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Neural evidence for long-term marriage shaping the functional brain network organization between couples

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ABSTRACT

Long-term married couples have been reported to share personality and behavioural similarities, but whether long-term marriage would shape the brain is hitherto unknown. In this study, 35 pairs of long-term married couples, who have married and living together at least 30 years, were recruited, and resting state functional magnetic resonance imaging was used to examine the neural correlates of long-term marriage between couples. Seven intrinsic connectivity networks were extracted using spatially constrained group independent component analysis, and the spatial similarity of each network as well as functional connectome similarity between couples were investigated respectively. The significant spatial similarities in the salience and frontoparietal networks as well as marginally significant connectome similarity were observed in long-term married couples. In addition, the marital duration showed a significantly positive correlation with the spatial similarity in the frontoparietal network and connectome similarity. The results provide objective evidence that long-term marriage would shape brain network organization, and the combination of initial personality traits and long-term common experience of the couples may be potential factors that account for similar brain network organizations between couples.

1. Introduction

It has long been believed that married couples share many similarities in personality traits (Hoffeditz, 1934), social attitudes (Kalmijn, 2005), and even intelligence (Mascie-Taylor et al., 1987), which may possibly be a result of multiple factors, e.g. similar diets, lifestyles, emotional experiences, and genetics of assortative mating (Humbad et al., 2010). Moreover, a longitudinal study has been carried out on married couples to determine if shared experiences can cause similarity in personality (Caspi et al., 1992). Further studies have attempted to determine how the similarities between married couples may be correlated to psychological health and cognitive functions (Dufouil and Alperovitch, 2000). However, this similarity has only been anecdotally observed or assessed using subjective scoring, e.g., questionnaires or behavioural measures (Dufouil and Alperovitch, 2000; Zajonc et al., 1987), little objective neural evidence was provided. Therefore, a detailed objective investigation of the similarities between long-term married couples is of significant interest.

Marriage is a significant landmark event for every individual due to the identity changes (Soulsby and Bennett, 2015; Stets and Burke, 2005) and potential behavioural changes (Rauer et al., 2014) over the long run. Investigations carried out on newly married couples have found a role shift after marriage, where men act more masculine while women act more feminine—these changes are even greater after the birth of their

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first child (Burke and Cast, 1997). Moreover, a long-term marriage can result in a transformation from person-centred to relationship-centred behaviours (Lewis et al., 2006). Obviously, for the sake of maintaining a good relationship within couples, partners tend to act cooperatively, interdependently and modify their own behaviours. Long-term behavioural changes can possibly lead to some anatomical changes in the brain network as a consequence of neural plasticity (Kolb and Whishaw, 1998).

In line with the behavioural evidence, the connectome derived through neuroimaging also suggests that marriage and love can influence individual's brain network, which provides an objective basis for the examination of psychological and behavioural observations. In studying romantic relationships, Bartels and Zeki (2000) firstly reported that, for individuals who are in a committed relationship, there are differences in brain activity between viewing pictures of a loved partner to that of their friends, by using functional magnetic resonance imaging (fMRI). Many researchers have used similar approaches to investigate the neural basis of romantic love or marriage-experience on the human brain (Acevedo et al., 2012; Langeslag et al., 2014; Ortigue et al., 2007; Petrican et al., 2015). Xu et al. (2012) reported that brain activations of intense romantic love in the early stage of a relationship can be used to predict relationship stability and quality after 40 months. A recent study found love-related changes in brain activity may be examined even using resting-state fMRI (Song et al., 2015). That study investigated the regional homogeneity and functional connectivity of the fMRI signal during the resting state, and reported love-related brain alterations among subjects who are "in-love", "ended--love", and "single", which suggested the underlying neural mechanisms of how the brain is modulated by love using resting-state fMRI. However, it is still unclear how marriage, especially in a long-term marriage relationship, modulates the functional network of the brain.

