31*(44), 15775–15786.

Hughes, B. L., & Beer, J. S. (2012). Orbitofrontal cortex and anterior cingulate cortex are modulated by motivated social cognition. *Cerebral Cortex, 22*(6), 1372–1381.

Humphries, M. D., & Gurney, K. R. (2008). Network 'small-world-ness': A quantitative method for determining canonical network equivalence. *PLoS One, 3*(4), e0002051.

Jackson, P. L., Brunet, E., Meltzoff, A. N., & Decety, J. (2006). Empathy examined through the neural mechanisms involved in imagining how I feel versus how you feel pain. *Neuropsychologia, 44*(5), 752–761.

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *Neuroimage, 17*(2), 825–841.

Kelly, C., Zuo, X. N., Gotimer, K., Cox, C. L., Lynch, L., Brock, D., … & Milham, M. P. (2011). Reduced interhemispheric resting state functional connectivity in cocaine addiction. *Biological Psychiatry, 69*(7), 684–692.

Knutson, B., Fong, G. W., Adams, C. M., Varner, J. L., & Hommer, D. (2001). Dissociation of reward anticipation and outcome with event-related fMRI. *Neuroreport, 12*(17), 3683–3687.

Konova, A. B., Moeller, S. J., Tomasi, D., & Goldstein, R. Z. (2015). Effects of chronic and acute stimulants on brain functional connectivity hubs. *Brain Research, 1628*.

Kringelbach, M. L. (2005). The human orbitofrontal cortex: Linking reward to hedonic experience. *Nature Reviews. Neuroscience, 6*(9), 691–702.

Kringelbach, M. L., & Rolls, E. T. (2004). The functional neuroanatomy of the human orbitofrontal cortex: Evidence from neuroimaging and neuropsychology. *Progress in Neurobiology, 72*(5), 341–372.

Langer, N., Pedroni, A., Gianotti, L. R., Hänggi, J., Knoch, D., & Jäncke, L. (2012). Functional brain network efficiency predicts intelligence. *Human Brain Mapping, 33*(6), 1393–1406.

Liu, J., Liang, J., Qin, W., Tian, J., Yuan, K., Bai, L., & Li, Q. (2009). Dysfunctional connectivity patterns in chronic heroin users: An fMRI study. *Neuroscience Letters, 460*(1), 72–77.

Maslov, S., & Sneppen, K. (2002). Specificity and stability in topology of protein networks. *Science, 296*(5569), 910–913.

Milo, R., Shen-Orr, S., Itzkovitz, S., Kashtan, N., Chklovskii, D., & Alon, U. (2002). Network motifs: Simple building blocks of complex networks. *Science, 298*(5594), 824–827.

Newman, M. E. (2006). Modularity and community structure in networks. *Proceedings of the National Academy of Sciences of the United States of America, 103*(23), 8577–8582.

O'Doherty, J., Winston, J., Critchley, H., Perrett, D., Burt, D. M., & Dolan, R. J. (2003). Beauty in a smile: The role of medial orbitofrontal cortex in facial attractiveness. *Neuropsychologia, 41*(2), 147–155.

Ortigue, S., Bianchi-Demicheli, F., Hamilton, A. D. C., & Grafton, S. T. (2007). The neural basis of love as a subliminal prime: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience, 19*(7), 1218–1230.

Ray, S., Gohel, S. R., & Biswal, B. B. (2015). Altered functional connectivity strength in abstinent chronic cocaine smokers compared to healthy controls. *Brain Connectivity, 5*(8).

Reis, H. T., & Aron, A. (2008). Love: What is it, why does it matter, and how does it operate? *Perspectives on Psychological Science, 3*(1), 80–86.

Richang, Z. (1999). Psychological diagnosis, Shandong Education Publishing House. (in Chinese).

Rolls, E. T., Kringelbach, M. L., & De Araujo, I. E. (2003). Different representations of pleasant and unpleasant odours in the human brain. *The European Journal of Neuroscience, 18*(3), 695–703.

Rubinov, M., & Sporns, O. (2010). Complex network measures of brain connectivity: Uses and interpretations. *Neuroimage, 52*(3), 1059–1069.

Rypma, B., Fischer, H., Rieckmann, A., Hubbard, N. A., Nyberg, L., & Bäckman, L. (2015). Dopamine D1 binding potential predicts fusiform BOLD activity during face-recognition performance. *The Journal of Neuroscience, 35*(44), 14702–14707.

Small, D. M., Gregory, M. D., Mak, Y. E., Gitelman, D., Mesulam, M. M., & Parrish, T. (2003). Dissociation of neural representation of intensity and affective valuation in human gustation. *Neuron, 39*(4), 701–711.

Song, H., Zou, Z., Kou, J., Liu, Y., Yang, L., Zilverstand, A., Zhang, X. (2015). Love-related changes in the brain: a resting-state functional magnetic resonance imaging study. *Front Hum Neurosci,* 9.

Song, S., Zou, Z., Song, H., Wang, Y., Uquillas, F. D. O., Wang, H., & Chen, H. (2016). Romantic love is associated with enhanced inhibitory control in an emotional stop-signal task. *Frontiers in Psychology, 7*(687).

