

Altered default-mode and frontal-parietal network pattern underlie adaptiveness of emotion regulation flexibility following task-switch training

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Abstract

Emotion regulation flexibility (ERF) refers to one's ability to respond flexibly in complex environments. Adaptiveness of ERF has been associated with cognitive flexibility, which can be improved by task-switching training. However, the impact of task-switching training on ERF and its underlying neural mechanisms remain unclear. To address this issue, we examined the effects of training on individuals' adaptiveness of ERF by assessing altered brain network patterns. Two groups of participants completed behavioral experiments and resting-state fMRI before and after training. Behavioral results showed higher adaptiveness scores and network analysis observed a higher number of connectivity edges, in the training group compared to the control group. Moreover, we found decreased connectivity strength within the default mode network (DMN) and increased connectivity strength within the frontoparietal network (FPN) in the training group. Furthermore, the task-switch training also led to decreased DMN–FPN interconnectivity, which was significantly correlated to increased adaptiveness of ERF scores. These findings suggest that the adaptiveness of ERF can be supported by altered patterns with the brain network through task-switch training, especially the increased network segregation between the DMN and FPN.

Keywords: emotion regulation flexibility; adaptiveness; task-switch; DMN; FPN

Introduction

Flexible responses in emotion regulation support and maintain individuals' heightened work efficacy, improved quality of life, and enhanced psychological well-being. In recent years, the theory of emotion regulation flexibility (ERF) proposed the adaptiveness of ERF to depict an individual's ability to respond flexibly to changing situations and goals, which is an important function of human survival and socialization development (Bonanno and Burton 2013, Aldao et al. 2015, Nardelli 2023). Adaptiveness of ERF refers to one's capacity to achieve different goals during emotion regulation and is believed to support individuals in adapting to complex living situations (Aldao et al. 2015, Kashdan et al. 2020). Conversely, a person's decreased adaptiveness of ERF serves as a significant risk for the onset and progression of mood disorders, such as depression and anxiety (Gross and Jazaieri 2014, McKone and Silk 2022). Therefore, it is important to improve the adaptiveness of ERF and clarify the underlying mechanisms to help people with mood disorders adapt to real life.

Previous theories and research suggested that enhancing individuals' task-switching abilities may be a potential way to improve individuals' adaptiveness of ERF (Meiran 2010, Ravizza and Salo 2014, Pruessner et al. 2020). Previous studies found that inflexible patterns of emotion regulation are often associated with poorer task-switching performance. For instance, experimental studies observed that individuals with lower levels of task-switching waste more cognitive resources in processing emotional information, leading to less effectiveness in emotion regulation (Genet and Siemer 2011, Sperduti et al. 2017). Other studies also indicated that the rumination pattern in depressed patients is considered a maladaptive form of emotion regulation, which is closely related to the individual's weak task-switching ability (Whitmer and Gotlib 2012, Chen et al. 2016). Moreover, situations and goals, as two crucial factors influencing the adaptiveness of ERF, have been found to be linked to individuals' task-switching abilities. For example, several studies found individuals with low task-switching ability are more likely to feel stress and experience

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anxiety in changing situations, which reduces people's behavioral performance and emotional experience (Levy et al. 2012, Edwards et al. 2015). In addition, researchers also found that task-switching difficulties interfere with the goal-pursuit process and prevent people from monitoring their ongoing tasks and outcomes, which finally leads to a disrupted sense of control and increased helplessness, as well as negative emotions (Plessow et al. 2011, Toh and Yang 2023). These studies suggested the potential possibility of task-switching training to improve individuals' emotion regulation processes.