It is therefore intriguing to employ neuroimaging as a tool to investigate if brain connectivity between long-term married couples has greater similarity and, if so, in what manner. Functional connectivity, derived from independent component analysis (ICA) or seed-based correlation approaches, has been widely used to explore the intrinsic functional architecture of the brain during the resting state (Power et al., 2014; Smith et al., 2013). In the present study, resting-state functional connectivity via fMRI was used to examine elderly healthy married couples to elucidate possible intra-couple connectomic similarity. Such knowledge would potentially expand our understanding with regards to the concordance of the aging brain within couples; thus providing neuroimaging evidence for understanding marriage, family caregiving and early interventions for cognitive decline in later life.

2. Materials and methods

2.1. Participants

Thirty-five pairs of long-term married couples (aged 62–84 years, Mean ± SD = 71.96 ± 5.31 years) were recruited from local elderly community centres. Part of the participants were from the Risk Index for Subclinical brain lesions in Hong Kong (RISK) study (Wong et al., 2015). The inclusion criteria were: (1) community-dwelling older adults and had sufficient communication competency for cognitive testing; (2) married and living together for at least 30 years (range from 30 to 55 years, Mean ± SD = 44.2 ± 5.41 years); and (3) normal cognitive capacity (scores of Chinese version of Mini-Mental State Examination (CMMSE) > 26, Mean ± SD = 28.6 ± 1.04). The exclusion criteria were: (1) any history of profound sensory deficits, psychiatric, and/or other neurological disorders; (2) presenting any contraindications to MRI scanning. The study was approved by the Clinical Research Ethics Committee of the Chinese University of Hong Kong (NTEC-CUHK ethics committee). Written informed consent was provided by each participant.

The relationship satisfaction of the long-term couples were also assessed based on a 5-item self-report measure of relationship assessment scale (Hendrick, 1988), including (1) How well does your partner meet your needs? (2) In general, how satisfied are you with your relationship? (3) How good is your relationship compared to most? (4) To what extent has your relationship met your original expectations? (5) How much do you love your partner? Participants answered each item on the seven-point Likert scale from 1 (very unsatisfied) to 7 (very satisfied). A subset of 17 pairs of couples completed the assessment. The averaged satisfaction score of each couple was used to represent the relationship satisfaction of that couple (Mean ± SD = 28.35 ± 4.16).

2.2. Image acquisition

MRI images were acquired using a 3 T Philips MRI scanner (Achieva TX, Philips Medical System, Best, The Netherlands) with an eight-channel SENSE head coil. A 3D T1-weighted anatomical image was firstly obtained with the following parameters: repetition time (TR) = 7.5 ms, echo time (TE) = 3.5 ms, flip angle = 8°, field of view (FOV) = 250 × 250 mm^2, voxel size = 1.04 × 1.04 × 0.55 mm^3. The resting-state fMRI images were acquired with a T2-weighted gradient echo-planar imaging (EPI) sequence: TR = 2050 ms, TE = 25 ms, flip angle = 90°, FOV = 205 × 205 mm^2, matrix = 64 × 64, slices = 47, voxel size = 3.2 × 3.2 × 3.2 mm^3. Participants were instructed to keep their eyes open and focus on a cross of the screen. A total of 210 vol were obtained for 29 pairs of couples, and 170 vol were obtained for 6 pairs of couples. In order to keep the same length of volumes, the last 40 vol for the subjects with 210 vol were discarded.

2.3. Data preprocessing

Functional MR imaging data were preprocessed using Statistical Parametric Mapping software (SPM12, http://www.fil.ion.ucl.ac.uk/spm/). The first ten volumes were discarded to allow for T1 equilibration. Then the functional images were realigned to the first image to correct for head motion between scans and adjusted for slice-timing to correct for timing offsets between different slices. The high-resolution T1 anatomical image was coregistered to the mean of the corrected functional images, and segmented into gray matter, white matter, cerebrospinal fluid, etc. A study-specific template was created using the Diffeomorphic Anatomical Registration Exponentiated Lie algebra (DARTEL) toolbox (Ashburner, 2007). The corrected functional images were spatially normalized to the standard Montreal Neurological Institute (MNI) space by using the nonlinear normalization parameters estimated by the DARTEL toolbox. The spatially normalized functional images were resampled to 3 × 3 × 3 mm^3 and spatially smoothed with a 6 mm full-width half maximum (FWHM) Gaussian kernel. Subjects with head movement larger than 3 mm of translation, 3° of rotation in any direction, or mean framewise displacement value larger than 0.5 mm were deemed "excessive" and would be excluded from the study group. In addition, a further wavelet despiking was also performed to reduce the head movement artefacts (Patel et al., 2014). In this method, a maximum-overlap discrete wavelet decomposition (MODWT) was first applied to the time series of each voxel. Then, the chains of outlying wavelet coefficients at different frequencies were identified as non-stationary artefacts, and only the "signal" coefficients were used to recompose the denoised time series using inverse MODWT. This approach has been demonstrated to provide an effective way to remove the movement-related low and high frequency artefacts from resting-state fMRI (Geerligs et al., 2017; Patel et al., 2014).

