OXFORD

Trait self-control mediates the association between resting-state neural correlates and emotional well-being in late adolescence

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Abstract

Trait self-control (TSC), defined as the capacity to alter predominant response to promote desirable long-term goals, has been found to facilitate emotional well-being (EWB). However, the neural correlates underlying this association remain unclear. The present study estimated resting-state brain activity and connectivity with amplitude of low-frequency fluctuations (ALFFs) and resting-state functional connectivity (rsFC) among late adolescents. Whole-brain correlation analysis showed that higher TSC was associated with increased ALFFs in regions within the executive control network (inferior frontal gyrus, IFG) and the salience network (anterior insula, AI) and decreased ALFF in regions (e.g. medial frontal gyrus, MFG; posterior cingulate, PC) within the default-mode network (DMN). TSC was also linked with the integration (e.g. increased IFG-PC connectivity) and segregation (e.g. decreased AI-MFG connectivity) among brain networks. Mediation analysis indicated that TSC totally mediated the links from the IFG and the precuneus, FC of the AI and regions of the DMN (e.g. bilateral PC and MFG), to EWB. Additionally, ALFF in the IFG and the MFG could predict negative affect in the pandemic through TSC. These findings suggest that TSC is involved in several regions and functional organizations within and between brain networks and mediated the association between neural correlates and emotional wellness in adolescence.

Key words: trait self-control; emotional well-being; negative affect; brain network

Introduction

With the rising tide of positive psychology and health psychology, a growing body of research have been exploring subjective well-being and its potential determinants. As the affective component, emotional well-being (EWB) is characterized by a range of holistic and subjective feelings including positive affect (e.g. confident, enjoyable and calm) and negative affect (e.g. sad, stressed and angry) (Diener *et al.*, 2017). Promoting EWB is vitally important for individual psycho-social development and public health management (Dolan and White, 2007; Steptoe *et al.*, 2015). Trait self-control (TSC) is defined as the capacity to alter and regulate predominant response to promote desirable long-term goals (Baumeister *et al.*, 2007; De Ridder *et al.*, 2012), and whether and how it affects EWB has received increasing concerns of researchers (Hofmann *et al.*, 2014; De Ridder and Gillebaart, 2017;

Wiese *et al.*, 2017). This association is intriguing as it challenges the stereotypical perception of high self-control as a dutiful self-discipline in which individuals deny themselves pleasure (Hofmann *et al.*, 2014; Wiese *et al.*, 2017).

Studies have demonstrated that TSC is vital for many valued outcomes in life, such as physical and mental health (Tangney *et al.*, 2004; Moffitt *et al.*, 2011), life satisfaction (Hofmann *et al.*, 2014; Briki, 2018), and success at work and in social relationship (Allemand *et al.*, 2019; Converse *et al.*, 2018). In particular, previous investigations of the relationship between TSC and EWB have shown that individuals with higher TSC experience less negative emotion and more positive emotion (Hofmann *et al.*, 2014; Wiese *et al.*, 2017), and report lower psychological maladjustment (e.g. anxiety, stress and depression) (Tangney *et al.*, 2004; Nielsen *et al.*, 2020). Moreover, possessing high TSC is associated with effective emotion regulation (Paschke *et al.*, 2016), stable emotions in daily life (Daly *et al.*, 2014), fewer problematic desires and conflict when facing temptation (Hofmann *et al.*, 2012). Although these behavioral findings are encouraging, the neural correlates that explain this association remain largely undocumented.

Evidence-based resting-state and task fMRI research suggests that self-control capacity recruits a wide range of brain areas distributed in different networks (Dwyer *et al.*, 2014; Kumfor *et al.*, 2015; Krönke *et al.*, 2020). According to the dual-system model, self-control ability can be reflected by the relative strength between the cognitive control system and the socioemotional system (Steinberg, 2008; Hofmann *et al.*, 2009). Converging neuroimaging evidence suggests that the cognitive control system is closely associated with the executive control network (ECN) commonly involved in executive control, working memory and decision-making (Cole and Schneider, 2007; Dosenbach *et al.*, 2008). Studies have shown that the inferior frontal gyrus (IFG) in the lateral prefrontal cortex of the ECN is closely linked to deliberative processing, response inhibition and affective regulation (Heatherton and Wagner, 2011; Aron *et al.*, 2014; Morawetz *et al.*, 2015). For instance, individuals with higher activation of the IFG in an inhibition task were more likely to keep a healthy dietary pattern in daily life (Lopez *et al.*, 2014). The socioemotional system is involved in a variety of social and affective function including automated processing, social cognition and emotional experience, which are greatly associated with the default mode network (DMN) (Adolphs, 2009; Amft *et al.*, 2015; Raichle, 2015; Vatansever *et al.*, 2017; Satpute and Lindquist, 2019). The DMN encompasses a distributed set of regions including the medial frontal cortices (MFG), the posterior cingulate (PC), the precuneus and the angular gyrus, which are normally more active during rest and internally directed task (e.g. self-referential processing, mind-wandering and episodic memory retrieval) (Harrison *et al.*, 2008; Stawarczyk and D'Argembeau, 2015; Davey *et al.*, 2016). Studies indicate that task-related suppression of the DMN in the inhibition task is linked to the efficiency of cognitive-demanding and goal-directed cognition (Bonnelle *et al.*, 2012; Whitfield-Gabrieli and Ford, 2012; Ma *et al.*, 2018).