On the other hand, the adaptiveness of ERF deemed to be "hot" executive functions may benefit from task-switching training, which has been demonstrated to be useful in enhancing individuals' "cold" executive functions (Ho et al. 2018, Wang et al. 2019, Zelazo 2020). For example, experimental studies suggested that task-shifting training is an appropriate approach to facilitate individuals' selective attention and working memory, which may be the underlying cognitive functions needed to cope with changing situations and goals (Zinke et al. 2012, Pereg et al. 2013). Furthermore, recent studies indicated that deficits in task-switching may disrupt individuals' understanding of the emotional information around them, which causes inflexible emotion regulation and maladaptive emotional consequences (Twivy et al. 2021, Ng et al. 2023). Additionally, evidence from cognitive neuroscience also suggested that lower task-switching ability is associated with lower brain network dynamics and complexity (Liu et al. 2021b, Ye et al. 2023), while higher task-switching ability can enable individuals to inhibit the hyperactivation of their prefrontal cortex during emotional tasks, thereby effectively alleviating the cognitive resource strain in emotion regulation processes (Piguet et al. 2016, Zaehring et al. 2018). These findings provided indirect behavioral and imaging evidence of the association between task-switching and flexible emotion regulation. Taken together, it is reasonable to improve one's adaptiveness of ERF by training task-switching abilities.

Accumulating evidence have suggested that cognitive training programs of task-switching may provide individuals with multiple behavioral benefits that are accompanied by alterations in neural activity, which are generally observed as significantly altered clusters or functional connectivity within regions of the default mode network (DMN) and frontoparietal network (FPN) (Smith et al. 2018, Yin et al. 2018). Prior studies indicated that cognitive control processes entailed in ERF have been associated with frontal lobe networks and nodes within both the DMN and FPN. Specifically, the DMN is associated with emotional processing, self-referential mental activity, the recollection of prior experiences, and rumination (Sheline et al. 2009, Marchetti et al. 2012). Several studies have shown altered resting-state FC between the MPFC and medial temporal lobe in the DMN after cognitive training, as well as concomitant improvements in the performance of emotion regulation (Dolcos et al. 2021, Li et al. 2022). Moreover, recent neuroimaging studies of cognitive training effects have pointed to the FPN as a primary mechanism of adaptive change (Cole et al. 2013, Cocuzza et al. 2020). The flexible hub theory posits that the FPN is both highly flexible and rapidly shifts cognitive engagement to exert emotion regulation across a wide variety of challenges (e.g. novel stimuli, situational information, and goal-pursuit tasks) (Zanto and Gazzaley 2013). These findings of cognitive neuroscience suggested that the adaptiveness of ERF may benefit from the contributions of DMN and FPN after cognitive training.

However, little is known about the promoting effect of task-switching training on adaptiveness of ERF as well as underlying

neural mechanisms. Many studies showed that poor emotion regulation performance (i.e. during event-related fMRI) is associated with a failure to restrain hyperactivation of the DMN, while inefficient organization of the FPN (Whitfield-Gabrieli and Ford 2012, Brzezicka 2013, Bartova et al. 2015). Moreover, a recent review emphasized increases in the anti-correlation between task-negative (i.e. DMN) and task-positive networks (FPN) after cognitive training, which showed an enhanced degree of network segregation (van Balkom et al. 2020). Besides, several studies found that enhanced segregation of the DMN and FPN supports better cognitive functioning in goal-driven behavior and flexible emotion regulation in changing situations (Mohr et al. 2016, Liu et al. 2021a). Taken together, the neural correlation of DMN and FPN may play a role in balancing the neurological resources related to task-switching, allowing individuals to cope with different situations and goals flexibly. Given coping with situations and goals is a fundamental mechanism for the adaptiveness of ERF, we hypothesized that task-switching training can promote individuals' adaptiveness of ERF by enhancing the degree of network segregation between DMN and FPN.

The purpose of this study is to explore the effects and neural mechanisms of cognitive training on the adaptiveness of ERF by using resting-state fMRI. We investigated whether brain network pattern is altered in DMN and FPN by task-switching training and, if so, whether intrinsic pattern changes in networks "at rest" are associated with any improvements in the adaptiveness of ERF. In this study, participants performed a 14-day task-switching training and completed resting-state fMRI scanning before and after training. We then used resting-state fMRI data to reconstruct participants' neural network activity within the whole brain before and after training. Examining correlations in brain networks allowed us to investigate whether task-switching training had any effect on neurophysiological activities between DMN and FPN areas typically recruited for emotion regulation and how these changes relate to gains in adaptiveness of ERF measured outside the scanner.