2.4. ICA analysis

The preprocessed functional MRI images were decomposed into a set of independent components using the group spatial independent component analysis (ICA) of fMRI toolbox (GIFT, http://mialab.mrn.org/software/gift/) (Calhoun et al., 2001). In this study, a semi-blind spatially constrained ICA approach was used to extract the ICA components (Lin et al., 2010). This approach could estimate the subject-specific ICA components based on the prior information about the networks of interest and avoid the bias of choosing the number of components for ICA decomposition

(Goulden et al., 2014). With the seven stable cortical networks derived from 1000 subjects as prior spatial information (Yeo et al., 2011), seven subject-specific ICA components and their time courses were obtained independently for each subject. The obtained ICA maps and time courses were then transformed to z-score for further similarity analysis.

To evaluate the statistically spatial map of each component, a voxel-wise one-sample *t*-test was firstly performed to each ICA component across all participants. The significant statistical threshold was set at $p < 0.01$ with family wise error (FWE) correction, and the statistically spatial map of each component was obtained. Then, the spatial similarity of each network within each couple was assessed using the Pearson's correlation. For each network, the z-score values within the mask of the identified network were vectorized and then the Pearson correlation coefficient between the husband and the wife was estimated as the spatial similarity of the couple in that network.

A non-parametric permutation-based method was used to compare the similarity of the functional brain networks of couples to those of randomly permuted pairs (Bilek et al., 2015) (as shown in Fig. 1). The permuted pairs were selected by randomly pairing non-spousal couples of the opposite gender without replacement. The network spatial similarity of non-spousal pairs was estimated and permutation was repeated 5000 times. An empirical distribution of the averaged similarity for the randomly reallocated non-couples was obtained and compared with the averaged similarity across married couples. The 95% points of the empirical distribution were used as critical values in a one-tailed test of whether the similarity differences of the functional brain network between couples and non-couples could occur by chance.

To explore whether the long-term marriage could shape the spatial similarity of functional brain network, the relationship between marital duration and network spatial similarity was also investigated using Spearman correlation for the significantly similar networks. In addition, we also explored the relationship between the relationship satisfaction scores and network spatial similarity.

2.5. Intrinsic functional connectome similarity analysis

The individual time courses of each network were then used to investigate the functional connectivity of intrinsic resting-state networks (i.e. connectome). Before the functional connectome analysis, additional head motion related parameters (i.e. the six realignment parameters) regression was performed to remove the remaining noise related to participant movement (Allen et al., 2014; Geerligs et al., 2014, 2017). Then the functional connectome for each subject was estimated using Pearson correlation between any pairs of time-courses of the seven identified networks. Finally, the functional connectome was transformed to a normal distribution using Fisher's r-to-z transformation. The upper triangular part of the matrix was unfolded, resulting a vector with 21 functional connectivity edges for each subject. The mean connectivity of each participant was regressed out across participants to reduce the residual effects of head motion and vascular health on connectome estimation (Geerligs et al., 2017). Similar as previous studies, the functional connectome similarity of each couple was defined as the Pearson correlation between vectors of edges from the husband and the wife (Finn et al., 2015; Lee et al., 2017; Liu et al., 2019). The similar non-parametric permutation with 5000 repetitions was used to test whether the functional connectome similarity difference between couples and non-couples occur by chance. The relationships between functional connectome similarity and marital duration as well as relationship satisfaction were also explored.

