Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Research paper

True grit and brain: Trait grit mediates the connection of DLPFC functional connectivity density to posttraumatic growth following COVID-19

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ABSTRACT

Background: There is increasing interest in identifying factors to predict posttraumatic growth (PTG), a positive psychological response following traumatic events (e.g., the COVID-19 pandemic). Grit, a psychological trait of perseverance and passion to pursue long-term goals, has emerged as a promising predictor for PTG. This study aimed to examine the functional connectivity markers of grit and the potential brain-grit mechanism in predicting PTG.

Methods: Baseline brain imaging scans and grit scale and other controlling measures were administered in 100 normal young adults before the COVID-19 pandemic, and follow-up PTG measurement was obtained during the period of community-level outbreak. Whole-brain correlation analysis and prediction analysis were used to identify the brain regions whose functional connectivity density (FCD) related to individuals' grit scores. Mediation analyses were performed to explore the mediation relation between FCD, grit and PTG.

Results: Grit was positively related to FCD in the right dorsolateral prefrontal cortex (DLPFC), a core hub implicated in self-regulation and reward-motivation processes. Furthermore, grit mediated the effect of right DLPFC FCD on COVID-related PTG. These results survived controlling for self-control and family socioeconomic status.

Limitations: Our study is limited by only one-session neuroimaging data and self-reported behavioral measures in a sample of normal adults.

Conclusions: This study indicates grit and right DLPFC FCD as neuropsychological contributors for the development of PTG. It deepens our understanding of the neural bases of grit, and may have clinical potential to develop targeted brain interventions aimed at improving grit to raise PTG and mental health during the pandemic.

1. Introduction

There is growing recognition for the persistent negative mental health outcomes of the coronavirus disease 2019 (COVID-19) pandemic (Kumar and Nayar, 2021; Pfefferbaum and North, 2020), an unprecedented global public health crisis that can be deemed to be a compounding traumatic event (Gruber et al., 2021). Nevertheless, as many other traumatic events, the COVID-19 pandemic has also lead to positive psychological reactions labeled as posttraumatic growth (PTG) (Chen et al., 2021; Dominick et al., 2022; Feng et al., 2022; Hyun et al., 2021; Kalaitzaki, 2021; Li et al., 2022; Zhen and Zhou, 2022), which is generally defined as the positive changes of personal strength, life philosophy and interpersonal relationship following a traumatic event (Tedeschi and Calhoun, 1996, 2004). Given the promoting role of PTG in psychological functioning and well-being (Helgeson et al., 2006; Tedeschi and Calhoun, 2004), abundant studies have focused on the factors that may improve PTG and indicated that PTG is mainly affected by a series of psychosocial factors including personality tendencies, coping strategies, psychological flexibility and environmental factors (e.g., socioeconomic status [SES] and social support) (Henson et al., 2021; Prati and Pietrantoni, 2009). In this study, we centered on the strengthening role of a newly explored personality trait, i.e., grit (Duckworth, 2016), in

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the development of PTG following the outbreak and peak of COVID-19 pandemic.

A psychological construct that was first introduced in 2007 (Duckworth et al., 2007), grit is a compound personality of perseverance and passion to achieve long-range goals (Duckworth, 2016). Abundant evidence has indicated the beneficial role of grit in personal development and well-being, e.g., higher grit is linked to greater school and workplace performance, better subjective well-being, healthier life-style, and lower risks of mental disorders and problematic behaviors (Datu, 2021; Fernández-Martín et al., 2020). Although there is limited evidence on the relation between grit and PTG, grit has been assumed to be crucial for the development of PTG (Silverstein et al., 2018), given that both grit and PTG are conceptualized as goal-directed approach tendencies, i.e., challenging oneself and struggling to achieve goals (Duckworth, 2016; Tedeschi and Calhoun, 2004). To our knowledge, only one research has directly examined the link of grit with PTG and revealed a moderate positive relation between grit and PTG (Silverstein et al., 2018). Nevertheless, recent studies have shown that during the COVID-19 pandemic, grittier individuals would choose more effective coping strategies, report better psychological flexibility, engage in healthier lifestyle behaviors, and have increased psychological well-being (Bono et al., 2020; de Zepetnek et al., 2021; Masuyama et al., 2021; McCracken et al., 2021; Urban and Urban, 2020), all of which are conductive to PTG (Henson et al., 2021; Prati and Pietrantoni, 2009; Tedeschi and Calhoun, 2004). Collectively, grit is a core positive character strength that might contribute to PTG.