Materials and methods

Participants

A total of 100 participants between 19 and 28 years [mean = 23.75 years (SD = 2.72); 53 females] were recruited via local schools. All participants had normal or corrected-to-normal vision, and they were randomly allocated to either the training or control group. Seven participants failed to complete the training and did not return for the second session, so the subsequent analysis was performed on the datasets from the remaining 93 participants, 47 of whom had been allocated to the training group [mean = 23.79 years (SD = 2.84); 25 female] and 46 to the control group [mean = 24 years (SD = 2.56); 22 female]. At baseline, the two groups were measured in emotion regulation-related possible control variables such as ER strategies and personality factors, and two-sample t-tests were applied to investigate the differences in cognition measurements at baseline between the two groups. All participants provided written informed consent to procedures approved by the local Ethics Committee of the Southwest University.

Behavioral assessment

Before and after training, we assessed each participant's adaptiveness scores using an adapted ERF task that was employed in prior behavioral study (Gao et al. 2024), and the experimental design is shown in Fig. 1. In each trial, participants were presented with

different goals (“open square” or “open triangle”) at the top of each picture (“fear” or “disgust”) and were asked to complete regulation or memory task according to the goal (Fig. 1a). Following each image presentation, participants rated their affective state on a 9-point Self-Assessment Scale (1 = Very good, 5 = No feelings, 9 = Very bad). We distinguished two situation conditions in the experiment: (I) congruent emotional stimuli in adjacent trials were identified as the conditions of situation repeat (CSR); (II) incongruent emotional stimuli in adjacent trials were identified as the conditions of situation change (CSC). The differences in emotion ratings between negative and neutral pictures were used to measure the achievement of emotion regulation goals in two conditions. After 30 min, participants need to finish a picture retrieval task by assessing their familiarity with pictures on a 9-point Scale (1 = Very unfamiliar, 5 = Uncertain, 9 = Very familiar), which was used to measure memory ratings to quantify the achievement of non-emotion regulation goals in two conditions. In this experiment, we recorded participants’ actual performance as T scores including emotion rating and memory rating under different goals, which reflect the achievement of different goals for each condition (Fig. 1b).

Following each run, participants were asked to assess their efforts to regulate emotions or remember pictures under different goals, recorded as w by using a percentage scale. Specifically, participants need to move the cursor to allocate their effort within two goals. For example, if a participant moved the cursor position as shown in Fig. 1b, the participant’s w ratings indicated the effort of memory under “open triangle” goal is 60%, and the effort of regulation under “open triangle” goal is 40%; while the effort of memory under “open square” goal is 30%, and the effort of regulation under “open square” goal is 70%. Moreover, $w * T$ assessed the level of adaptiveness for each goal, that is, individuals with higher $w * T$ scores reflected better performance with personal goal-driven behavior. Therefore, we used the formula: $Adaptiveness = \frac{\sum (w_1 * T_1 + \dots + w_n * T_n)}{n}$ to calculate the overall performance of both emotion regulation and non-regulation goals, which assessed the achieved outcomes of different goal-driven behaviors in this experiment (more details see in [Supplementary Materials](#)). To help the subjects understand the experimental operation, participants additionally practiced several trials on their own before taking part in the actual experimental task.

