Received: 31 January 2023 | Revised: 25 June 2023 | Accepted: 27 July 2023

DOI: 10.1111/psyp.14463

ORIGINAL ARTICLE

PSYCHOPHYSIOLOGY SPR WILEY

Psychological resilience-related functional connectomes predict creative personality

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Funding information
Chongqing Social Science Planning Project, Grant/Award Number: 2022PY14; National Natural Science Foundation of China, Grant/Award Number: 32071070 and 32100850; Natural Science Foundation of Chongqing Municipality, Grant/Award Number: cstc2019jcyj-msxmX0520 and cstc2021jcyj-bshX0072; Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University; Chongqing Humanities and Social Sciences, Grant/Award Number: 2019PY51 and 2018PY80; 111 Program, Grant/Award Number: B21036; Fundamental Research Funds for the Central Universities, Grant/Award Number: SWU119007; Chang Jiang Scholars Program; National Outstanding Young People Plan

Abstract

Both psychological resilience and creativity are complex concepts that have positive effects on individual adaptation. Previous studies have shown overlaps between the key brain regions or brain functional networks related to psychological resilience and creativity. However, no direct experimental evidence has been provided to support the assumption that psychological resilience and creativity share a common brain basis. Therefore, the present study investigated the relationship between psychological resilience and creativity using neural imaging method with a machine learning approach. At the behavioral level, we found that psychological resilience was positively related to creative personality. Predictive analysis based on static functional connectivity (FC) and dynamic FC demonstrated that FCs related to psychological resilience could effectively predict an individual's creative personality score. Both the static FC and dynamic FC were mainly located in the default mode network. These results prove that psychological resilience and creativity share a common brain functional basis. These findings also provide insights into the possibility of promoting individual positive adaptation from negative events or situations in a creative way.

KEYWORDS
creative personality, fMRI, functional connectivity, prediction, psychological resilience

1 | INTRODUCTION

Undesirable things always happen in our life and affect our peace of mind. When suffering traumatic events, some people adjust well and return to their normal lives with ease, while others develop stress-related disorders (Bryant et al., 2011). Psychologists have proposed the concept of "psychological resilience" to explain this phenomenon. Although some controversy remains about the connotation of the concepts, "psychological resilience" commonly refers to the positive adaptation and response to stress and adversity (Luthar et al., 2000). It is indeed a complex concept, and previous studies have explored it from the perspective of traits, outcomes, and processes related to recovery (Bonanno et al., 2015). Central to the concept of psychological resilience is the positive adaptation to stress or adversity.

Similar to psychological resilience, creativity also promotes an individual's positive adaptation to the negative effects of stress or adversity. "Creativity" is usually defined as the ability to produce something that is novel and useful (Beaty et al., 2016; Benedek et al., 2020; Runco & Jaeger, 2012; Sternberg & Lubart, 1996). Although most studies about creativity focused on the cognitive mechanism underlying creative thinking, recent studies have indicated that creativity is useful in regulating one's emotional response to negative events or situations (Fink et al., 2017; Perchtold et al., 2018; Wu et al., 2019). Although psychological resilience and creativity seem to be associated in a remote way, the cognitive mechanism and neural basis underlying these concepts indicate that they may have similarities in terms of their ability to adjust the effect of negative events and boost well-being.

From the perspective of cognition, the cognitive processes related to psychological resilience and creativity have overlapped parts. Both of psychological resilience and creativity involve the process about flexibility. In particular, individuals with high psychological resiliency are often flexible and resourceful when adapting to new situations, including negative events (Oshio et al., 2018). They are capable of changing their behaviors flexibly and adjusting their emotional resources to adapt to sudden changes in their lives. On the contrary, individuals with low psychological resiliency are often vulnerable to stressful situations or adversity and act in a perseverative way (Causadias et al., 2012). Their behavioral performance lacks flexibility, and therefore, leads to difficulties in recovering from adversity.

The ability of flexible behavioral change is also critical for creativity. To generate original ideas, individuals must overcome the influence of existing experiences and think in new ways. Individuals with high creative ability always have richer and more flexible semantic networks, which help them search their memories and build connections among apparently unrelated concepts (Kenett et al., 2018; Mednick, 1962). They are more capable of switching among different modes of thinking, such as abstract, analytical, thinking, dreaming, and reverie thinking (Chen et al., 2014; Fink, Grabner, et al., 2009; Sun et al., 2019). The flexible process employed by creative people enables them to think in an original way and gain creative achievements (Zhang et al., 2020).

Based on the abovementioned similarities, the assumption that a positive correlation exists between psychological resilience and creativity comes naturally. On the one hand, several empirical studies support this assumption on the behavioral level. For example, one study demonstrated that psychological resilience, as a kind of positive psychological capital, can predict creative performance effectively (Helson, 1999; Sweetman et al., 2011). Furthermore, both psychological resilience and creativity are related to depression, and psychological resilience is positively related to creativity during the COVID-19 pandemic (Xu et al., 2021). On the other hand, the neural basis underlying psychological resilience and creativity shows a similar pattern. Although studies interested in the capacity for psychological resilience in the face of adversity have grown exponentially (Afek et al., 2021; Connor & Davidson, 2003), investigations into the neural basis underlying this concept are still in their initial stages. Several resting-state functional imaging studies investigated the brain-functional foundation of psychological resilience using healthy adults. For example, Kong et al. (2015) found that the regional brain activities in the insula as well as the dorsal and rostral anterior cingulate cortex, as measured by regional homogeneity, were negatively correlated with individual differences in psychological resilience. Subsequent studies demonstrated a positive correlation between psychological resilience and the functional connectivity (FC) between the insula and the parahippocampus (Shi et al., 2019). A similar positive correlation was observed between psychological resilience and FC between the orbitofrontal gyrus and the inferior frontal gyrus (Shi et al., 2019).