Studies have indicated that the functional connection within, and the interaction between, large-scale networks is necessary for goal-directed cognition and execution (Dosenbach *et al.*, 2007; Seeley *et al.*, 2007; Spreng *et al.*, 2010; Kumfor *et al.*, 2015). The anterior insula (AI) within the salience network (SN) has been previously identified to be maintaining interoceptive awareness of one's homeostatic state (Craig, 2009) and integrating signals from emotional and affective processes (Uddin, 2015). Evidence suggests the AI is not only involved in inhibitory control and decision-making (Menon and Uddin, 2010; Cai *et al.*, 2014; Uddin, 2015) but also considered as a critical node for suppressing the DMN activity and reallocating attentional resources to salient events (Sridharan *et al.*, 2008; Menon and Uddin, 2010). Moreover, neuroimaging studies show that the AI plays a key role in dynamically supporting more efficient switching between the ECN and the DMN, which is also crucial for self-control ability (Sridharan *et al.*, 2008; Tang *et al.*, 2012; Ham *et al.*, 2013). In summary, the neurobiological correlates of TSC may reside in the brain regions (e.g. MFG, IFG, PC and AI) and functional connectivity within and between brain networks (e.g. ECN, DMN and SN).

These above brain networks are also considered as the neural correlates underlying subjective well-being. Previous study has indicated that individuals with greater activation of the MFG and the PC within the DMN were associated with feelings of depression and hopelessness (Grimm *et al.*, 2009; Sheline *et al.*, 2009). Moreover, increased functional connection within regions of the DMN has been negatively associated with people's perceived happiness (Luo *et al.*, 2015). Emerging studies suggest that the ECN also plays an important role in the experience of well-being (Tang and Huang, 2012; Pe *et al.*, 2013). For instance, the lateral prefrontal cortex (e.g. IFG) of the ECN is positively correlated with emotional and cognitive well-being (Takeuchi *et al.*, 2014; Kong *et al.*, 2015). In addition, the AI within the SN is considered to be an integrative region that is essential for the feeling of well-being (Harrison *et al.*, 2010; Reeve and Lee, 2019). Neuroimaging studies also indicate that both subjective well-being (Rutledge *et al.*, 2014; Li *et al.*, 2020) and experience of potential realization are found be associated with the AI (Lewis *et al.*, 2014). In short, these findings suggest that EWB might be implicated in multiple regions and connections within and between large-scale brain networks.

The neural correlates underlying stable individual differences in personality trait, disposition and holistic experience could be directly and reliably examined by using task-free designs (e.g. resting state fMRI). Two resting state fMRI methods can be used to provide insights into self-control capacity: the amplitude of low-frequency fluctuations (ALFFs) that reflects the intrinsic properties of spontaneous local brain activity (Zou *et al.*, 2008); the resting state functional connectivity (rsFC) that reflects the synchronization and interaction among brain regions located in different brain networks (Fox *et al.*, 2007). Given these behavioral and neural findings of the relationship between TSC and EWB, both TSC and EWB may be implemented via overlapping brain regions and FCs within and between networks implicating in socioemotional processing (e.g. DMN), executive control (e.g. ECN) and integrating adjustment (e.g. SN). Therefore, TSC was hypothesized to mediate the association between these neural correlates and EWB.

Additionally, as the coronavirus disease-2019 (COVID-19) spread globally, people are at risk of being infected and even death, which undoubtedly will lead to negative affect among the public. Evidence from a large-scale public survey in China demonstrated that most people showed anxiety (66.9%), worry (71.7%) and fear (58.2%) during the pandemic (Pneumonia Cognitive Survey, 2020). To explore the protective factor for negative affect during the pandemic, the present study also examined whether those above brain regions and connections within and between networks (e.g. DMN, ECN and SN) before the outbreak (September 2019, T1) could longitudinally and negatively predict negative affect during the pandemic (February 2020, T2) through TSC.