Although the research of grit has obtained significant recognition over the past decade, less has explored where individual variations in grit originate from, especially for those intrinsic brain features supporting differences in grit, which are critical for understanding grit per se (Wang and Li, 2021). Recent years have witnessed the huge development of the brain imaging techniques, particularly the magnetic resonance imaging (MRI), allowing researchers to specifically link individual differences in grit to structural and functional variations in the brain. Indeed, a pinch of studies using MRI have provided initial evidence for the neurobiological basis of grit. Concretely, individual variations in grit have been associated with the structure and function of regions in prefrontal cortex (PFC) such as the dorsolateral PFC (DLPFC), medial PFC (MPFC) and anterior cingulate cortex (ACC), which are involved in self-regulation and goal-directed behaviors (Myers et al., 2016; Wang et al., 2018b; Wang et al., 2017); some evidence has also revealed the link of grit with brain regions subserving reward-motivation functioning, which mainly locate in the striatum (e.g., the putamen, caudate and nucleus accumbens) (Myers et al., 2016; Nemmi et al., 2016; Wang et al., 2018b). However, these neural findings of grit were all confined to school-aged children and adolescents, leaving a knowledge gap in the neural substrates of grit in other populations. Particularly, prior evidence has shown that grit would increase with age (Duckworth and Eskreis-Winkler, 2013), it is thus of great necessity to explore the link of grit with the brain in other populations (e.g., adults and the elderly). In addition, these MRI studies were mainly based on measures of local brain activity and structure (Nemmi et al., 2016; Wang et al., 2018b; Wang et al., 2017), it remains to be seen how grit links with brain connectivity features that reflect the interactions between multiple brain regions. In light of the above, this study aimed to identify the functional connectivity (FC) markers of grit in a cohort of adults based on resting-state functional MRI (RS-fMRI).

A handful of studies have also examined the link of PTG with the brain and revealed that the neurobiological basis of PTG primarily resides in the PFC. An electroencephalogram study first reported that higher levels of PTG were related to lower relative right fronto-central activity in 82 survivors of motor vehicle accidents (Rabe et al., 2006). Another study using magnetoencephalography among 193 veterans found that synchronous neural interactions between the left and right MPFC were linked with PTG (Anders et al., 2015). Moreover, based on structural MRI data, Nakagawa and colleagues observed that individuals with higher PTG after an earthquake showed increased gray matter volume (GMV) in the right DLPFC in relative to the GMV value evaluated at 3-month before the earthquake (Nakagawa et al., 2016). Evidence from the functional neuroimaging studies has further confirmed the role of DLPFC in PTG, namely, individual differences in PTG have been linked with DLPFC activity during the resting-state (Fujisawa et al., 2015) and the condition of emotional pictures stimulating (Wei et al., 2017). Informed by these findings and the role of grit in PTG, the second aim of this study was to explore the potential neuropsychological pathways by which grit improves PTG.

Specifically, we administered MRI scanning and grit scale in a group of university students before the pandemic, and then collected the COVID-related PTG data during the pandemic. Here we used functional connectivity density (FCD), a recent developed method for detecting the distribution of hubs in the brain (Tomasi et al., 2015; Tomasi and Volkow, 2010; Tomasi and Volkow, 2011), which refers to the number of functional connections between a voxel and the other brain voxels, as the measure of intrinsic FC. As a popular analytical method for RS-MRI data, the FCD has been widely used in personality neuroscience studies to explore whether the intrinsic FC predicts personality traits and behaviors (Hilger and Markett, 2021; Pang et al., 2017; Yang et al., 2015). To identify the brain regions whose FCD linked with grit, whole-brain correlation analyses and prediction analyses were conducted. Considering the existing neural findings of grit, we expected FCD in the regions of PFC (e.g., the DLPFC, MPFC and ACC) and striatum (e.g., the putamen, caudate and nucleus accumbens) would predict grit. Then mediation analyses were performed to explore the neuropsychological mechanism of grit promoting PTG. Given the positive role of grit in PTG and the prior brain findings on PTG, we further expected that some PFC regions linked with grit (e.g., the DLPFC, MPFC and ACC) would predict PTG and there would be a mediation relation between FCD, grit and PTG.

2. Methods

2.1. Participants

The participants included 151 normal university students who are part of an ongoing project aimed to explore the neuropsychological mechanism of personality and mental health. All participants were right-handed and had no history of neuropsychiatric diseases, and they underwent MRI scanning and completed a group of paper-based tests from October 2019 to January 2020 (T1). Particularly, the World Health Organization declared the COVID-19 as a public health emergency on January 30, 2020 (Wang et al., 2020). Thus, all the baseline data were collected prior to the widely publicized recognition of the COVID crisis. These participants were then re-contacted for COVID-19-related behavioral online survey from February to April 2020 (T2, the initial outbreak and peak period of COVID-19 in China). Among them, 115 participants responded and finished the tests of T2. After excluding 15 participants with excessive head motion (see Section 2.3), data from 100 participants (58 females, aged from 19 to 27 years) were eligible for the final analyses. Notably, none of the participants were infected with COVID-19 proved by their nucleic acid testing report. According to the power analysis with the G*Power software (Faul et al., 2007), the current sample size was enough to detect a medium-sized effect with an adequate power ($r = 0.3$, $\alpha = 0.05$, $1\text{-}\beta = 0.8$). This study was approved by the local Medical Research Ethics Committee and informed written consent was obtained from all participants at each testing stage.