In addition, we also quantified the edgewise contributions of similarity between couples using a similar approach as Finn et al. (2015). Given the two z-score normalized vectors of edges from the husband R_i^M and the wife R_i^F, their corresponding edge-wise product vector $\varphi_i(e)$ is defined as,

$$\varphi_i(e) = R_i^M(e) * R_i^F(e),\ e = 1, 2, \ldots, M$$

where *i* indicates the *i*-th pair of couples, *e* indexes edge and M is the total number of edges in the vector (M = 21 in this study). The mean of $\varphi_i(e)$ across all pairs of couples was then computed (∅) and thought as the quantization of the edgewise contributions of connectome similarity (Finn et al., 2015; Wu et al., 2019). Large positive entries in ∅ indicate the edges contribute most to the connectome similarity.

3. Results

3.1. Network spatial similarity

Using spatially constrained group ICA, seven functional networks of interests, i.e., visual network (VN), somatomotor network (SMN), dorsal

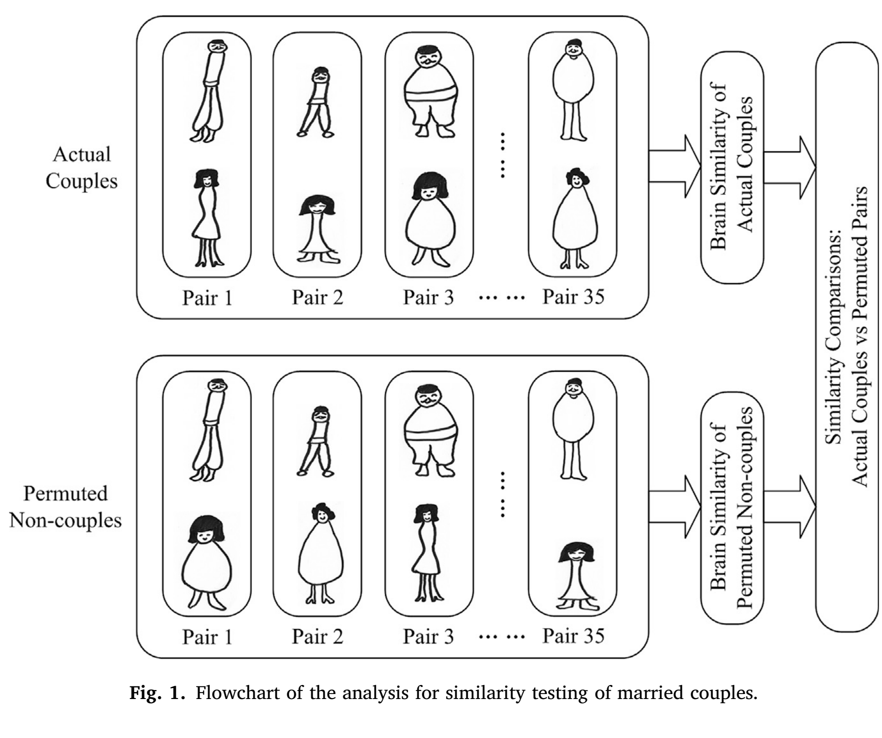

Fig. 1. Flowchart of the analysis for similarity testing of married couples.

attention network (DAN), salience network (SN), limbic network (LN), frontoparietal network (FPN) and default mode network (DMN), were identified (as shown in Fig. 2). For each network, the spatial similarity of actual couples were estimated. The permutation test indicate only the salience network ($p = 0.004$) and frontoparietal network ($p = 0.037$) showed significant similarity compared to permuted noncouple pairs.

The Spearman correlation between married years and the spatial similarity in the identified networks showed that it is only the spatial similarity of the frontoparietal network ($r = 0.381, p = 0.024$) but not the salience network was significantly positively correlated with the married years (Fig. 3(a)). We also explored whether the marriage relationship satisfaction scores would influence the network spatial similarity of couples in a subset of 17 pairs of couples. However, no significant correlation between the relationship satisfaction scores and spatial similarity network was found in couples.