Methods

Participants and procedure

The data were derived from the Behavioral Brain Research Project of Chinese Personality, which is designed to investigate the neurobiological correlates of personality in Chinese late adolescents. This project used a random method to recruit healthy college students from various departments of a university in Chongqing, China. All participants signed the informed consent document prior to the experiment and received an honorarium at the end of the study. Ethical approval of this study was granted by the Ethics Committee of the University, and all procedures were in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). The first wave (T1, September 2019) obtained personality, well-being and imaging data from 538 college students. The second wave (T2, February 2020) obtained data by following up with 483 students from the original group (m_{age} = 18.75, s.d. = 1.56, range 17–20 years; female: n = 337; male: n = 146). Chi-squared test and t-test were used to assess the effect of attrition (e.g. sex, age and TSC), and no significant differences were found between those remained and those excluded (0 = missing, 1 = complete): χ^2_{sex} = 0.43, P = 0.51; t_{age} = 0.34, P = 0.73; t_{TSC} = 0.92, P = 0.36.

Behavioral measurements

TSC was measured using a brief and well-validated Chinese version of 19-item Self-Control Scale (Tangney *et al.*, 2004; Tan and Guo, 2008). Participants were required to answer on a 5-point Likert scale (e.g. 'I am good at resisting temptation') ranging from 1 (not at all like me) to 5 (very much like me) to indicate their dispositional self-control ability. Higher scores on this scale indicated greater self-control capacity. Cronbach's alpha was 0.88 in the present study.

EWB was measured by the 20-item Positive and Negative Affect Schedule (PANAS; Watson *et al.*, 1988). Global positive affect (e.g. enthusiastic, inspired) and negative affect (e.g. jittery, distressed) were measured by 10 items, separately. Participants rated the scale on a 5-point Likert scale ranging from 1 (not at all) to 5 (extremely) to indicate the frequency with which it occurred in the past month, with higher scores indicating greater positive/negative affect. A composite EWB scores was computed by averaging all 20 items (reverse coding the negative affect items) (e.g. Tong *et al.*, 2019). Cronbach's alpha for both positive and negative affect (T1) were 0.90, and for negative affect in the pandemic was 0.91(T2).

Resting state fMRI data acquisition and preprocessing

Image acquisition. All participants underwent a total of 8 minutes resting-state fMRI scanning in Siemens PRISMA 3 Tesla scanner (Erlangen, Germany). During the process of scanning, each participant was asked to remain still and relaxed, not open his/her eyes and not think of anything deliberately. Foam pads and earplugs were employed to reduce head motion and scanning noise. We used a gradient echo planar imaging sequence to obtain the resting-state functional image, and the scanning parameters were as follows: repetition time = 2000 ms; echo time = 30 ms; slices = 62; slice thickness = 2 mm; field of view read = 224×224 mm^2; flip angle = 90°; resolution matrix = 112×112; voxel size = $2 \times 2 \times 2$ mm^3; phase encoding direction = PC ≫ AC. Each section contained 240 volumes. The 3-D spoiled gradient-recalled sequence used the following parameters: TR = 2530 ms; TE = 2.98 ms; field

of view read = 256×224 mm^2; flip angle = 7°; base resolution = 256×256; slice per slab = 192; slice oversampling = 33.3%; voxel size = $0.5 \times 0.5 \times 1$ mm^3; phase encoding direction = AC ≫ PC. The high-resolution T1-weighted structural images provided an anatomical reference for the functional scans.

Image data preprocessing. The Data Processing and Analysis for Brain Imaging (resting-state) (DPABI, Yan *et al.*, 2016) was used to preprocess the image data. The preprocessing was conducted with the following steps. The first 10 images were discarded to allow for participants' familiarization and fMRI signal stabilization. The remaining images were corrected for temporal shifts between slices, realigned to the middle volume. Next, by using the EPI templates in SPM12, each image volume was spatially normalized to the Montreal Neurological Institute 152-brain template, with a resolution voxel size of $3 \times 3 \times 3$ mm^3. The images were then spatially smoothed with a 4 mm full width at half maximum of Gaussian kernel and linear trends were subsequently removed. Then, we regressed nuisance signals including white matter, cerebrospinal fluid and head motion parameters, and regressed their derivatives using a Friston 24 parameter model to control the effects of potential physiological artifacts (Friston *et al.*, 1996). In addition, linear and quadratic trends were also included as regressors since the BOLD signal exhibits low-frequency drifts. To remove the effects of very-low-frequency drifts and high-frequency noises, all images were filtered using a temporal band pass filter (0.01–0.08 Hz) (for rsFC but not for ALFF). Finally, we implemented data scrubbing to better address head motion concerns. The bad time points were regarded as regressors that defined as volumes with framewise displacement (FD) power >0.5 mm as well as the two succeeding volumes and one preceding volume to reduce the spillover effect of head motion (Power *et al.*, 2012). For all participants, none has head motion between volumes in any direction was >3 mm or rotation in any axis >3 during scanning, the mean FD values did not exceed 0.50; hence, no participants were excluded during preprocessing.

Statistical analysis

ALFF-behavior correlation analysis. The time series in each voxel was transformed to a frequency domain with a fast Fourier transform. Next, the power spectrum was obtained. Then, the square root of the power spectrum was calculated and averaged across 0.01–0.08 Hz for each voxel. This averaged square root was considered to be the ALFF. For standardization purposes, the ALFF value of each voxel was divided by the global mean ALFF value to normalize the global volume effects across subjects (Zang *et al.*, 2007). Calculations were conducted using DPARSF software.