2.2. Behavioral tests

2.2.1. Short Grit Scale (Grit-S)

The individuals' levels of grit were measured at T1 by the Chinese version of the Grit-S (Li et al., 2018), which was originally developed by Duckworth and colleagues (Duckworth and Quinn, 2009). It has two

subscales (passion and perseverance) and each subscale includes four items that are rated on a 5-point Likert scale ranging from 1 to 5. By summing the ratings of all items, the Grit-S score was obtained and higher scores indicated higher levels of grit. Previous studies have indicated that the Chinese version of the Grit-S has adequate internal reliability (Cronbach's $\alpha = 0.80$), test-retest reliability ($r = 0.78$) and external validity linked with self-control, conscientiousness and personal achievement (Duckworth et al., 2021; Li et al., 2018). In our dataset, internal reliability for Grit-S was adequate (Cronbach's $\alpha = 0.79$).

2.2.2. Posttraumatic Growth Inventory (PTGI)

Pandemic-specific PTG levels were measured at T2 using the PTGI (Tedeschi and Calhoun, 1996). This contains 21 items and five aspects (personal strengths, appreciation of life, new possibilities, spiritual changes, and relation to others). Participants were asked to rate each item on a 6-point Likert scale ranging from 1 to 6. The ratings of all items were summed as the overall PTGI score and higher scores indicated higher levels of PTG. The Chinese version of the PTGI has excellent internal reliability (Cronbach's $\alpha = 0.92$), split-half reliability (0.90) and construct validity (Dong et al., 2013), and has been widely used for assessing pandemic-specific PTG in different populations (Chen et al., 2021; Feng et al., 2021; Li et al., 2021; Zhen and Zhou, 2022). In our dataset, internal reliability for PTGI was satisfactory (Cronbach's $\alpha = 0.95$).

2.2.3. Other controlling measures

To test the specificity of the relationships between grit, FCD and PTG, another two measures were administered at T1: the Brief Self-Control Scale (BSCS), which assesses perceived ability to inhibit desire, control thought, and regulate emotion and behavior (Li et al., 2018; Tangney et al., 2004); and the Socioeconomic Status Scale (SSS), which assesses subjective family SES levels (Adler et al., 2000; Peng et al., 2021). In our dataset, internal reliability for BSCS and SSS was adequate (Cronbach's $\alpha = 0.78$ and 0.76 respectively).

2.3. MRI scanning and preprocessing

2.3.1. MRI scanning

Whole-brain MRI scanning was conducted on a 3.0 T Siemens-Trio Erlangen MR scanner with a 12-channel head coil. The RS-fMRI data were obtained using a gradient-recalled echo-planar imaging sequence: 240 volume, echo time, 30 ms; repetition time, 2000 ms; voxel size, 3.75 × 3.75 × 5 mm^3; slices, 30; thickness, 5 mm; field of view, 24 × 24 cm^2; matrix, 64 × 64; flip angle, 90°. During the scanning, participants were asked to lie quietly, keep their eyes closed, not fall sleep, and not systematically think of anything. Besides, high-resolution T1-weighted anatomical MRI images were obtained for each participant: repetition time, 1900 ms, echo time, 2.26 ms, flip angle, 9°, 176 slices, voxel size, 1 × 1 × 1 mm^3, matrix size, 256 × 256.

2.3.2. Image preprocessing

Pre-processing of RS-fMRI images was conducted using DPABI software (Yan et al., 2016) in the following steps: removing the first 10 images, slice-timing correction, realignment, co-registration of functional and structural images, normalization with the Diffeomorphic Anatomical Registration Through Exponentiated Lie (DARTEL) strategy (Ashburner, 2007), resampling to 3 × 3 × 3 mm^3 isotropic voxels, spatial smoothing with a 6 mm full-width half-maximum, linear trend remove, and temporal filtering at 0.01–0.08 Hz. White matter and cerebrospinal fluid signals and head motion parameters were regressed out as nuisance covariates. In addition, the mean framewise displacement (FD) of each participant was calculated as the measure of head motion and the data of participants whose mean FD exceeded 0.25 mm were excluded; and then motion scrubbing was applied for the remaining participants based on the FD threshold of 0.50 mm (Suo et al., 2022; Yan et al., 2013). Finally, 15 participants were excluded for excessive head motion and 100 participants remained for subsequent analyses.

2.3.3. FCD calculation

The preprocessed RS-fMRI data were used to compute the FCD using the DPABI software (Yan et al., 2016). The Pearson's correlations between the time series of each pair of voxels across the brain were first computed, and then a whole-brain FC matrix was obtained. To avoid counting the voxels with weak temporal correlations due to signal noise, a threshold of 0.6 was applied to each correlation in the matrix given that a correlation >0.7 would lead to lower sensitivity while a correlation <0.4 would increase false-positive rates for the FCD maps (Tomasi et al., 2015; Tomasi and Volkow, 2010; Tomasi and Volkow, 2011). Indeed, the threshold of 0.6 has been shown to be the most reliable and popular value to detect the brain functional hubs (Pijnenburg et al., 2015; Qin et al., 2015; Wang et al., 2018a). Next, the binary FCD of a voxel was obtained by calculating the number of significant suprathreshold correlations between a given voxel and all other voxels. Finally, via the Fisher's r-to-z transformation, the voxel-wise FCD raw map was converted to z-map.