3.2. Functional connectome similarity

The functional connectome similarity analysis showed that the connectome similarity of couples is marginally significant compared to randomly reallocated pairs ($p = 0.084$). We also examined the relationship between connectome similarity and marital years as well as relationship satisfaction. The result showed a significantly positive correlation between connectome similarity and marital years ($r = 0.382$, $p = 0.024$) (Fig. 3(b)). Consistent with the network spatial similarity analysis, no significant correlation between relationship satisfaction scores and connectome similarity was found.

We also quantified the edgewise contributions to connectome similarity across couples to explore which inter-network connections contribute most to connectome similarity in couples. The quantified edgewise contributions of connectome similarity are shown in Fig. 4. Consistent with the network spatial similarity results, the edges connected with the salience network and the frontoparietal network, i.e., SN-SMN, FPN-LN and FPN-DAN, provided the most contributions to connectome similarity.

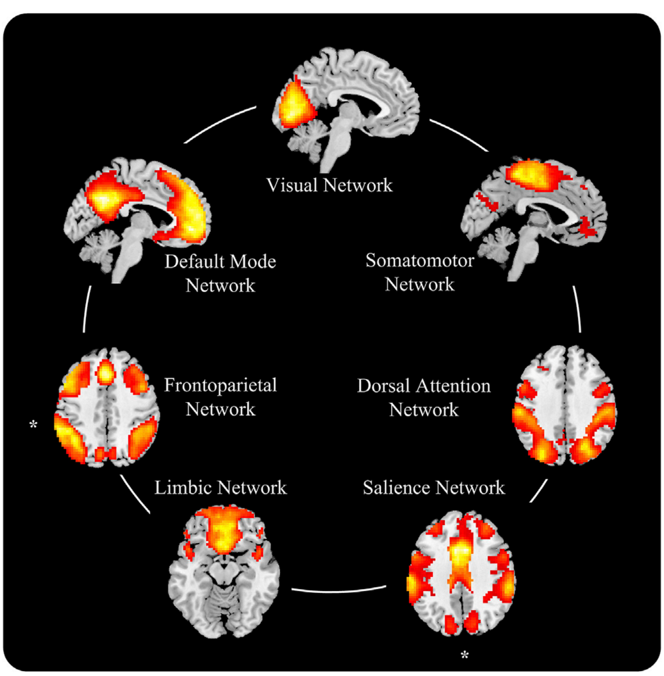

Fig. 2. Seven networks of interest that were identified by using spatially constrained group independent component analysis. The permutation test showed significant spatial similarity in the salience network and the frontoparietal network for long-term married couples compared to non-couples.

4. Discussion

In this study, the spatial similarity of functional brain network as well as functional connectome similarity in long-term married couples were explored. The spatial similarity in the salience network and frontoparietal network showed a significant similarity in long-term married couples. The spatial similarity of frontoparietal network also showed a significantly positive correlation with the duration of marriage. In addition, further connectome similarity analysis also confirmed the results of spatial similarity and revealed a marginally significant similarity in couples and positive correlation with the duration of marriage. The significant similarity revealed in long-term married couples may be a result of a combination of initial personality traits and/or common life experiences. It is reasonable that a long period of common life experience in married couples may gradually shape individual's functional brain network organization.

The salience network, anchored in the insular and anterior cingulate cortex, is crucial in behavioural relevant stimuli detection and neural resources coordination, and considered to be associated with social, self-oriented, affective, attention and cognitive control processing (Uddin, 2015). Previous resting-state fMRI studies have demonstrated that the functional connectivity in the salience network could reflect human personality traits (Markett et al., 2013, 2016). Toller et al. (Toiler et al., 2018) found that the functional connectivity in the salience network could predict the socioemotional sensitivity in elderly. The core regions of the salience network (such as insular and anterior cingulate) were also thought to reflect self-referential processing (Enzi et al., 2009; Northoff et al., 2006), and related with the closeness with the partner measured as inclusion other in the self (Acevedo et al., 2012). Recent structural connectivity study also pointed out that the fiber tract integrity of the salience network was related with self-directedness character trait (Prillwitz et al., 2018). Previous studies suggested that similarity and convergence of initial personality and interpersonal behaviours, attachment styles within couples may predict a higher probability of getting married (Gonzaga et al., 2007; Senchak and Leonard, 1992). It is possible that the similarity in the salience network implied the similar personality traits in couples. However, no significant correlation between marital duration and salience network similarity was found in this study. It is likely that the similarity of the salience network might only respond to the initial personality traits similarity but not long-term common life experience at this stage.