Structural imaging studies also investigated the brain structure basis of psychological resilience. For example, Kahl et al. (2020) used morphological methods and found that psychological resilience was positively correlated to cortical thickness in the middle and inferior temporal cortex, the inferior parietal cortex, the lateral occipital cortex, and the fusiform gyrus. Task fMRI studies showed that compared with high-resilient individuals, individuals with low resilience exhibited greater response in affective regions such as the anterior insula to the aversive stimulates (Waugh et al., 2008). Although brain regions related to psychological resilience seem to be distributed, these results are mainly located in brain networks such as the default mode network (DMN), executive network (EN), and salience network (SN). Neuroimaging studies in patient populations further confirmed the role of these networks in psychological resilience. For example, FC within the DMN subsystem and FC between the DMN subsystem and dorsal anterior cingulate cortex in post-traumatic stress disorder patients with low resilience was found to be lower than that in healthy participants (Miller et al., 2017).

Numerous studies have investigated the neural basis underlying creativity. These studies adopted various kinds of methods and drew a picture about the key brain areas which was implicated in creative tasks (Abraham et al., 2012; Dietrich & Kanso, 2010; Fink, Graif, & Neubauer, 2009; Huang et al., 2015, 2019; Sun et al., 2019). Meta-analysis studies using the quantitative analysis method further revealed that the precuneus, the lateral prefrontal cortex, the posterior parietal cortex, the anterior cingulate cortex, and the temporal cortex were activated in creativity tasks based on task fMRI (Gonen-Yaacovi et al., 2013; Pidgeon et al., 2016; Wu et al., 2015). From the perspective of brain functional networks, the DMN is involved in the generation process of original ideas, the EN is devoted to the top-down cognitive control process to allocate the cognitive resources, and the SN works in modulating the interaction between large scale networks, such as DMN and EN (Abraham, 2014; Beaty et al., 2016; Jung et al., 2013; Mok, 2014).

Based on these findings, there are obvious overlaps between the key brain regions and brain networks related to psychological resilience and creativity, making it possible for psychological resilience and creativity to share some common brain basis. However, to our knowledge, the common basis of psychological resilience and creativity from the perspective of neuroscience remains unexplored. We can, however, take inspiration from recent studies that linked the ability of negative emotion regulation and creativity through task-based fMRI studies. For instance, Fink et al. (2017) explored real-life creativity in relation to emotion regulation. They asked participants to generate different ways to reappraise the presented anger situations to reduce their emotional reaction and found that cognitive reappraisal and creativity tasks had similar patterns of alpha oscillations. Brain regions, such as inferior prefrontal gyrus, superior prefrontal gyrus, middle prefrontal gyrus, and the anterior cingulate cortex were activated both in affective and classic creativity tasks (Perchtold et al., 2018). Another study found that adopting creativity as a new strategy in regulating negative emotions increase the emotion regulation effect of reappraisal (Wu et al., 2019). Compared with ordinary reappraisal, creative reappraisal is associated with the greater engagement of the inferior prefrontal gyrus, middle prefrontal gyrus, hippocampus, and regions in the temporal and parietal lobes (Wu et al., 2019). Although these studies provided indirect evidence, they nevertheless support the hypothesis that psychological resilience and creativity share some common brain basis, especially in the cognitive process of negative emotion regulation.

Owing to the complexity of these two concepts, researchers studied psychological resilience and creativity from different perspectives, such as personality characteristics. The core components of psychological resilience contain lower levels of negative emotions and high levels of self-control and achievement motivation, positive emotions, and emotional stability (Oshio et al., 2018). The creative person profile includes several elements, such as ambition, associative orientation, motivation, emotional instability, flexibility, agreeableness, and need for originality (Martinsen, 2011). Meta-analysis studies indicated that both psychological resilience and creativity personality were positively related to openness (Dollinger et al., 2004; Oshio et al., 2018). These findings indicate that individuals with high levels of psychological resilience and creativity may share common personality elements.

Based on the abovementioned findings, the present study focuses on the problem of whether psychological resilience and creativity have some common brain basis. To address this problem, we combined behavioral measure and brain imaging methods and used a machine learning approach to test the hypothesis of this study: psychological resilience and creativity shared some common brain functional basis. Specifically, the common brain basis of psychological resilience and creativity may locate in brain networks that have been reported to be related to these two concepts such as DMN, EN, and SN. Based on machine learning framework, we used the behavioral data of psychological resilience and creativity and brain FC data and constructed regression models to predict individuals' creativity scores. Considering that previous studies have shown that dynamic FCs are biomarkers of both psychological resilience and creativity, the present study adopted both static and dynamic FCs as brain functional indexes (Miyagi et al., 2020; Sun et al., 2019).

2 | METHOD

2.1 | Participants

Participants in this study were a part of the Gene-Brain-Behavior (GBB) Project and Longitudinal Imaging Multimodal (SLIM) project at Southwest University. These projects are ongoing and longitudinal cohorts aiming at understanding the genetic and neural basis of personality, creativity, and brain structural and functional features. Participants who completed the behavioral questionnaire (Creative Personality Scale and 25-item Resilience Scale™, CPS and RS) and resting state fMRI scanning were included in this study. The behavioral measures about creativity personality and psychological resilience and the data collection parameters for the resting state data are the consistent in these two projects. This study included 343 participants (133 in the GBB project and 210 in the SLIM project). The participants were recruited from Southwest University, China. They were all healthy and right-handed, had no previous experience of alcohol or substance abuse, and had no history of neurological or psychiatric illness. They also met the safety criteria of fMRI research. The present study was approved by the Research Ethics Committee of Southwest University Brain Imaging Center. Informed consent was obtained from all of the participants before they participated in the study in accordance with the Declaration of Helsinki. There were 12 participants who were excluded because of excessive head motions during the resting state fMRI scanning (>3 mm maximum translation, 3° rotations, or 0.2 mm mean frame-wise displacement than). Finally, 331 participants were included in this study. The participants' ages ranged from 18 to 27 years (mean age = 21.83, SD = 1.98, 129 males).