2.4. Statistical analyses

2.4.1. Whole-brain correlation analyses

To identify the FC markers of grit, we performed a whole-brain correlation analysis between the Grit-S scores and voxelwise FCD values, with sex, age and FD as the nuisance covariates. Besides, to examine sex differences in the link of grit with FCD, we performed a condition-by-covariate interaction analysis (Wang et al., 2018b; Wang et al., 2019) with sex as a condition, grit score as a covariate of interest and age and FD as covariates of no interest. Before these analyses, the scores of grit, age and FD were demeaned using a standardized method (i.e., subtracting the mean and dividing by the standard deviation). The resulting map was corrected for multiple comparisons with a cluster threshold of $p < 0.05$ combined with a voxelwise threshold of $p < 0.005$ using the Gaussian random field (GRF) method (Worsley et al., 1992), a popular correction approach for RS-fMRI data (Cox et al., 2012; Wang et al., 2019). All of the analyses were performed using the REST software (Song et al., 2011).

2.4.2. Prediction analyses

To test the stability of the grit-FCD linkage and to examine whether the linkage was influenced by factors such as data distribution and outliers, a confirmatory prediction analysis, which combined four-fold balanced cross-validation and linear regression (Evans et al., 2015; Lai et al., 2020; Supekar et al., 2013; Wang et al., 2019), was performed. Specifically, the whole dataset was randomly and equally divided into four folds so that the variables distributions across folds were balanced. Then three folds were used to construct a linear regression model, leaving out the fourth fold, to predict the fourth fold. In the analysis, FCD of the identified cluster was entered into the linear regression model that predicted the Grit-S scores to evaluate the predictive ability by correlations of the predicted values with the observed values [i.e., $r_{(predicted,\ observed)}$]. An $r_{final\ (predicted,\ observed)}$ [i.e., the mean of the four $r_{(predicted,\ observed)}$ values] was obtained by repeating the above steps four times. Following the established testing procedure from previous studies (Evans et al., 2015; Lai et al., 2020; Supekar et al., 2013; Wang et al., 2019), a nonparametric testing procedure via generating 5000 surrogate datasets was implemented to determine the statistical significance of $r_{final\ (predicted,\ observed)}$. All of the analyses were conducted using the Matlab codes used in our prior research (Lai et al., 2020; Wang et al., 2019).

2.4.3. Mediation analyses

To test whether grit mediated the link of FCD with PTG, we adopted the PROCESS macro in SPSS (Hayes, 2017) to build a mediation model.

FCD of the identified cluster was the predictor variable (X), Grit-S scores were the mediator variable (M), PTGI scores were the outcome variable (Y), and sex, age and FD were the covariates. To determine the significance of the mediating effect, a bootstrapping procedure was implemented with 5000 iterations. To examine another possible mediation relation between FCD, grit and PTG, we constructed another mediation model in which Grit-S scores were the X, FCD of the identified cluster was the M, PTGI scores were the Y, and sex, age and FD were the covariates.

3. Results

3.1. Behavioral characteristics of grit and PTG

Table 1 presents the descriptive statistics and bivariate correlations of study variables. Participants differed widely in the scores of grit and PTG (Fig. 1A); and the absolute kurtosis and skewness values were below 1, indicating that the scores of grit and PTG were normally distributed (Marcoulides and Hershberger, 2014). As expected (Fig. 1B), there was a moderate positive correlation between grit and PTG ($r = 0.29$, $p = 0.003$). Besides, grit was not correlated with sex ($r = 0.01$, $p = 0.948$), age ($r = 0.15$, $p = 0.131$) or head motion (FD; $r = -0.05$, $p = 0.611$).

3.2. FCD markers of grit

The whole-brain correlation analysis showed a positive relation between higher grit and increased FCD in a cluster located in the part of right DLPFC (Brodmann area [BA] 9; $r = 0.32$, $p < 0.001$; Table 2 and Fig. 2), a broad brain region mainly including BA 46, 9 and 8 (Miller and Cohen, 2001; O'Reilly, 2010). No other region was found to be significantly linked with grit in this analysis. Further prediction analysis revealed that there was a stable relation between grit and FCD in the right DLPFC across individuals ($r_{[predicted,\ observed]} = 0.28$, $p = 0.005$) after adjusting for sex, age and FD. Moreover, the condition-by-covariate interaction analysis found that there were no significant regions for the interaction effect of grit by sex. For the follow-up analyses, we utilized the right DLPFC identified from the whole-brain correlation analysis as a region of interest and examined its link with other measures.