The frontoparietal network also shows a significant similarity in couples, and the similarity value is positively correlated with marital duration. The frontoparietal network was reported to be involved in motor planning and cognitive control (Ptak et al., 2017). The frontoparietal network similarity in couples may be shaped by their converging routine and reciprocal behaviours in marriage. Byrge et al. (2014) recently pointed out the importance of understanding the interplay between behaviour and brain networks. A similar behaviour in everyday life potentially modulates the statistics of inputs to the brain, and then modulating the brain networks. Because of the large overlap in leisure activities, daily routine, and life habits, long-term married couples potentially have similar bodily motion habits, e.g., walking speed, due to spontaneously "mirroring" or matching with each other. As shown in a recent study, closeness partners showed higher synchronized motion (e.g., riding a bicycle with similar rhythm) (Sharon-David et al., 2018). Therefore, the similar motor habits in long-term marriage may gradually shape and modulate the correlations among the emulated action systems, which induce higher similarity in the frontoparietal network.

Moreover, the frontoparietal network is considered to be essential for cognitive control that coordinates other networks together towards a target goal and rule-based problem solving (Menon, 2011; Spreng et al., 2010; Waskom et al., 2014). Similarities found in the frontoparietal network may reflect that couples tend to adopt similar or cooperative approaches and actions in many daily life processes after long-term marital life. Supporting evidence was found that older couples, as

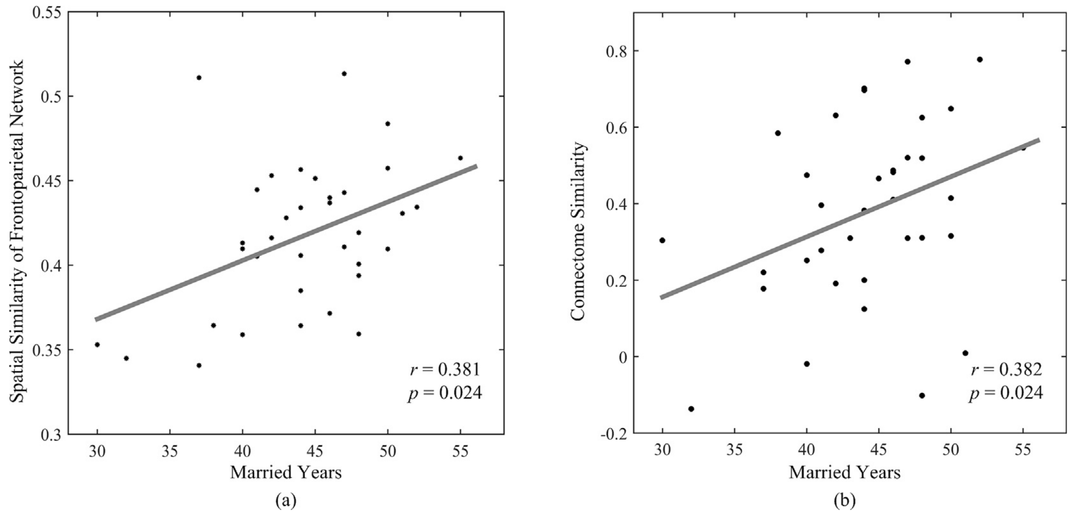

Fig. 3. The correlation between married years and spatial similarity in the frontoparietal network(a) and connectome similarity (b).