To identify the brain regions of spontaneous brain activity related to TSC, we employed whole-brain correlation analyses of TSC scores and ALFF values of each voxel in the brain, with sex, age and FD as controlling covariates. To determine statistical significance, the results were corrected for multiple comparisons using the Gaussian random field (GRF) program, and the threshold was set as a corrected cluster $P < 0.05$ (single voxel $P < 0.005$, cluster size ≥ 35 voxels). These analyses were conducted using the DPABI software toolbox (http://rfmri.org/dpabi, version 2.3) in MATLAB platform.

rsFC-behavior correlation analysis. We performed rsFC-behavior correlation analyses to investigate whether the clusters identified through the ALFF-behavior analyses interacted with

Table 1. Descriptive statistics of model variables ($n = 483$)

Variable	Mean	s.d.	1	2	3	4	5
1 age	19.48	0.86	–	–	–	–	–
2 TSC(T1)	3.16	0.55	0.06	–	–	–	–
3 PA(T1)	2.68	0.68	0.01	0.28[**]	–	–	–
4 NA(T1)	1.64	0.58	0.01	−0.12[*]	0.17[**]	–	–
5 EWB(T1)	3.52	0.41	−0.01	0.32[**]	0.71[**]	−0.57[**]	–
6 NA(T2)	2.29	0.77	0.08	−0.25[**]	−0.03	0.25[**]	−0.21[**]

Notes: n, number; s.d., standard deviation; T1, Time1, September, 2019; T2, Time 2, February, 2020. *$P < 0.05$, **$P < 0.01$.

other regions to explain self-control ability. To do so, seed regions were created using the clusters with a significant relation to TSC. For each participant, we first averaged the time series of all voxels in each seed. We then performed correlation analyses between the mean time series in each seed and that of other voxels in the brain, obtaining participant-level correlation maps. For standardization purposes, the correlation maps were normalized to z maps using Fisher's r-to-z transformation. In the group-level analyses, we conducted correlation analyses between the z maps and the TSC scores to detect any association, with age, sex and FD as controlling variables. For multiple comparisons correction, we used the GRF program with the threshold set to a corrected cluster $P < 0.05$ (single voxel $P < 0.005$, cluster size ≥ 100 voxels). These analyses above were performed using DPABI software.

Mediation model analysis. To determine the indirect effect of TSC on the association between resting-state brain activity and EWB, we conducted a mediation analysis using SPSS 22.0. To this end, the ALFF of the voxels and rsFC among regions specifically associated with TSC were considered as the independent variable (X), TSC scores were considered as the mediator variable (M), EWB scores (T1) and negative affect (T2) in the pandemic were considered as the dependent variable (Y), with sex, age and FD as the controlling variables. The mediating effect was tested by a bootstrapping analysis with 5000 iterations using the SPSS macro PROCESS (Model 4) (Hayes and Scharkow, 2013). If the 95% confidence interval (CI) did not contain zero, then the mediating effect was deemed significant.

Results

Behavior correlation results

The descriptive statistics of all measures are presented in Table 1. The kurtosis and skewness values of all variables are between −1 and +1, indicating that the data present a normal distribution. As shown in Table 1, TSC in the baseline time point (T1) was positively related to positive affect (T1) and EWB (T1), and negatively associated with negative affect in two time points (T1, T2). In addition, results showed that there was sex difference in TSC ($M_{male} = 3.23 \pm 0.55$, $M_{female} = 3.13 \pm 0.54$, $F_{(1, 481)} = 3.66$, $P = 0.06$) and NA in the pandemic ($M_{male} = 2.09 \pm 0.76$, $M_{female} = 2.37 \pm 0.76$, $F_{(1, 481)} = 13.75$, $P < 0.001$) rather not in PA ($M_{male} = 2.72 \pm 0.70$, $M_{female} = 2.66 \pm 0.67$, $F_{(1, 481)} = 0.92$, $P = 0.34$) and NA ($M_{male} = 1.61 \pm 0.57$, $M_{female} = 1.66 \pm 0.58$, $F_{(1, 481)} = 0.70$, $P = 0.40$) before pandemic. In order to control potential influence, the following analysis would take sex as a control variable.