2.2 | Behavioral measures

All the participants completed two behavioral questionnaires: the CPS and the RS (Gough, 1979; Wagnild & Young, 1993). Because all of the participants in our study were native Chinese speakers, the Chinese version of these questionnaires were given. CPS is a self-reported personality questionnaire that measures creativity personality, including 30 adjectives (18 positive items and 12 negative items; Gough, 1979). This questionnaire asked participants to choose the adjectives that best described themselves. On the basis of Gough's scoring protocol, one point is given when one of the positive items (e.g., capable, confident, and humorous) is selected, and one point is subtracted when one of the 12 negative items (e.g., cautious, conservative, and honest) is selected. CPS was used to measure creative personality for serval reasons. The first reason is we are looking for a personality measure about creativity. RS which we used to measure resilience is a personality questionnaire (Oshio et al., 2018). In order to match RS, we need an instrument about creative personality. The second reason is CPS can be implemented conveniently. We can get the scores of the participants easily. This is very important for studies with a large sample. Another reason is CPS is still widely used recently (Carswell et al., 2019; Hunter et al., 2016; Luescher et al., 2019; Mccabe et al., 2020; Qian et al., 2019).

RS is also a self-reported questionnaire that measures psychological resilience from the perspective of personality (Wagnild & Young, 1993). This questionnaire includes 25 items, such as "I can get through different times because of experience" and "It's okay if there are people who don't like me." The participants were required to indicate their agreement about each item on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). The reliability coefficient for the CPS is 0.80, and the reliability coefficient for the RS is 0.91. Because the original work about RS used older adults as participants, it is unsuitable to use this work as a norm sample (Wagnild & Young, 1993). Instead, we used the study conducted by Madewell and Ponce-Garcia (2016) as a reference. They used college students as participants which is similar to the present study. The mean score of RS they reported was 138.85 (SD = 20.12). One-sample t-test showed that the mean score of our study is statistically different from the reference we used. The difference of the mean scores may be due to the cultural difference.

2.3 | fMRI data acquisition

All neuroimaging data were obtained using a 3T Trio MRI scanner (Siemens Medical, Erlangen, Germany). The participants were instructed to lie down and close their eyes. High-resolution 3D T1-weighted structural images were obtained using 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) = $256 \times 256\ mm^2$, slices = 176; thickness = 1.0 mm, and voxel size = $1 \times 1 \times 1\ mm^3$. Resting-state BOLD images were obtained using an Echo Planar Imaging sequence: RT = 2000 ms, TE = 30 ms, slices = 32, FA = 90°, thickness = 3 mm, resolution matrix = 64×64, FOV = $220 \times 220\ mm^2$, slice gap = 1 mm, and voxel size = $3.4 \times 3.4 \times 4\ mm^3$. A total of 242 volumes were collected.

2.4 | Imaging data preprocessing

The preprocessing of fMRI data was performed using the Data Processing Assistant for Resting-State fMRI (DARSF, http://resting-fmri.sourceforge.net/; Yan & Zang, 2010), which was based on SPM8 (www.fil.ion.ucl.ac.uk/spm). The participants whose head motion was greater than 3 mm maximum translation, 3.0° rotation, or 0.2 mm mean frame-wise displacement were excluded. The first 10 functional volumes were discarded. The remaining volumes were preprocessed in the following steps: slice-timing correction, head motion correction, normalization to the MNI space (resampling voxel size = $3 \times 3 \times 3\,mm^3$), spatial smoothing (6 mm Full Width at Half Maximum Gaussian kernel), and detrend. The Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra algorithm (DARTEL) was adopted to compute the transformations from the native space to MNI space. Nuisance covariates such as the white matter signals, cerebrospinal fluid, global mean signals, and Friston 24-parameter head motion were regressed out (Friston et al., 1996). Band-pass filter was subsequently performed (0.01–0.1 Hz). Considering the potential interference effect of head motion, scrubbing procedure was conducted to further reduce this potential effect. Bad time points were deleted (framewise displacement, FD > 0.5 mm), and the ratio of the remaining time points across all participants was 97%.

2.5 | Functional network construction

We adopted the Power 264 atlas as the brain network nodes, which included 264 regions (Power et al., 2011). The data of brain functional signals were extracted from every voxel within each brain region (regions of interest, ROIs) and averaged to obtain the time series. Pearson correlation was employed to construct static functional networks. The correlations were performed between the time series of each pair of the ROIs. This step generated an FC matrix (264×264) with 34,716 edges for each participant. Each matrix contained 34,716 FCs. Fisher's z transformation was performed on the matrices.

To explore the temporal fluctuations in the FC time-series of underlying psychological resilience and creativity, this study also constructed dynamic functional networks. The dynamic FC fluctuations were evaluated by their variability, which we defined as the standard deviation of the FCs across the sliding windows. Specifically, the time series of the ROIs was divided into sliding windows (window size = 25 TRs) with a step of 2 TR. A window size of 25 TRs (50s) was chosen because previous research showed that window sizes between 30 and 60 s could capture the dynamic variations in FC (Allen et al., 2014; Hutchison et al., 2013). Then, Pearson correlations were performed between the time series of each pair of ROIs in each window, resulting in FC matrices (264×264) of sliding windows. The dynamic FC matrices were obtained by calculating the standard deviation of the FCs across the sliding windows. Previous studies have shown that this method is effective in measuring the dynamic characteristics of FCs (Tian et al., 2018; Zhu et al., 2021).