Procedure of training

Both groups performed the training at a laboratory and each participant’s progress was monitored by the research team. In the training group, we used a computerized self-adaption training program to guarantee adaptability to training difficulty by individually adjusting task difficulty to bring individuals to their cognitive behavioral performance maximum. Training tasks which were effectively used in previous studies of task switching were applied (Koch et al. 2018). On each training day, the participants were required to complete mixed-rule tasks three times (for a total daily test time of 30 min), difficulty of the task was increased when the accuracy rate exceeds 80%. Participants assigned to the control group completed an identical training program save for the fact that the tasks did not get frequent switching. The training program implemented for 14 days in both training and control group, and it ensured that the training duration is the same, 30 min per day.

MRI data acquisition and basic preprocessing

Whole-brain fMRI data were acquired on the Siemens Trio MRI scanner of 3 Tesla (Siemens Medical Department, Erlangen,

Germany) (Siemens MAGNETOM Prisma 3T). Preprocessing was performed using statistical parametric mapping (SPM12) tools (www.fil.ion.ucl.ac.uk) implemented in DPARSF (v5.3 <http://rfmri.org/DPARSF>) (Yan et al. 2016). Preprocessing comprised adjusting for variable acquisition time over slices (slice-timing), head motion correction (realignment). Two steps were adopted in this study to control for the effects of head motion on the signals. First, if frame wise displacement was found to be greater than 0.5, then that time point was deemed as a “bad” time point and the time points before and after that bad time point were scrubbed using each of the bad time points as a regressor (Power et al. 2012). Second, we calculated the mean FD for each participant and compared it between the two groups. The results of this analysis are as follows: training group with Mean FD (0.17 ± 0.09) and control group Mean FD (0.19 ± 0.08). The statistical comparison (using an independent samples t-test) revealed no significant difference in mean FD between the two groups. The subjects whose data satisfied our criteria for head motion, displacement of <3 mm in any plane and rotation of $<3^\circ$ in any direction were included in final analysis. We performed these steps by using DPARSF and no participants were excluded because of motion artifacts according to our criteria. A total of 106 subjects were entered into the final data analysis. Then, normalization was conducted by applying DPARSF, which leads to an improved registration between subjects (more details see in [Supplementary Materials](#)). In the current study, the nuisance signal (global signal, white matter, and cerebrospinal fluid) and the Friston 24-parameter model were regressed to reduce possible sources of artefacts. Finally, spatial smoothing was performed using an 8 mm Gaussian kernel to increase signal-to-noise ratio.

Functional network construction and analysis

In the current study, we used the Graph Theoretical Network Analysis (GRETNA) (Wang et al. 2015) toolbox (<https://www.nitrc.org/projects/gretna/>) to construct the brain network. The Power-264 atlas (Power et al. 2011), a high-resolution parcellation scheme based on the results of a large meta-analysis was selected to define the nodes (i.e. functional areas) in the brain network. This atlas includes 264 putative functional areas, and its robustness for network construction has been proved by many studies (Power et al. 2013, Lin et al. 2019). We first extracted the time series in each node by averaging the time series of all voxels in the same nodal areas. Then, we calculated the Pearson correlation coefficient between the time series of each possible node pair. Thus, a 264×264 functional correlation matrix was generated for each subject. To improve the normality of the correlation coefficient, a Fisher’s r -to- z transformation was applied to the correlation matrices. In accordance with prior studies (Zhao et al. 2017, Xiao et al. 2019), we applied a range of sparsity thresholds (range of 0.05–0.50 with an interval of 0.05) to ensure that the generated networks had sparse properties with the minimum number possible of spurious edges. This sparsity level was used for the whole-brain network visualization of altered functional connection patterns with two groups before and after task-switch training based on Power-264 atlases (A: control group, B: training group). For the ROI network analysis, we calculate the average connection strength using those significant edges that remain after statistical testing and correction (FDR, $P < .05$). Comparisons of brain network were made within participants before and after the training for both two groups, while age, gender, and personality factors were entered as co-variates of no interest.