Table 2. Brain regions where ALFF were associated with TSC

Region	Cluster size	BA	MNI coordinates			R
			x	y	z	
Correlation with ALFF						
MFG (L)	35	10	−6	63	−6	−0.179
IFG(R)	58	44	42	15	15	0.214
PC (L)	35	31	−3	−72	18	−0.206
AI (L)	41	13	−30	0	21	0.201
Precuneus(L)	82	5	−3	−45	63	−0.205

Note: The threshold for significant regions was set at $P < 0.05$ at the cluster level, combined with $P < 0.005$ at the voxel level (GRF approach; ALFF analysis: cluster size ≥ 35 voxels).
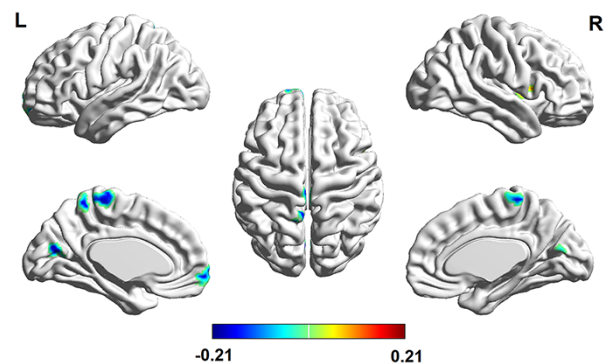BA, Brodmann area; MNI, Montreal Neurological Institute; R, right; L, left.

Fig. 1. Brain regions associated with TSC after controlling for age, sex and FD.

Imaging results

To reveal the relationship between spontaneous brain activity and self-control ability, we correlated TSC with the ALFF of each voxel in the brain with sex, age and FD as covariates. As shown in Table 2 and Figure 1, TSC was negatively related to ALFF in the left MFG, the PC and the precuneus, and positively related to the right IFG and the left AI.

The rsFC analysis employed the activation peaks in the ALFF as seed regions, with connectivity changes being calculated between all pairs of seed regions in whole-brain patterns. As shown in Table 3 and Figure 2, TSC was positively associated with FCs between the right IFG and the right PC (the red nodes and edge); the left PC and the inferior occipital gyrus (the yellow nodes and edge); the left precuneus and the middle temporal gyrus (the blue nodes and edges). With the left AI as

Table 3. RsFC among brain regions were associated with TSC

| Seed region | Target region | Cluster size | BA | MNI coordinates | | | |
				x	y	z	R
	Correlation with rsFC						
IFG (R)	PC (R)	797	30/31	18	−81	9	0.214
PC (L)	Inferior occipital gyrus (L)	219	18/19	−27	−78	15	0.199
AI (L)	PC (R)	379	30/31	15	−60	0	0.220
	Insula (R)	351	13	45	9	−6	0.203
	PC (L)	174	30/31	−15	−48	−3	0.196
	Supramarginal gyrus (R)	208	40	57	−27	27	0.198
	MFG (L)	275	10	−3	60	30	−0.189
	Angular gyrus (L)	124	39	−36	−51	30	−0.201
	Supplementary motor area (R)	140	6	9	3	51	0.215
Precuneus (L)	Middle temporal gyrus (L)	164	21	−45	−3	−15	0.219
	Middle cingulate gyrus (L)	129	24/31	−15	−33	39	−0.248
	Precuneus (R)	136	7	18	−39	45	−0.221

Note: The threshold for significant regions was set at $P < 0.05$ at the cluster level, combined with $P < 0.005$ at the voxel level (GRF approach; FC analysis: cluster size ≥ 100 voxels).
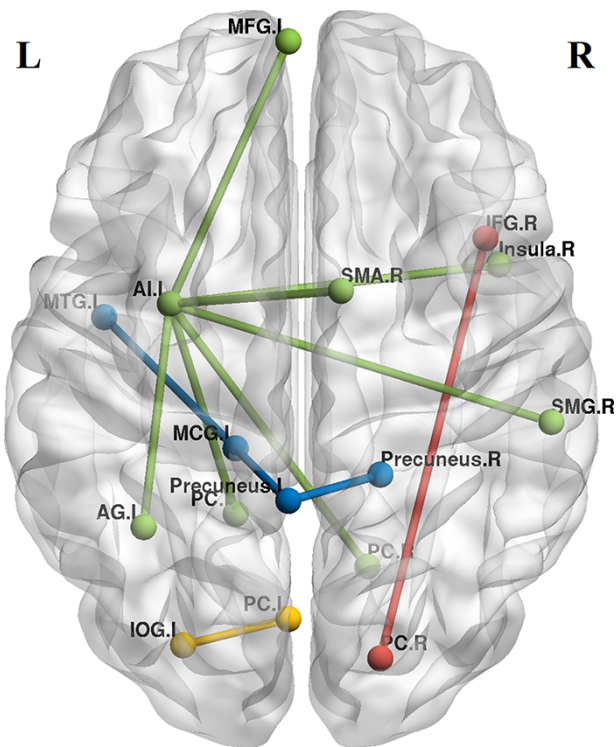R, right; L, left.

Fig. 2. Resting-state FCs among brain regions were associated with TSC with sex, age and FD as covariates.

the seed region, decreased FC with the left MFG and the angular gyrus, and increased FCs with the bilateral PC, the insula, the supramarginal gyrus and the supplementary motor area (the green nodes and edges), were found to be significantly associated with TSC. In addition, FCs of the left precuneus with the middle cingulate gyrus and the right precuneus (the blue nodes and edges) were found to be negatively related to TSC.