2.6 | Connectome-based predictive analysis

To investigate the predictive effect of psychological resilience-related FCs on creativity, leave-one-out cross-validation (LOOCV) was conducted using relevance vector regression (RVR; Tipping, 2001). Specifically, LOOCV was performed n times, where n represents the total number of participants. Because we used LOOCV, we ran LOOCV n times using RVR. After n times of LOOCV, we would obtain predicted CPS score for each of the participants. In each time of the LOOCV, one participant in the total sample was left to be a test set, while the rest of the $n-1$ participants were used as a training set. The data of the $n-1$ participants in the training set were used to establish the static FC networks associated with psychological resilience. When the FCs related to psychological resilience were defined, these FCs were used to fit a predictive model. The model was then used to predict the CPS score of the one subject who was left. The partial correlation between psychological resilience score and the whole-brain FC was used in the procedure of feature selection. The partial correlation controlled the age, gender, and mean FD. Mean FD was a head motion measure. It was used to control potential effect of head movement. To retain the significantly correlated FCs and remove the spurious FCs, a threshold of $p < .05$ was used.

In the training set, a predictive model was built that fit the linear regression between psychological resilience-related FCs and CPS scores. Then, the predictive model was applied to a new participant (test set) in the LOOCV procedure to acquire the predicted score of this participant. If psychological resilience-related FCs could predict CPS scores effectively, these FCs would be common FCs. That is to say, psychological resilience and creativity share common brain functional basis. The Pearson correlation coefficient between the actual measured CPS scores and predicted CPS scores and statistical significance was used to estimate the prediction performance of the predictive model. Permutation tests (1000 times) were conducted to generate a null distribution of correlation coefficients which represents the relationship between the actual measured and predicted CPS scores. In each time of the permutation tests the label of CPS scores were randomly shuffled and the prediction procedure was rerun. The significance level of the permutation test was set at 0.05. The analysis processes of the data are shown in Figure 1.

2.7 | Validation analysis

We also performed validation analysis to examine the robustness of the predictive effect using the 10-fold

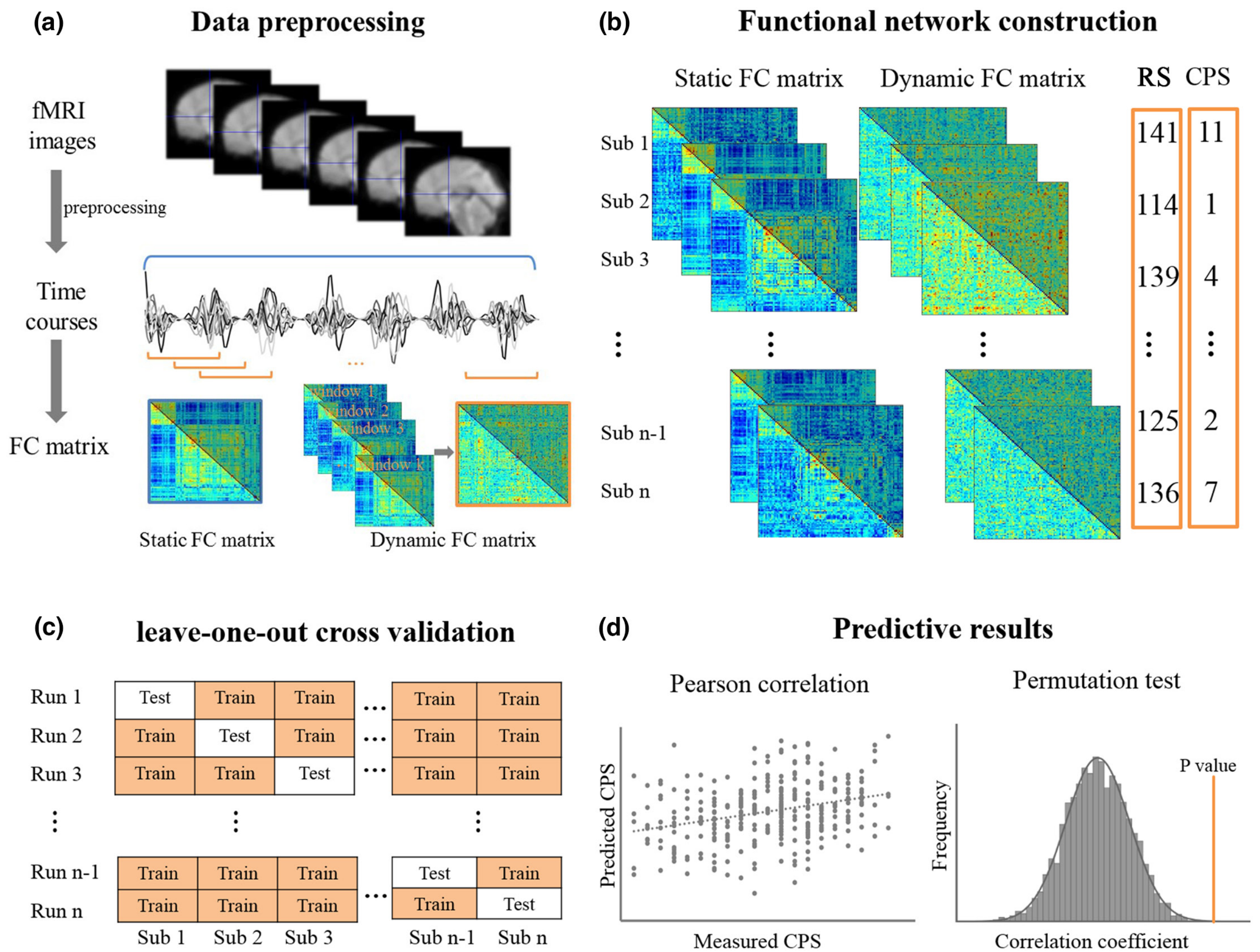

FIGURE 1 Flowchart of analysis processes. (a) The time series from Power 264 atlas were extracted to construct functional connectivity (FC) matrix. (b) 264 × 264 static and dynamic FC matrices were constructed for each participant. (c) Leave-one-out cross-validation were conducted. (d) 1000 times permutation tests were performed.

cross-validation. In this procedure, the total sample was randomly divided into a training set and a test set, which included 90% and 10% of the whole sample, respectively. Due to the difference of test sets and training sets in each time of random division, the 10-fold cross-validation procedure was repeated 100 times (He et al., 2021). The final prediction scores of all participants were obtained by averaging across the 100 times.