Stam, C. J., & Reijneveld, J. C. (2007). Graph theoretical analysis of complex networks in the brain. *Nonlinear Biomed Phys, 1*(1), 1.

Steenbergen, H. V., Langeslag, S. J. E., Band, G. P. H., & Hommel, B. (2014). Reduced cognitive control in passionate lovers. *Motivation and Emotion, 38*(3), 444–450.

Sternberg, R. J. (1986). A triangular theory of love. *Psychological Review, 93*(2), 119–135.

Sutin, A. R., & Gillath, O. (2009). Autobiographical memory phenomenology and content mediate attachment style and psychological distress. *Journal of Counseling Psychology, 56*(3), 351–364.

Takahashi, K., Mizuno, K., Sasaki, A. T., Wada, Y., Tanaka, M., Ishii, A., & Zeki, S. (2015). Imaging the passionate stage of romantic love by dopamine dynamics. *Frontiers in Human Neuroscience, 9*, 191.

Thakral, P. P., Madore, K. P., & Schacter, D. L. (2017). A role for the left angular gyrus in episodic simulation and memory. *The Journal of Neuroscience, 37*(34), 8142–8149.

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., & Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *Neuroimage, 15*(1), 273–289.

Volkow, N. D., Fowler, J. S., & Gene-Jack, W. (2003). The addicted human brain: Insights from imaging studies. *The Journal of Clinical Investigation, 111*(10), 1444–1451.

Wlodarski, R., & Dunbar, R. I. M. (2014). The effects of romantic love on mentalizing abilities. *Review of General Psychology, 18*(4), 313–321.

Xia, M., Wang, J., & He, Y. (2013). BrainNet viewer: A network visualization tool for human brain connectomics. *PLoS One, 8*(7), e68910.

Xu, X., Aron, A., Brown, L., Cao, G., Feng, T., & Weng, X. (2011). Reward and motivation systems: A brain mapping study of early-stage intense romantic love in Chinese participants. *Human Brain Mapping, 32*(2), 249–257.

Xu, X., Brown, L., Aron, A., Cao, G., Feng, T., Acevedo, B., & Weng, X. (2012). Regional brain activity during early-stage intense romantic love predicted relationship outcomes after 40 months: An fMRI assessment. *Neuroscience Letters, 526*(1), 33–38.

Yan, C. G., & Zang, Y. F. (2010). DPARSF: A MATLAB toolbox for "pipeline" data analysis of resting-state fMRI. *Frontiers in Systems Neuroscience, 4*(13), 13.

Yeo, B. T. T., Krienen, F. M., Jorge, S., Sabuncu, M. R., Danial, L., Marisa, H., & Polimeni, J. R. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology, 106*(3), 1125–1165.

Yin, J., Zhang, J. X., Xie, J., Zou, Z., & Huang, X. (2013). Gender differences in perception of romance in Chinese college students. *PLoS One, 8*(10), e76294.

Yin, J., Zou, Z., Song, H., Zhang, Z., Yang, B., & Huang, X. (2018). Cognition, emotion and reward networks associated with sex differences for romantic appraisals. *Scientific Reports, 8*(1), 2835.

Yuan, K., Qin, W., Liu, J., Guo, Q., Dong, M., Sun, J., & Wang, Y. (2010). Altered small-world brain functional networks and duration of heroin use in male abstinent heroin-dependent individuals. *Neuroscience Letters, 477*(1), 37–42.

Zeki, S., & Romaya, J. P. (2010). The brain reaction to viewing faces of opposite-and same-sex romantic partners. *PLoS One, 5*(12), e15802.

Zhang, X., Chen, X., Yu, Y., Sun, D., Ma, N., He, S., Hu, X., & Zhang, D. (2009). Masked smoking-related images modulate brain activity in smokers. *Human Brain Mapping, 30*(3), 896–907.

Zhang, X., Salmeron, B. J., Ross, T. J., Gu, H., Geng, X., Yang, Y., & Stein, E. A. (2011). Anatomical differences and network characteristics underlying smoking cue reactivity. *Neuroimage, 54*(1), 131–141.

Zhang, J., Wang, J., Wu, Q., Kuang, W., Huang, X., Yong, H., & Gong, Q. (2011). Disrupted brain connectivity networks in drug-naive, first-episode major depressive disorder. *Biological Psychiatry, 70*(4), 334–342.

Zhang, Y., Ndasauka, Y., Hou, J., Chen, J., Yang, L. Z., Wang, Y., & Zhou, Y. (2016). Cue-induced behavioral and neural changes among excessive internet gamers and possible application of cue exposure therapy to internet gaming disorder. *Frontiers in Psychology, 7*(844).

Zilverstand, A., Huang, A. S., Alia-Klein, N., & Goldstein, R. Z. (2018). Neuroimaging impaired response inhibition and salience attribution in human drug addiction: A systematic review. *Neuron, 98*(5), 886–903.

Zou, Z., Song, H., Zhang, Y., & Zhang, X. (2016). Romantic love vs. drug addiction may inspire a new treatment for addiction. *Front Psychol, 7*(687).