Mediation results

To examine whether TSC could mediate the influence of the ALFF and rsFC at the baseline time point on EWB (T1) and negative affect (T2), we conducted mediation analysis. As depicted in Figure 3, the effect of ALFF in the right IFG and the left precuneus on EWB was totally mediated by TSC. Indirect path was found from the IFG (indirect effect = 0.08, SE = 0.02) and the precuneus (indirect effect = −0.07, SE = 0.02) to EWB through TSC.

As shown in the top part of Figure 4, the effect of FC between the right AI and the bilateral PC on EWB was totally mediated by TSC. Indirect path was found from FC of the AI and the right PC (indirect effect = 0.07, SE = 0.02) and the left PC (indirect effect = 0.06, SE = 0.02) to EWB through TSC. As shown in the upper part of Figure 4, TSC totally mediated the effect of FC of the right AI with the right MFG and the left angular gyrus on EWB was totally mediated by TSC. Indirect path was found from FC of AI-MFG (indirect effect = −0.07, SE = 0.02) and AI-angular gyrus (indirect effect = −0.07, SE = 0.02) to EWB through TSC.

Moreover, as shown in Figure 5, TSC totally mediated the effect of ALFF in the right IFG and the left MFG on negative affect in the pandemic. Indirect path was found from the IFG (indirect effect = −0.06, SE = 0.02) and the MFG (indirect effect = 0.05, SE = 0.01) to negative affect through TSC. However, there is no significant effect of FCs on negative affect during the pandemic. These results suggested that resting activity and connectivity among different brain areas and network could affect adolescents' EWB and predict their negative emotion in the pandemic through self-control capacity.

Discussion

The present study utilized the rsfMRI method to examine the brain correlates underlying adolescents' self-control capacity and revealed the association among brain activity and connectivity, TSC and emotional wellness. Results showed that higher levels of TSC were associated with increased ALFF in the
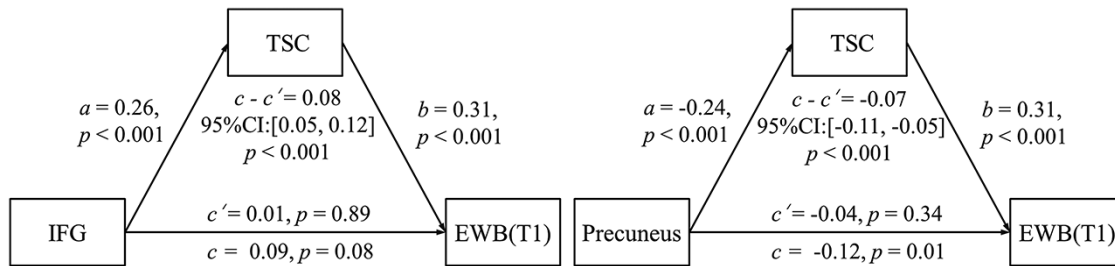
Fig. 3. The mediation models in the association between ALFF in different brain regions and EWB.
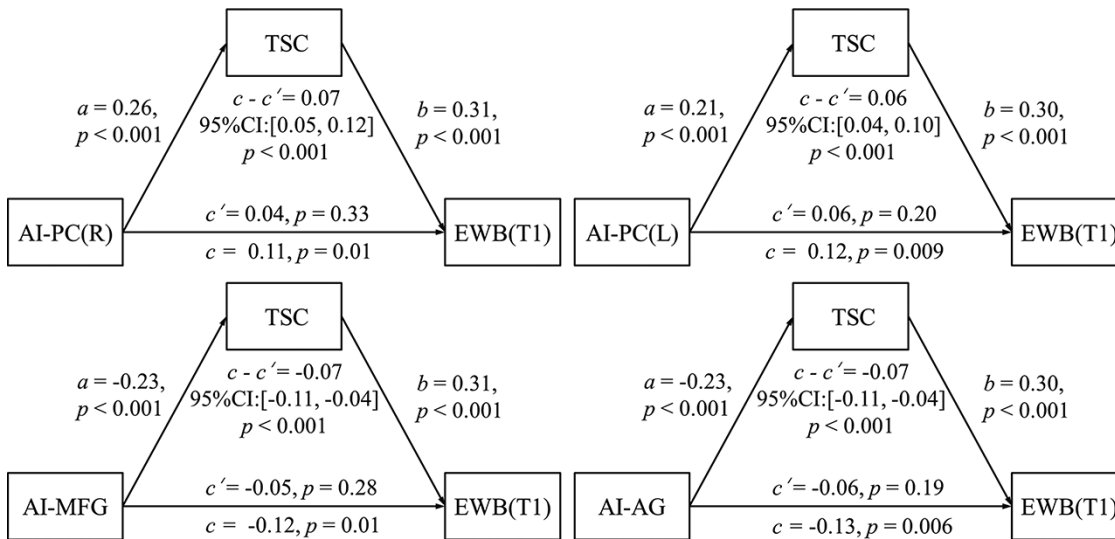