3 | RESULTS

3.1 | Behavioral results

The descriptive statistics of demographic data and psychological measures are shown in Table 1. Results from the correlation analysis of behavioral data showed that RS scores were positively correlated to the CPS scores ($r = 0.42$, $p < .001$).

TABLE 1 Descriptive statistics of demographics data and psychological measures.

Items	Total participants
No. of participants	331
Age (years)	21.83 ± 1.98
Males/females	129/202
RS scores	128.12 ± 16.06
CPS scores	3.08 ± 4.56

3.2 | Cross-validation results

In the LOOCV, we found that psychological resilience-related FCs could predict individual CPS scores significantly (see Figure 2). When using psychological resilience-related static FCs (955 FCs), the correlation coefficient

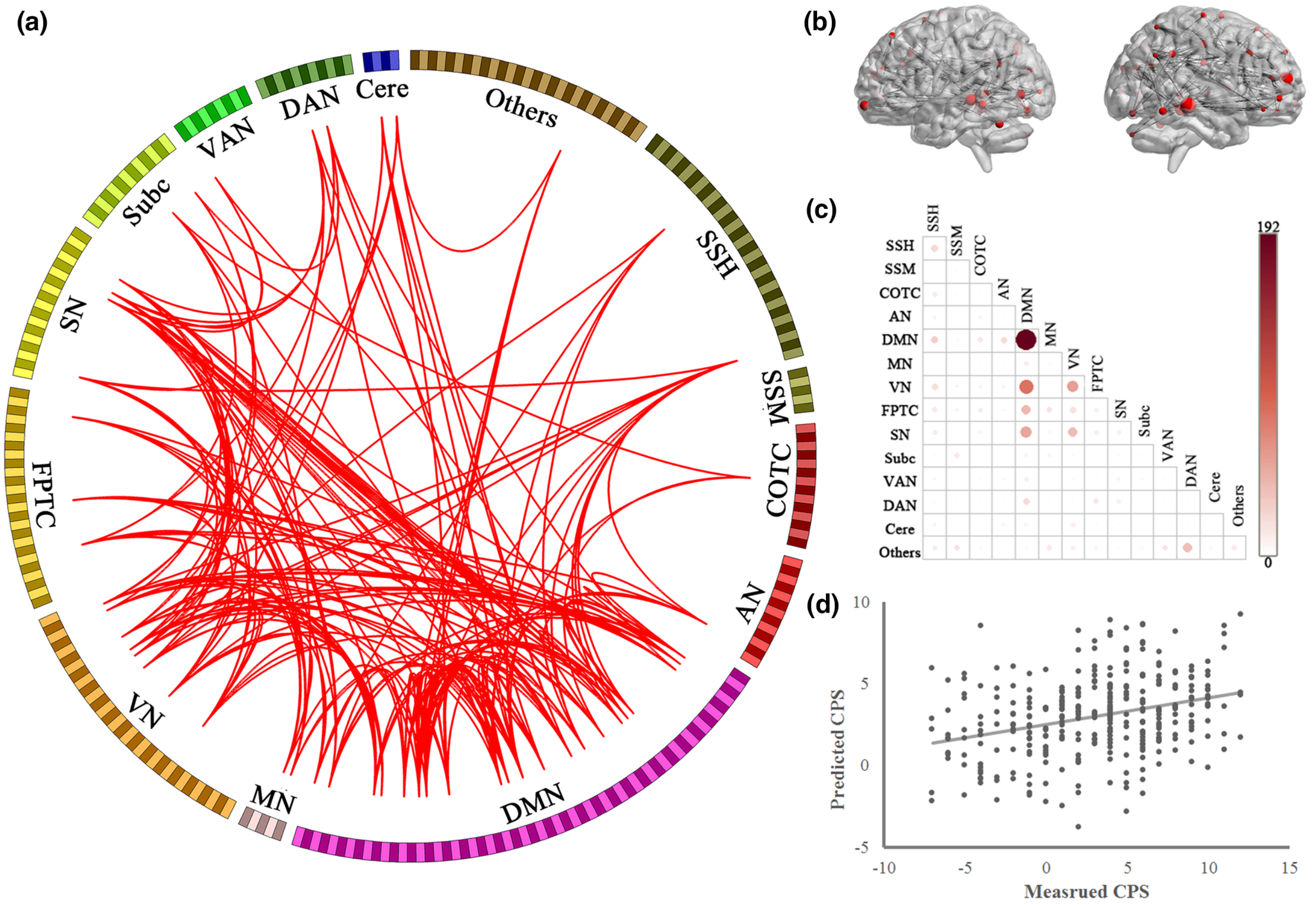

FIGURE 2 Predictive results using static FCs. (a) The circle plot shows static FCs that can predict CPS scores. The top 20% regions with the largest number of connections were present for visual presentation. (b) The brain map shows the static FCs in the predictive model and the node size represents the degree. (c)The matrix map shows the connection number between brain networks. (d) The scatter plot shows the correlation between measured and predicted creative personality scores. AN, auditory network; Cere, cerebellar; COTC, cingulo-opercular task control network; DAN, dorsal attention network; DMN, default mode network; FPTC, fronto-parietal task control network; MN, memory retrieval network; SN, salience network; Subc, subcortical network; SSH, sensory/somatomotor hand network; SSM, sensory/somatomotor mouth network; VAN, ventral attention network; VN, visual network.

between actual measured CPS scores and predicted CPS scores was 0.31 ($p = 7.74 \times 10^{-9}$). The regions of the FCs mainly located in the DMN (e.g., region 105, medial frontal gyrus, degree = 25; region 119, middle temporal gyrus, degree = 35), the SN (e.g., region 216, dorsal anterior cingulate gyrus, degree = 18; region 218, middle frontal gyrus, degree = 31), and the visual network (VN, e.g., region 164, middle occipital gyrus, degree = 21). These results were significant in the permutation tests with a threshold of $p < .05$.