3.3. FCD linking grit with PTG

After identifying the FC markers of grit, we further explored the underlying brain-grit mechanism in the prediction of PTG. To this end, a mediation analysis was performed with sex, age and FD as covariates. We found that the original significant link of DLPFC with PTG ($r = 0.20$ $p = 0.042$) disappeared when grit was added as an additional covariate ($r = 0.10$, $p = 0.291$). A bootstrap simulation ($n = 5000$) indicated that grit had a significant indirect effect on the link of DLPFC FCD to PTG (indirect effect = 0.10, 95 % CI = [0.03, 0.18], $p < 0.05$; Fig. 3). These results suggest the notion that the link of DLPFC to PTG may involve grit.

To test the directionality of the link between DLPFC, grit and PTG, another mediation model was constructed with grit as the X, DLPFC as the M and PTG as the Y. Interestingly, there was no significant indirect effect of DLPFC on the link of grit with PTG after controlling for sex, age and FD (indirect effect = 0.03, 95 % CI = [−0.04, 0.11], $p > 0.05$). Collectively, the DLPFC FCD may influence PTG via grit.

3.4. The specificity of the findings

First, given that self-control is a psychological construct paralleling with grit and highly correlated with grit (Duckworth, 2016), we tested whether our findings were affected by self-control. Self-control was correlated with grit ($r = 0.66$, $p < 0.001$), PTG ($r = 0.23$, $p = 0.022$) and FCD in the DLPFC ($r = 0.25$, $p = 0.013$). Importantly, after adding self-control as another covariate, grit was still linked with PTG ($r = 0.21$, $p = 0.040$) and FCD in the DLPFC (r = 0.21, $p = 0.035$). Mediation analyses showed that grit still mediated the link of DLPFC FCD to PTG after additionally controlling for self-control (indirect effect = 0.04, 95 % CI = [0.01, 0.10], $p < 0.05$). In sum, our findings are specific to grit to some degree, despite that self-control reduced the effect sizes of the findings.

Second, we examined the possible effect of family SES on our findings because family SES has been found to be linked with grit (Kwon, 2017), brain FC (Farah, 2018) and PTG (Prati and Pietrantoni, 2009). Family SES was marginally correlated with grit ($r = 0.18$, $p = 0.074$) but not with PTG ($r = 0.01$, $p = 0.901$) and FCD in the DLPFC ($r = 0.02$, $p = 0.885$). Crucially, after adding family SES as another covariate, grit was still linked with PTG ($r = 0.34$, $p < 0.001$) and FCD in the DLPFC ($r = 0.32$, $p < 0.001$). Mediation analyses showed that grit still mediated the link of DLPFC FCD to PTG after additionally controlling for family SES (indirect effect = 0.10, 95 % CI = [0.03, 0.19], $p < 0.05$). Thus, our findings are independent of family SES.

Third, we interrogated our results by excluding all covariates. The supplemental analyses showed that grit was significantly correlated with FCD in the DLPFC ($r = 0.31$, $p = 0.002$). Furthermore, there was a significant mediation effect of grit in the link of DLPFC FCD to PTG (indirect effect = 0.07, 95 % CI = [0.02, 0.15], $p < 0.05$). Therefore, our results remained unchanged when all covariates were excluded.

4. Discussion

In this prospective study of a healthy population, we examined the FC correlates of grit before the COVID-19 pandemic and then explored the underlying brain-grit mechanism to predict PTG during the pandemic. There are two main findings. First, individual variations in grit were positively linked with FCD in the right DLPFC. Second, grit mediated the effect of DLPFC FCD on COVID-related PTG. Critically, these findings remained adjustment for self-control and family SES. Taken together, we indicated that the DLPFC FCD may be an underlying functional neural marker of grit and revealed a potential

Table 1
Means, SD and bivariate correlations of study variables ($N = 100$).

Variable	Mean ± SD	Range	1	2	3	4	5	6
1. Sex (Male, 0; Female, 1)	–	–	–					
2. Age (T1)	22.42 ± 2.12	19–27	−0.09	–				
3. FD (T1)	0.16 ± 0.04	0.05–0.24	−0.11	−0.08	–			
4. Grit (T1)	24.51 ± 4.36	16–40	0.01	0.15	−0.05	–		
5. Self-control (T1)	35.86 ± 6.60	23–52	−0.05	0.20	−0.05	0.66***	–	
6. Family SES (T1)	4.94 ± 1.49	1.5–9	−0.01	0.03	−0.07	0.18	0.28**	–
7. Posttraumatic growth (T2)	63.36 ± 20.91	21–111	−0.04	−0.22*	−0.04	0.29**	0.23*	0.01

Note: N, number; SD = standard deviations; SES, socioeconomic status; FD, framewise displacement; T1, from October 2019 to January 2020; T2, from February to April 2020.

*** $p < 0.001$.

** $p < 0.01$.

* $p < 0.05$.