Fig. 4. The mediation models in the association between rsFC among different brain regions and EWB.
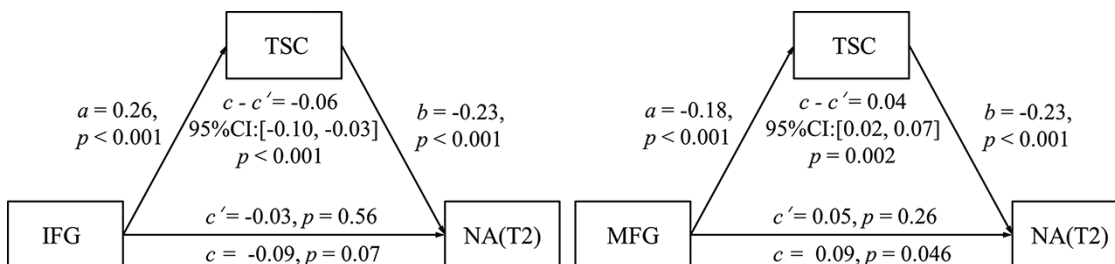

Fig. 5. The mediation models in the association between ALFF in different brain regions and negative affect in the pandemic. NA, negative affect; T2 = Time 2, February, 2020.

right IFG of the ECN and the left AI of the SN, and associated with decreased ALFF in the left MFG, PC and precuneus within the DMN. RSFC results showed that TSC could be reflected by the coordination (e.g. FC of IFG-PC) and segregation (e.g. FC of AI-MFG) among different brain networks. Behaviorally, TSC was found to be positively correlated with EWB and negatively correlated with negative affect in the COVID-19 pandemic. Furthermore, mediation analysis indicated that TSC totally mediated the links from the ALFF in the IFG and the precuneus, FC of the AI and regions (e.g. bilateral PC, MFG) within DMN, to EWB. Additionally, ALFF in the IFG and the MFG could predict negative affect in the pandemic through TSC. These findings suggest that TSC could be reflected by several regions and functional organizations within and between different brain networks and plays a

mediating role in the association between neural correlates and emotional wellness in adolescence even in the stressful event.

The present finding revealed that high TSC was associated with enhanced ALFF in the right IFG of the ECN. This positive association fits well with the existing studies that have indicated the IFG in the lateral prefrontal network has been implicated in tasks requiring executive control, goal maintenance, emotional regulation, and inhibiting prepotent response and inappropriate thoughts (Levy and Wagner, 2011; Grecucci et al., 2013; Aron et al., 2014). Evidence also indicates that depletion of self-control resources could weaken the IFG function, leading to failed control task execution (Friese et al., 2013). Moreover, TSC was positively associated with increased ALFF in the left AI of the SN. Studies have demonstrated that the AI acts the key

hub of receiving and integrating cognitive and affective information from multiple modalities and domains (Kelly *et al.*, 2012; Chang *et al.*, 2013; Uddin, 2015), which greatly determined one's global cognitive ability (e.g. encoding, integrating, switching and controlling) (Sridharan *et al.*, 2008; Menon and Uddin, 2010; Cocchi *et al.*, 2013). Researchers suggest that the AI not only is associated with integration function but also serves as a bottleneck limiting the capacity of cognitive control (Wu *et al.*, 2019). Evidence shows that lesions of the AI impair the capacity of cognitive control (Power *et al.*, 2013; Gratton *et al.*, 2018; Wu *et al.*, 2019).

Additionally, the negative associations between TSC and ALFF in the MFG, the PC and the precuneus within the DMN were in accordance with previous resting-state neuroimaging studies of personality neuroscience. Specifically, the activity of regions (MFG, PC and precuneus) in the DMN were positively associated with personality dimension (i.e. agreeableness) characterized by social cognition but negatively associated with self-regulation process (i.e. conscientiousness) (Deyoung *et al.*, 2010; Sampaio *et al.*, 2014). Moreover, the DMN was proposed to support computations for self-referential information, which seems to contrast with externally oriented, goal-directed cognitive processing (Amft *et al.*, 2015; Raichle, 2015; Davey *et al.*, 2016). Task-related suppression of the DMN in the inhibition task has been linked to the efficiency of cognitive-demanding and goal-directed cognition (Bonnelle *et al.*, 2012; Ma *et al.*, 2018). Thus, it suggests that the inhibited DMN appears to be a vital mechanism through which the brain suppresses goal-irrelevant functions (e.g. mind-wandering) to optimize externally goal-directed cognitive control (Anticevic *et al.*, 2012). Generally, these results may indicate that individuals with high level of self-control ability tend to immerse themselves in enduringly initiating and adhering to long-term goal-directed thoughts and behaviors and show a low tendency to be influenced by emotional stimuli and social information.