We further explored the predictive effect of dynamic FCs. The results showed that psychological resilience-related dynamic FCs (FCs = 980) could predict individual CPS scores significantly (see Figure 3). The r value between actual and predicted CPS scores was 0.25 ($p = 5.26 \times 10^{-6}$). The FCs were mainly located in nodes in the DMN (e.g., region 91, posterior cingulate gyrus, degree = 17; region 110, medial frontal gyrus, degree = 20), task control network (e.g., region 54, supplementary motor area, degree = 12; region 190, inferior parietal lobule, degree = 23), and sensory/somatomotor hand network (SSH, e.g., region 30, postcentral gyrus, degree = 16). These results were significant in the permutation tests with a threshold of $p < .05$.

3.3 | Results from the validation analysis

To examine the power of our predictive models, we further performed 10-fold cross-validation. The results showed that when using static FCs, psychological resilience-related FCs predicted CPS scores effectively ($r = 0.31$, $p = 5.45 \times 10^{-9}$). Furthermore, when using dynamic FCs, FCs related to psychological resilience also predicted CPS scores effectively ($r = 0.17$, $p = 2.20 \times 10^{-3}$). These results were significant in the permutation tests with a threshold of $p < .05$. The prediction results were found to be

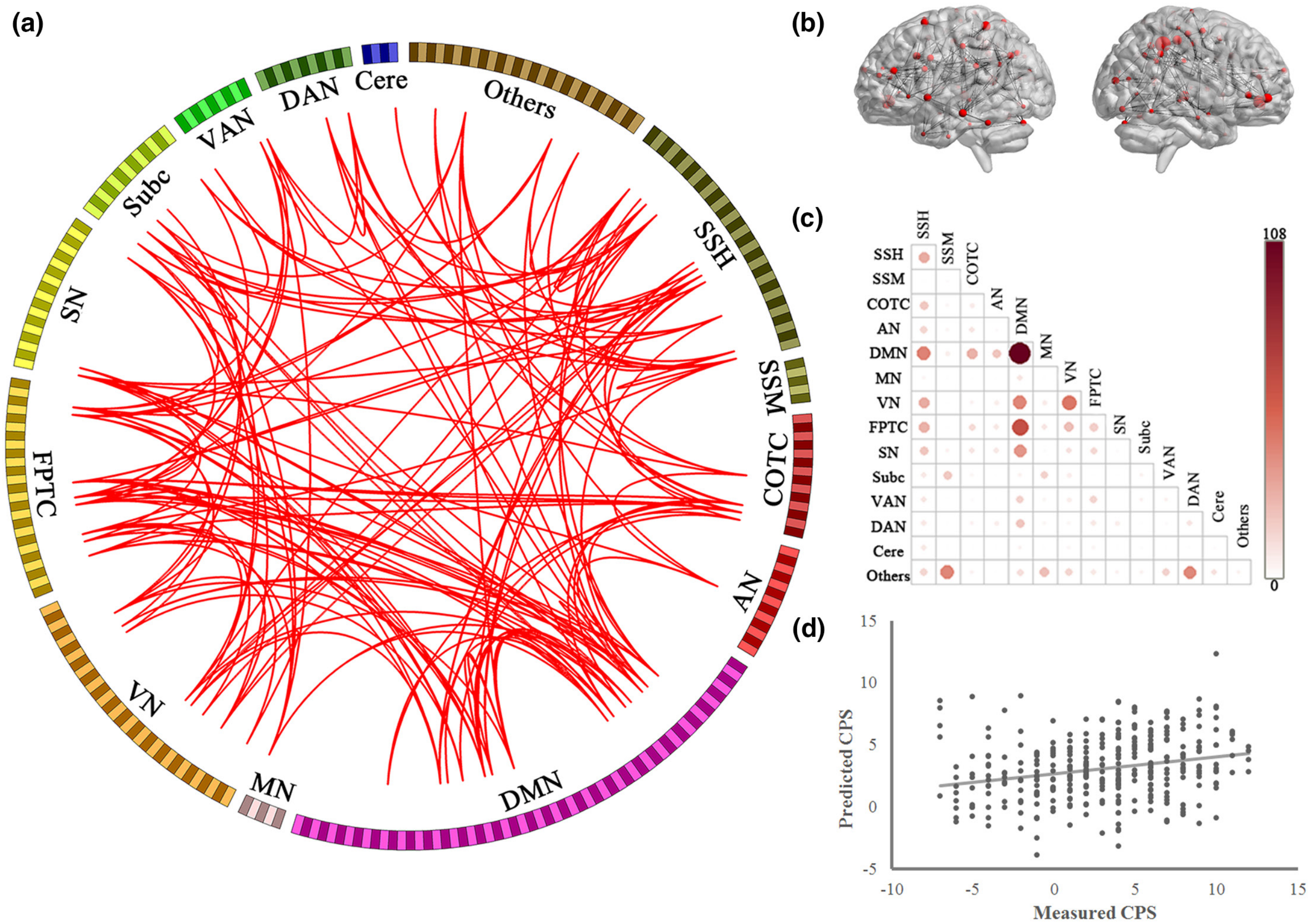

FIGURE 3 Predictive results using dynamic FCs. (a) The circle plot shows dynamic FCs that can predict CPS scores. The top 20% regions with the largest number of connections were present for visual presentation. (b) The brain map shows the dynamic FCs in the predictive model and the node size represents the degree. (c)The matrix map shows the connection number between brain networks. (d) The scatter plot shows the correlation between measured and predicted creative personality scores. AN, auditory network; Cere, cerebellar; COTC, cingulo-opercular task control network; DAN, dorsal attention network; DMN, default mode network; FPTC, fronto-parietal task control network; MN, memory retrieval network; SN, salience network; Subc, subcortical network; SSH, sensory/somatomotor hand network; SSM, sensory/somatomotor mouth network; VAN, ventral attention network; VN, visual network.

consistent with our findings using LOOCV. These findings demonstrate that the prediction performance of psychological resilience-related static and dynamic FCs on creative personality scores has high reproducibility.