Connectivity was assessed between regions of interest (ROIs), which were performed for structures in predetermined networks:

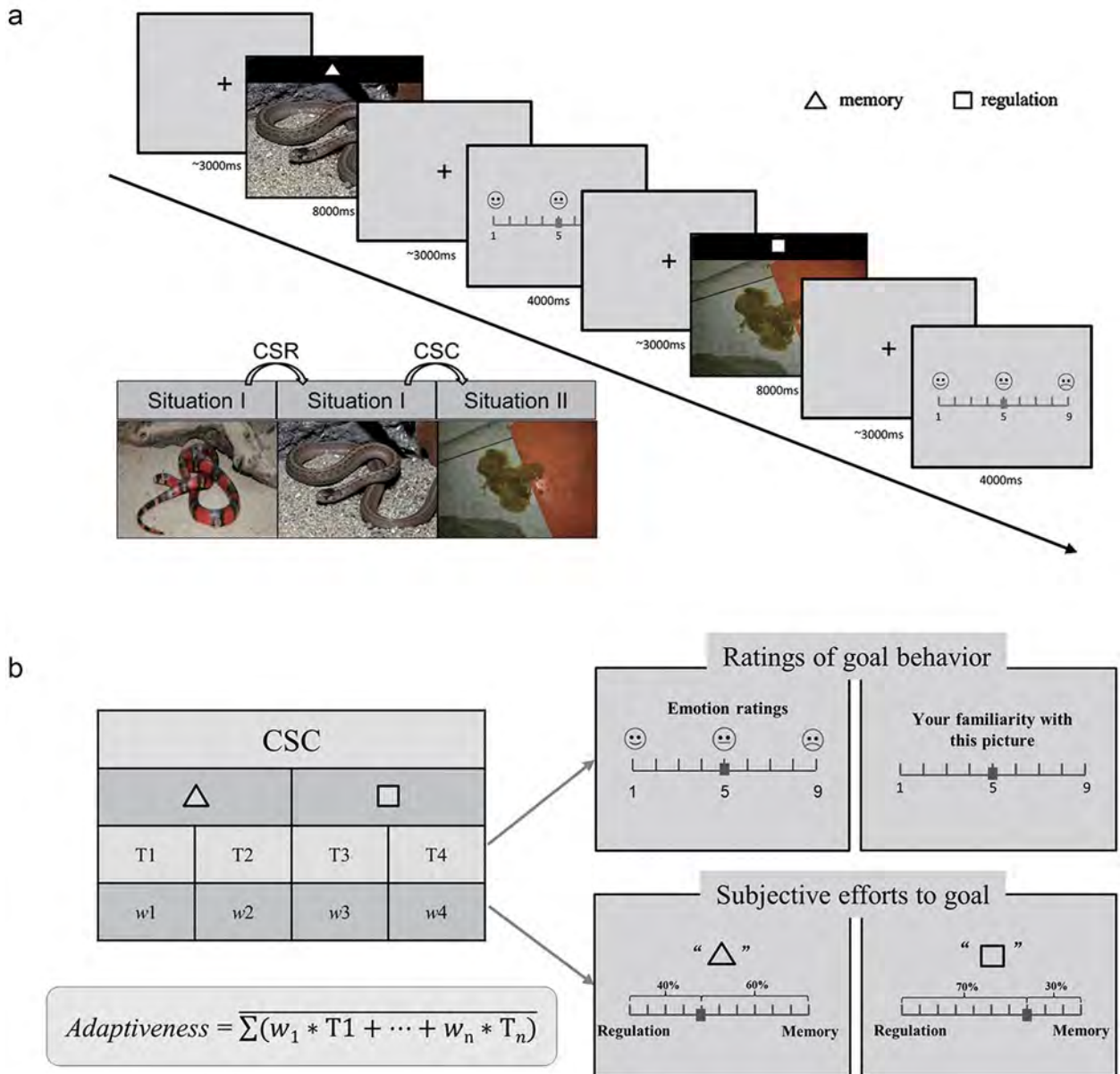


Figure 1. (a) Example trial sequence of the adaptiveness of ERF task and the experimental changing-situation conditions (CSR: congruent emotional stimuli in adjacent trials were identified as the conditions of situation repeat; CSC: incongruent emotional stimuli in adjacent trials were identified as the conditions of situation change). (b) The experimental changing-goal conditions and measurements of adaptiveness.