Examination of the organization of large-scale brain networks brain could also provide insights into self-control ability (Krönke *et al.*, 2020). RSFC results in the present study showed that TSC was positively associated with increased FCs between the AI of the SN and regions within the DMN (e.g. bilateral PC) and the ECN (e.g. supramarginal gyrus) and negatively associated with decreased FCs between the AI and regions within the DMN (e.g. MFG, angular gyrus). The AI has been identified as a network hub during resting state plays the role of receiving and integrating cognitive and affective information from multiple modalities and domains (Kelly *et al.*, 2012; Uddin, 2015) and plays a critical role in support dynamic switching and coordinating among different brain networks (e.g. ECN, DMN) to facilitate the access of task-relevant and salient information (Sridharan *et al.*, 2008; Menon and Uddin, 2010; Cocchi *et al.*, 2013). Previous studies indicated that inefficient information processing capacity in such a brain hub should significantly impair the network global communication (Power *et al.*, 2013; Gratton *et al.*, 2018; Wu *et al.*, 2019). Consistent with the existing findings, our results suggest that individual self-control capacity might greatly depend on the functional connectivity strength between the AI and large-scale brain network.

Neuroimaging studies have shown that well-being is involved in multiple regions and connectivity associated with integrating function (e.g. SN), cognitive control (e.g. ECN) and socioemotional processing (e.g. DMN) (Pe *et al.*, 2013; Kong *et al.*, 2015; Luo *et al.*, 2017; Shi *et al.*, 2018; King, 2019). In line with the exiting findings, our mediation models revealed that

through TSC, the IFG within the ECN could positively affect EWB and negatively predict negative affect in the pandemic, while the precuneus within the DMN could negatively affect EWB and the MFG positively predict negative affect in the pandemic. Studies indicate that the greater activity of regions (e.g. PC, precuneus and MFG) in the DMN might be implicated in maladaptive self-referential processing and excessively negative self-focus (e.g. self-rumination and depression) (Grimm *et al.*, 2009; Whitfield-Gabrieli and Ford, 2012; Ho *et al.*, 2015; Luo *et al.*, 2017). Furthermore, EWB was found to be associated with FCs between the SN and the DMN, to be specific, the increased FCs between the AI and the bilateral PC and decreased FCs between the AI and the MFG, the angular gyrus. Study has shown that the AI is a critical node for suppressing DMN activity and reallocating attentional resources to salient events (Sridharan *et al.*, 2008; Craig, 2009; Menon and Uddin, 2010; Uddin, 2015). Studies also indicate that higher levels of well-being experience may be related to more-efficient information transfer between networks (Dennis *et al.*, 2011; Shi *et al.*, 2018). It suggests that the functional integration and segregation organization between the AI within the SN and regions within the DMN (bilateral PC, MFG and angular gyrus) are crucial not only for achieving self-regulation but also for promoting EWB.

The present findings support the dual-system model that self-control ability was positively associated with the ALFF in the regions implicating in cognitive control (e.g. IFG), integration and regulation (e.g. AI) and negatively associated with the ALFF in the regions implicating in socioemotional function (e.g. MFG, PC). Meanwhile, in exploring the relationship between self-control and well-being outcomes, the existing evidence are mainly derived from behaviorally cross-sectional study. The present study provided initial neural evidence and further established the casual relationship with longitudinal evidence. The limitations in the present study also should be acknowledged. First, the participants were recruited from a relatively homogenous sample (a narrow range of age from 17 to 20) of healthy Chinese young adults, which may limit the generalizability of our findings. Second, measurement limitations include using brief self-report measures to assess trait-related constructs, which were vulnerable to subjectivity. Multiple measurements with ecological validity, such as third-party report, daily study and experience sampling methods should be considered in a variety of sample (e.g. different ages, subclinical and clinical groups) in future research. Finally, only negative affect was included in the second wave, which can't comprehensively portray emotional health in the pandemic.

The current study investigated the resting state neural correlates of self-control ability and reveal whether TSC mediated the relationship between the neural correlates and EWB. Specifically, higher TSC was associated with increased ALFF in region of the ECN (e.g. IFG) and the SN (e.g. AI), and associated with decreased ALFF in regions of the DMN (e.g. MFG, PC). TSC was also linked with the integration and segregation among different brain networks. Moreover, TSC totally mediated the links from the ALFF in the IFG and the precuneus, FC of the AI and regions (e.g. bilateral PC, MFG) within the DMN, to EWB. Additionally, ALFF in the IFG and the MFG could predict negative affect in the pandemic through TSC. Our finding provides initial evidence that TSC could be reflected by several regions and functional organizations within and between different brain networks, and further reveal a potential indirect effect of TSC on the association between neural correlates and emotional wellness in late adolescence.

Compliance of ethical standard statement

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. All study participants provided informed consent, and the study design was approved by the appropriate ethics review board.

Conflict of interest

There are no conflicts of interest to declare.

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