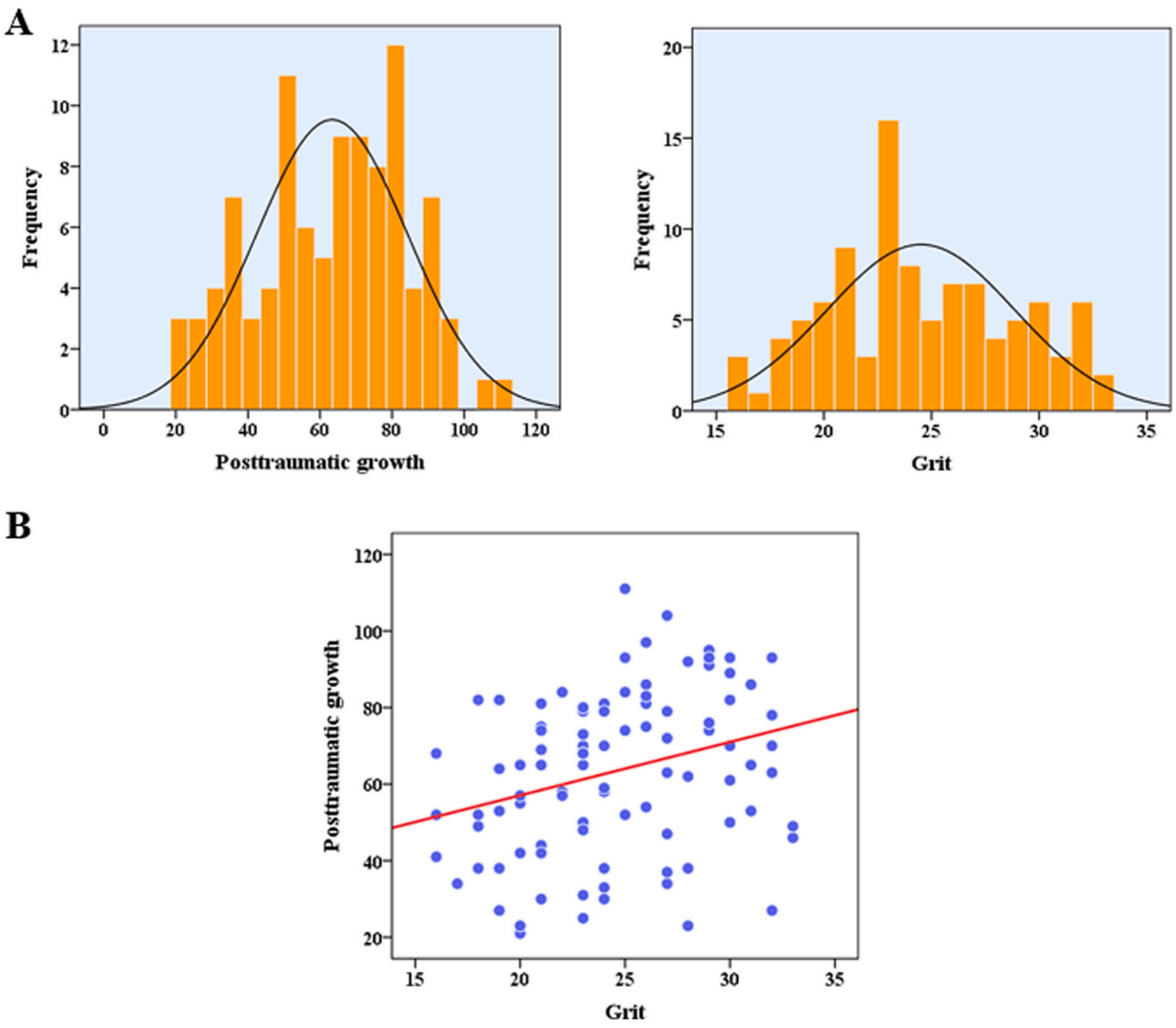

Fig. 1. (A) Distributions of grit and posttraumatic growth scores. (B) Scatter plots showing the correlation between grit and posttraumatic growth ($r = 0.29$, $p = 0.003$).

Table 2
Brain region linking with grit.

Region	BA	Peak MNI coordinates			Peak Z	Cluster size (voxels)
		x	y	z	score	
Right DLPFC	9	24	51	27	3.51	195

Note: MNI, Montreal Neurological Institute; BA, Brodmann's area; DLPFC, dorsolateral prefrontal cortex.

neuropsychological pathway in predicting PTG in which the DLPFC FCD affects PTG via grit. We discuss these findings briefly below.