the default mode network primarily includes the medial prefrontal cortex (mPFC), posterior cingulate cortex, precuneus, and angular gyrus and is involved with self-referential processes; the frontoparietal network primarily includes the dorsolateral prefrontal cortex (dlPFC), and posterior parietal cortex (PPC) and is involved with executive functions and cognitive control (Wen et al. 2020, Menon and D’Esposito 2022). Connectivity analyses were conducted using a general linear model and output values included a *t*-stat with degrees of freedom, uncorrected *P*-value (*P*-unc), and a false discovery rate *P*-value (*P*-FDR) when corrected for multiple comparisons. A corrected *P*-value of < 0.05 was considered significant. Greater positive *T* scores indicated stronger functional connectivity between regions while greater negative scores indicated weaker functional connectivity between regions. Moreover, to explore brain-behavior relationships, we conducted

correlation analyses between adaptiveness score and connections within and between the DMN and FPN. Additionally, as the meaning of negative correlations in the functional network is still controversial, we included positive correlations for the statistical analysis of the functional connectivity used in the ROI network analyses.

Results

Demographic and behavioral measurements

A total of 47 subjects from the training group and 46 subjects from the control group underwent the adaptiveness of ERF task and the fMRI scanning. No significant differences in age, sex, personality traits, and the use of ER strategies were found at baseline between the training group and the control group (*P* > .05). Details of