4 | DISCUSSION

The present study explored the relationship between psychological resilience and creativity using a neural imaging approach. At the behavioral level, we found that psychological resilience was positively related to creative personality. Connectome-based predictive analysis based on static FCs showed that FCs related to psychological resilience effectively predicted individuals' creative personality scores. The common static FCs are mainly located in the DMN, SN, and VN. In addition, connectome-based predictive analysis based on dynamic FCs showed that dynamic FCs related to psychological resilience also successfully predicted individuals' creative personality scores. The common dynamic FCs were mainly located in DMN, task control network, and sensory/somatomotor hand network. These results indicate that psychological resilience is positively related to creativity, as they share common brain functional basis.

The behavioral results demonstrated that psychological resilience was positively related to creativity. This result is supported by previous findings. On the one hand, the behavioral result in this study supports the opinion that psychological resilience and creative personality may share some common personality basis (Dollinger et al., 2004; Oshio et al., 2018). On the other hand, the behavioral result in this study provides evidence for the possibility that psychological resilience and creativity have similar effects on the regulation of negative events or situations. Resilient individuals experience more positive affect (Shi et al., 2019). They have the ability to use positive emotions to resist the negative events and find positive meaning in negative and stressful circumstances (Tugade & Fredrickson, 2004). Creativity is also effective in reducing negative emotional experience in the process of emotional regulation (Wu et al., 2017). The role of creativity in emotional regulation is further supported by the finding that trait creativity is positively correlated to emotional intelligence which refers to the ability to perceive, regulate, and utilize emotion (He et al., 2018). Therefore, our findings support direct evidence supporting the relationship between psychological resilience and creativity from personality trait.

Apart from the behavioral results, this study also found that FCs related to psychological resilience could effectively predict an individual's creative personality score. This finding implies that psychological resilience and creative personality share some common brain FC basis, with the most prominent result being located in the DMN. In particular, both the results from static and dynamic FCs showed that psychological resilience and creative personality share common FCs within the DMN. These results are consistent with previous studies. Task-based fMRI results showed that during the switching phase of auditory oddball task, FC within the DMN was correlated with psychological resilience scores (Miyagi et al., 2020). Resting state studies showed that FCs within the DMN were correlated with resilience in healthy participants (Hemington et al., 2018). Furthermore, individuals with posttraumatic stress disorder who have low resilience show disrupted resting state FCs in the DMN subsystem (Miller et al., 2017). The FCs within the DMN also play an important role in creativity. Meta-analysis showed that key regions of DMN, such as the precuneus and the temporal cortex, were activated in tasks related to creativity (Gonen-Yaacovi et al., 2013; Pidgeon et al., 2016; Wu et al., 2015). Resting state studies showed that creativity was related to the regional function and structure of key regions within DMN, as well as the FC between key regions within the DMN (Chen et al., 2015; Wei et al., 2014). Additionally, recent studies indicated that the dynamic characteristics of DMN are related to both psychological resilience and creativity (Miyagi et al., 2020; Sun et al., 2019). Psychological resilience was related to the dynamic FCs within the DMN during cognitive task (Miyagi et al., 2020), while creativity was positively correlated to the dynamic FCs within the DMN across different time windows (Sun et al., 2019). Our findings further linked psychological resilience and creativity using machine learning approach, thereby revealing that both the static and dynamic FCs within DMN may be the common neural basis of psychological resilience and creativity. The function of the DMN is associated with spontaneous thought such as mind-wandering, autobiographical retrieval, and episodic future thinking (Fox et al., 2015; Raichle et al., 2001). The DMN may support the common cognitive basis underlying psychological resilience and creativity. This is supported by previous findings that both psychological resilience and creativity are closely related to spontaneous thought which is supported by DMN (Beaty et al., 2016; Kong et al., 2015). Therefore, our findings show that psychological resilience and creativity may share some basic cognitive functions supported by DMN such as spontaneous and self-generated thought.

As shown in Figure 2, our findings showed that the common brain functional foundation of psychological resilience and creativity are also located in static FCs between DMN and several other brain networks, such as the frontoparietal task control network and SN. These between-networks results of static analysis are consistent with those of dynamic analysis. The frontoparietal task control network is a subnetwork of EN. Individual differences in psychological resilience have been linked to the functional interaction strength between these brain networks, while psychological resilience is positively related to the FCs between some key regions of the DMN and EN, such as the orbitofrontal gyrus and the inferior frontal gyrus (Shi et al., 2019). Previous studies have also shown that the FCs between the DMN and EN are critical to creativity. For instance, one research adopted resting state method and found that FCs between key region of EN, the inferior frontal cortex, and that the DMN was correlated with individuals' creative scores (Beaty et al., 2014). The EN is engaged in cognitive processes that require externally-directed attention, such as working memory, response inhibition and task-set switching (Aron, 2007; Curtis & D'Esposito, 2003; Dreher & Berman, 2002). In the process of creativity, this network supports the top-down control of attention and cognition to help individuals with high creativity to think in an original way. Such top-down process is also essential for psychological resilience (Shi et al., 2019). The EN involves the flexible use of emotional resources and flexible control in processing affective information. Because EN is related to basic cognitive functions such as working memory and inhibitory control, the results in the current study thus reflect that both psychological resilience and creativity needs basic cognitive functions to support the high-level cognitive processes.

Aside from the FCs between the DMN and EN, the results regarding FCs between DMN and SN are also supported by previous findings. For example, the dorsal anterior cingulate gyrus, the key region of SN, has been linked to the individual difference of psychological resilience (Kong et al., 2015). This region is also engaged in the cognitive process related to creativity (Abraham et al., 2012; Howard-Jones et al., 2005; Sun et al., 2016). Considering the function of SN in response to negative feedback and the modulation function in the interplay of brain networks (Claus & Shane, 2018; Jung et al., 2013), our findings demonstrated that both psychological resilience and creativity must deal with the complex information from different brain networks. The SN is responsible for switching between the DMN and the central EN (Goulden et al., 2014). This function of SN makes it possible to deal with the complex information delivered by brain networks such as DMN and EN, which not only enable us to think in a flexible and original way but also help us to deal with affective information.