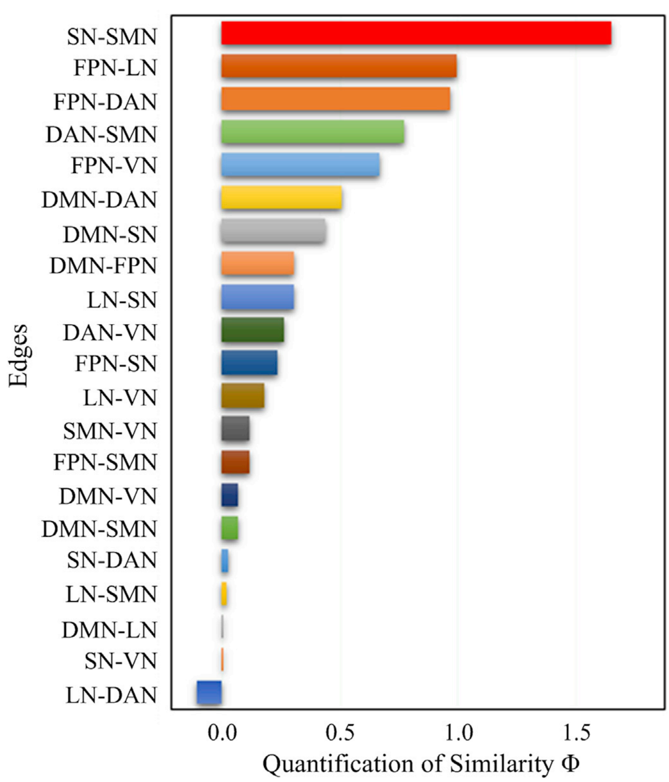

Fig. 4. Quantification of edgewise contributions to connectome similarity between couples.

compared to younger couples, are more likely to participate in discussion and adopt collaborative strategies when conducting cognitive tasks, which leads to better dyadic performance when individual-based cognition declines (Gould et al., 1994). Recent neuroimaging studies have also reported the synchronized patterns of prefrontal cortices during cooperative tasks (Cheng et al., 2015; Funane et al., 2011). Therefore, the higher similarity of the frontoparietal network between long-term married couples found in our current study may indicate that everyday cooperative actions between couples potentially shape the organization and enhances the coherence of their frontoparietal network.

Our exploratory investigation between relationship satisfaction and brain network similarity showed that the relationship satisfaction had no significant effect on brain network similarity. The result is consistent with personality similarity in long-term marriage. No significant correlation between similarity in Big Five personality factors and marital satisfaction was also reported in long-term marriages (Shiota and Levenson, 2007). Abe and Oshio (2018) investigated the moderate effect of marital duration for the personality similarity effects on marital satisfaction, and also found the personality similarity had no effect on marital satisfaction among those with longer marital duration (>28 years). The average duration of marriage in our sample is 44.2 years, which to some degree suggests a stable and relatively successful marital relationship. At this stage, the long-term married couples always show more affectionateness and less conflicts with each other overall, and the similarity shows less effect on relationship satisfaction (Shiota and Levenson, 2007).

There are also some limitations in the current study. First, no personality trait and behaviour performance were examined in the couples in this study. It is unclear whether the brain similarity found here is actually driven by the personality/behaviour similarity. It is needed to further explore the relationship between personality/behaviour similarity and brain network similarity in further study. Second, our cross-sectional study only focused on the elderly cohort with long-term marriage, a longitudinal study or investigating couples with different marital interval, i.e., new-married, middle-term married and long-term married, would further answer the question whether the brain similarities, found here, exist before marriage and serve as a protective factor for their relationship, or it is actually driven by the common life experience. In addition, the potentially overlapping network characteristic could not be ruled out in the current study, investigating the brain similarity using a well-designed task-fMRI may provide more specific information.

In conclusion, the network similarity was found in long-term married couples. The similarity in the salience network may reflect the initial similarity of personality traits in couples, and the similarity in the frontoparietal network may reflect the influence of long-term common life experiences in couples. The dyadic similarity found in the salience and frontoparietal networks provides first neuroimaging evidence for the evolutionary value of similarity in marriage, and may help us better understand the influence of marriage across life span.

Conflicts of interest

There is no conflict of interest for all authors.

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