Confirming our first expectation, individuals with higher grit showed increased FCD in the right DLPFC. This positive link of grit with DLPFC FCD fits well with a prior study revealing that individual variations in grit were positively linked with the FC between ventral striatum and DLPFC (Myers et al., 2016). There is also evidence that structural differences of the DLPFC could reliably predict individual variations in grit (Wang et al., 2018b). The DLPFC is widely considered a brain hub for dynamic aspects of self-regulatory functioning such as goal-setting, response inhibition, set shifting, action planning and emotional regulation (Heatherton and Wagner, 2011; Kelley et al., 2015). According to the theory of grit, people need self-regulation capacities to inhibit distractions, conquer discouragements and overcome difficulties when pursuing a long-term goal (Duckworth, 2016). Thus, higher FCD of the DLPFC reflecting improved brain hub functioning may develop greater efficiencies in self-regulation, which may further lead to higher levels of grit. The DLPFC is also implicated in initiation and organization of reward-motivated behaviors (Ballard et al., 2011; Staudinger et al., 2011), which corresponds to the motivation account of grit theory that underlines the role of drive or motivation in the pursuit of a certain goal with sustained passion and perseverance (e.g., lasting several months or even years) (Duckworth, 2016). Previous lesions studies have indicated that damage to DLPFC would result in apathy, diminished motivation, lacks of initiative and interest in the environment, and incapacity to planning and maintaining goals (Szczepanski and Knight, 2014). In contrast, evidence from intervention studies has shown that electrical stimulation to DLPFC benefits self-regulation and motivation-related processes (e.g., inhibitory control, emotional regulation and psychological flexibility) (Dedoncker et al., 2016; Nejati et al., 2020). In brief, the finding of the link of grit and DLPFC FCD may reflect the role of DLPFC in the development of self-regulation and motivation components in the conception of grit.

Confirming second expectation, grit served as a mediator in the linkage of DLPFC FCD to PTG. Behaviorally, we confirmed the assumption regarding the conceptual overlapping between grit and PTG and replicated the moderate correlation between them (Silverstein et al., 2018). Particularly, grit still explained significant variance in PTG ($\triangle R^2 = 3.8$ %, $\beta = 0.26$, $p = 0.042$) even excluding the influences of

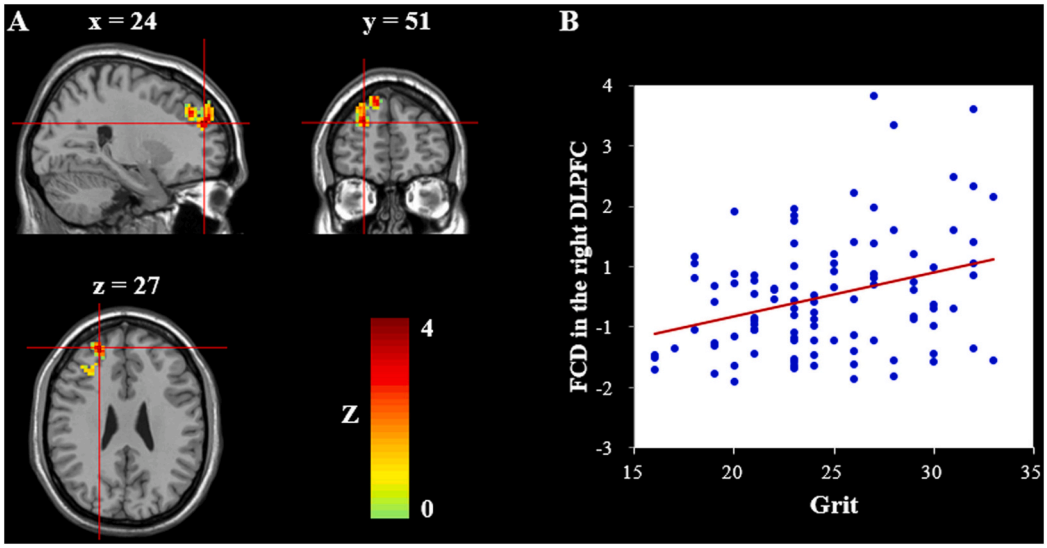

Fig. 2. (A) Brain images revealing that grit is positively linked with FCD in the right DLPFC after adjusting for sex, age and head motion. (B) Scatter plots showing the correlation between grit and FCD in the right DLPFC ($r = 0.32$, $p < 0.001$). FCD, functional connectivity density; DLPFC, dorsolateral prefrontal cortex.

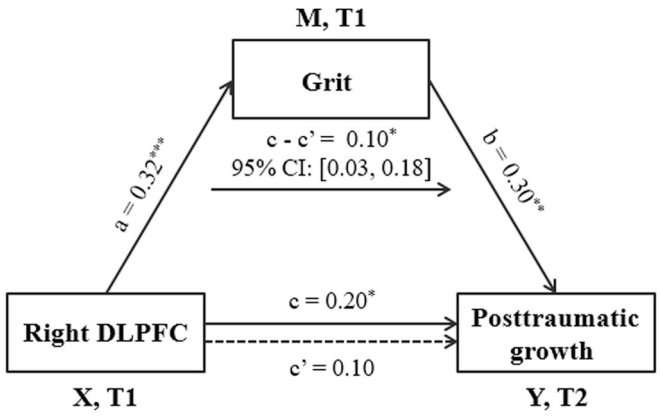

Fig. 3. Mediation results of right DLPFC, grit and posttraumatic growth. Sex, age and head motion are regressed out in the analysis and standardized estimates are indicated in the diagram. DLPFC, dorsolateral prefrontal cortex; X, independent variable; M, mediator variable; Y, dependent variable; CI, confidence interval; T1, from October 2019 to January 2020; T2, from February to April 2020.