In addition, this study also discovered that the common FCs related to psychological resilience and creativity involved sensory/somatomotor hand network and visual networks. Although these primary networks are usually not directly related to psychological resilience and creativity (Kong et al., 2015; Wu et al., 2015), these large-scale brain networks are functionally connected to high-order networks, such as DMN and SN. For example, Anderson et al. (2022) used graph theory measures of functional connectivity and found that big C creativity is related to more "random" rather than more "efficient" global network functional architecture. Their results support our findings and reveal that creative process needs the cooperation of multiple brain networks. Our results might show that both psychological resilience and creativity are related to dealing with external information from primary networks and that such information is subsequently processed by high-order networks.

In this study, common FCs from static analysis and dynamic analysis yield partly different results. The reason for this is that they are different brain functional measures. Although both of static analysis and dynamic analysis are based on functional connectivity, they are different in time scales. Static analysis calculates functional connectivity across the whole session, while dynamic analysis divides the whole session into different time windows and calculates the fluctuation of the brain functional connectivity (Miyagi et al., 2020; Sun et al., 2019). Dynamic properties provide the temporal features of spontaneous BOLD signal. This is the reason why we also adopted dynamic FCs as brain functional indexes in this study. The results in this study showed that the common static FCs and dynamic FCs underlying psychological resilience and creativity showed partly different patterns.

Some limitations of this study should be addressed, one of which is about the research design. Given that the fMRI data in the present study were obtained in the resting state, future research should use the fMRI task to further explore the common neural basis underlying psychological resilience and creativity. Task-based fMRI enables us to explore the cognitive process of dealing with stress in specific situations. Another limitation is that this study only explored the common brain basis underlying psychological resilience and creativity from the perspective of personality. Considering the complexity of these two concepts, future studies should combine various perspectives to explore the common cognitive and brain basis underlying psychological resilience and creativity. The cultural sensitivity in the questionnaires is also a limitation in this study. CPS is sensitive to cultural norms (Freiberg-Hoffmann et al., 2019). Hence, the CPS weighting system may not be optimal for the participants in this study. Future studies should consider this problem and try to avoid the potential effect of this problem. Another point we need to notice is the potential overlap between the behavioral measures. Items of the CPS are closely related to resilience factors. Because of this, the correlation between CPS and RS may due to the similar items in these measures instead of the similar cognitive mechanism and neural basis of these two concepts. It is difficult to address this point in the present study, but future studies can try to further explore this problem by including various kinds of behavioral measures about psychological resilience and creativity to avoid potential overlap.

5 | CONCLUSION

In conclusion, the present study adopted machine learning methods and provided evidence for the assumption that psychological resilience and creativity shared some common neural basis, with the common FCs being located in the DMN, EN, and SN. Using neuroimaging methods, our research also proved that psychological resilience and creativity shared some common cognitive neural mechanisms. These findings provide direct insights into the similarities between psychological resilience and creativity and developed the potential of using creative means to promote individuals' positive adaptation to negative events or situations.

AUTHOR CONTRIBUTIONS

JiangZhou Sun: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; visualization; writing – original draft. **Jingyi Zhang:** Investigation; visualization; writing – review and editing. **Qunlin Chen:** Methodology; writing – review and editing. **Wenjing Yang:** Methodology; writing – review and editing. **Dongtao Wei:** Methodology; writing – review and editing. **Jiang Qiu:** Funding acquisition; supervision; writing – review and editing.

ACKNOWLEDGMENTS

This research was supported by Chongqing Social Science Planning Project (2022PY14), the National Natural Science Foundation of China (32100850 and 32071070), Natural Science Foundation of Chongqing (cstc2021jcyj-bshX0072 and cstc2019jcyj-msxmX0520), the Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University, the planned project of Chongqing Humanities and Social Sciences (2018PY80 and 2019PY51), 111 Program (B21036), Fundamental Research Funds for the Central Universities (SWU119007), Chang Jiang Scholars Program, National Outstanding Young People Plan, and Chongqing Talent Program.

CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Data and code are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Supplementary analysis. Openness was added as a covariate in the predictive analysis.

How to cite this article: Sun, J., Zhang, J., Chen, Q., Yang, W., Wei, D., & Qiu, J. (2023). Psychological resilience-related functional connectomes predict creative personality. *Psychophysiology*, *00*, e14463. https://doi.org/10.1111/psyp.14463

报告编号：202403-208

检 索 报 告

项目名称：论文被收录引用情况证明

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日 期：2024 年 03 月 26 日

认证单位：教育部科技查新工作站 N08

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序号	排名	题名	检索号	影响因子	出版时间	语种	出版商
1	第一作者	Psychological resilience-related functional connectomes predict creative personality	WOS:001087465700001	IF_{2022}=3.7	2024 年	English	国外

Social Sciences Citation Index (SSCI)：收录 1 篇。

第 1 条，共 1 条

标题: Psychological resilience-related functional connectomes predict creative personality

作者: Sun, JZ (Sun, Jiangzhou);Zhang, JY (Zhang, Jingyi);Chen, QL (Chen, Qunlin);Yang, WJ (Yang, Wenjing);Wei, DT (Wei, Dongtao);Qiu, J (Qiu, Jiang)

来源出版物: PSYCHOPHYSIOLOGY 卷: 61 期: 4 DOI: 10.1111/psyp.14463 提前访问日期:OCT 2023 出版年: APR 2024

入藏号: WOS:001087465700001

语言:English

文献类型:Article

ISSN:0048-5772

eISSN:1469-8986

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