self-control and family SES as well as sex, age and head motion. In this sense, our findings offer prospective confirmation of the relation between grit and PTG under the pandemic condition. Neurally, a significant component of the variance in PTG could be explained by FCD in the DLPFC. This finding is consistent with known links of PTG with DLPFC function and structure (Fujisawa et al., 2015; Nakagawa et al., 2016; Wei et al., 2017). As a core brain hub of self-regulation, the DLPFC exerts inhibitory control and emotional regulation on subcortical regions (e.g., hippocampus and amygdala), which allows individuals to organize their behavioral and emotional reactions adaptively in face of stressful or adverse situations (Benoit and Anderson, 2012; Gagnepain et al., 2017). For example, a recent fMRI study found that compared to individuals with PTSD, exposed individuals without PTSD showed increased top-down regulation of the DLPFC to hippocampus during suppressing the intrusive unwanted traumatic memories (Mary et al., 2020). Indeed, the activation and morphology of the DLPFC have been associated with less PTSD symptoms and better recovery, resilience and coping with stress (Aupperle et al., 2012; Eaton et al., 2021; Lyoo et al., 2011). These findings suggested that the DLPFC may not only play a crucial role in the progression of PTSD, but also be involved in the psychological recovery and growth (e.g., PTG) after experiencing traumatic events. Additionally, the theory of PTG has assumed that the PTG is characterized with initiative psychological changes of goals, beliefs and personal relations, which require disengagements from unobtainable goals and initiation to new goals (Tedeschi and Calhoun, 2004). Thus when facing a severe traumatic event, the motivation function of the DLPFC might allow individuals to actively adjust their goals, formulate and maintain new goals and translate goals into actions (Ballard et al., 2011; Staudinger et al., 2011), which may further induce PTG. Overall, the DLPFC may contribute to the formation of grit so that individuals with higher grit may have better self-regulation and motivation processes, all of which are fairly conducive to develop PTG.

5. Limitations

This research has some limitations. First, we only collected one session fMRI data and behavioral measures, and our research design cannot assess the directionality of the relation between FCD, grit and PTG. Notably, our results of mediation analysis are statistical and do not imply causality. Future longitudinal work with measurements at multiple time points is needed to confirm the current findings. Second, our results from normal young adults do not necessarily generalize to other populations, so it remains to validate our findings in others, e.g., young and elderly, frontline healthcare workers, or patients with COVID-19. Third, the measurements of grit and PTG were self-reported and subjective, which may run the risk of response biases (Pedregon et al., 2012), though the psychometric properties of these measures have been well-confirmed (Chen et al., 2021; Li et al., 2018; Li et al., 2021; Wang et al., 2017). Future research might use alternatives such as implicit tasks and natural behavioral evaluations to reduce measurement errors. Fourth, the current FCD analyses were based on an 8-min scanning, which may limit the reliability and reproducibility of the findings, given that there is evidence indicating that a longer scanning length (e.g., 12–16 min) may improve the reliability of the FC analyses (Birn et al., 2013). Future studies with a longer scanning time are needed to confirm the current findings. Finally, we only found a linkage of grit with FCD in the DLPFC, but did not identify other hypothesized regions (e.g., MPFC, ACC, putamen, caudate and nucleus accumbens). Given that only FCD was used as the brain measure in this research, future researchers may consider using other brain measures (e.g., task-based functional activity and connectivity) to comprehensively unveil the neural substrates

supporting grit.

6. Conclusion

In conclusion, this study may extend our neural understanding of grit by showing that higher levels of grit are linked with increased DLPFC FCD. Importantly, we presented a potential neuropsychological pathway to predict PTG in which DLPFC FCD affects COVID-related PTG via grit. Altogether, our findings emphasize the importance of grit and brain features in the development of PTG and provide novel insights to examining how intrinsic brain characteristics and individual psychological traits affect mental health outcomes adherence to COVID-related challenges. These findings may help future researchers and practitioners design pertinent schemes and/or procedures to foster individuals' grit-related capacities to raise their resilience and coping levels when facing trauma events like the pandemic. For instance, some behavioral training programs (Datu, 2021) and neural intervention schemes on targeted brain region (Salehinejad et al., 2017) may be developed to improve grit to promote PTG and mental health after experiencing major epidemics such as the COVID-19 pandemic.

CRediT authorship contribution statement

S Wang designed the study and supervised the conduct of the study. S Wang and YJ Zhao contributed to the data collection. JG Li and S Wang performed the data analysis and results interpretation. JG Li and S Wang drafted the manuscript, and all authors reviewed and approved for publication.

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Data availability

West China Hospital of Sichuan University has an institutional commitment to data-sharing. To get access to the data and comply with the terms of our research ethics committee approval an application to the corresponding author will be required, specifying the geographical extent of sharing.

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Conflict of interest

The authors declare no conflict of interests.

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