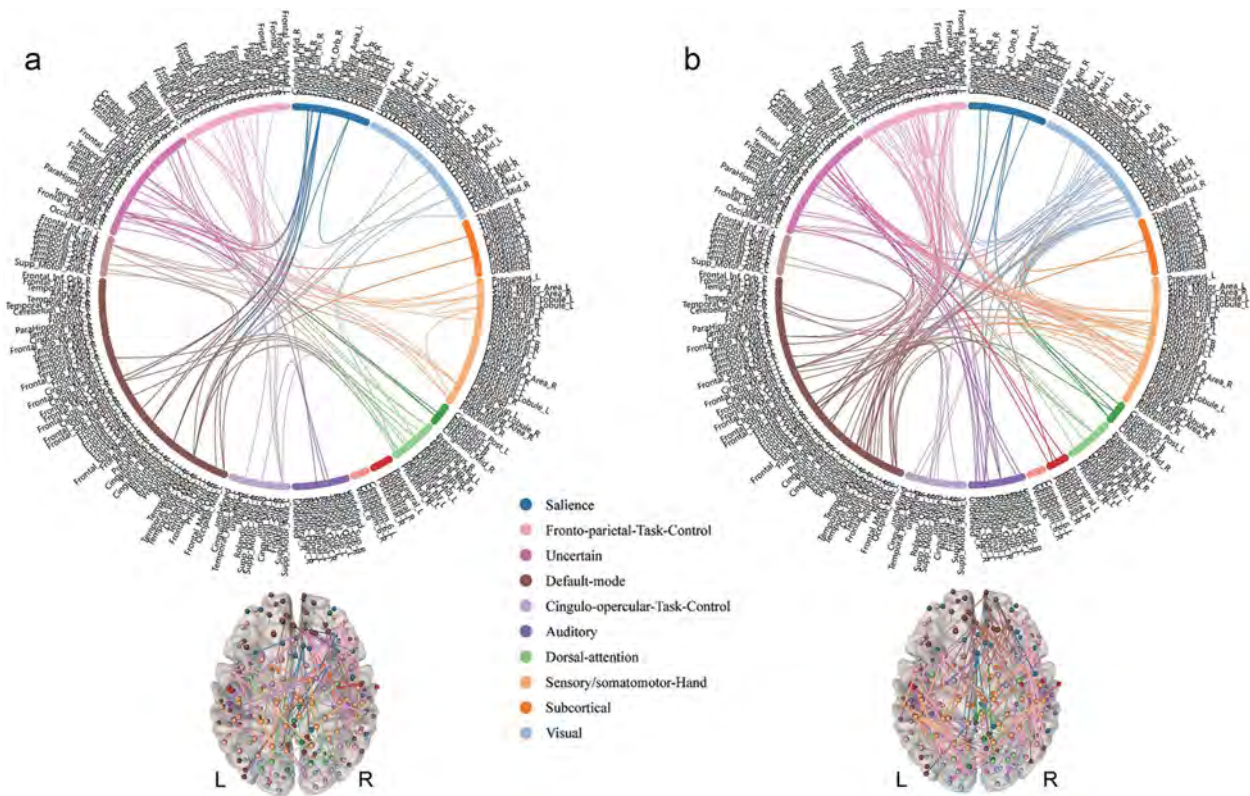


Figure 2. Visualization of altered functional connections patterns with two groups before and after task-switch training based on Power-264 atlases (a: control group, b: training group). In the given image, edges were classified and visualized using circle plots, in which nodes are grouped based on brain networks of Power-264 atlases. Different brain networks were represented by dots of the same color on the circumference of the big circle. The lines connecting of dots represent the connections between the corresponding brain network, including inter-network connections and intra-network connections.

demographic and behavioral data have been attached in [Supplementary Materials](#). Moreover, we conducted a 2 (group: training, control) \times 2 (time: pretraining, posttraining) mixed model ANOVA and found significant Group \times Time interaction in adaptiveness of ERF scores, $F(1, 91) = 26.14, P < .001, \eta^2 = 0.22$. Moreover, results of simple effects of time in each group indicated that the training group provided significantly greater adaptiveness scores at post-training than at pretraining, $t(46) = 8.22, P < .001, d = 3.02, 95\% \text{ CI}(2.28, 3.76)$, the control group did not differ in adaptiveness scores at pre- and post-training, $t(45) = 1.03, P = .307, d = 0.38, 95\% \text{ CI}(-.36, 1.11)$. These behavioral results indicated the effects of task-switch training and found a significant difference in adaptiveness of ERF between the two groups before and after training.

The effect of training on brain networks

The resting-state functional correlation matrix of Power-264 was altered between posttraining and pretraining in two groups. We found the whole-brain network connectivity was increased in both the control group (Fig. 2a) and the training group (Fig. 2b) after the training, including the DMN, FPN, cingulo-opercular network, salience network, and visual network. In addition, compared with the control group, more connectivity edges were found in the training group, which indicated that there were more changes in the whole-brain connectivity patterns after the training.

To evaluate the training effect on connectivity within and between the two ROI networks, we conducted a repeated analysis of variance (ANOVA) of 2 (between-subject factor: training and control groups) \times 2 (within-subject factor: baseline and after

training) was performed by extracting the mean functional connectivity strength. Post hoc comparisons were carried out for each significant interaction effect to clarify the effect of training on FC for each group. In this study, analysis was performed for the FCs that showed significant differences between the training and control groups at posttraining. The ANOVA revealed the significant Group \times Time interaction [$F(1, 91) = 21.53, P < .001, \eta^2 = 0.19$]. Moreover, results of simple effects of time in each group indicated that the training group showed a significantly decreased connectivity within the DMN at posttraining than at pretraining [$d = -0.04, P < .001, 95\% \text{ CI}(-.05, -0.03)$], the control group was not found significant differences at pre- and post-training [$d = -0.01, P = .093, 95\% \text{ CI}(-.02, 0.01)$] (Fig. 3a). We also found a significant Group \times Time interaction within the FPN [$F(1, 91) = 7.55, P = .007, \eta^2 = 0.08$] and the result of simple effects showed that the training group has a significantly increased connectivity within the FPN at posttraining than at pretraining [$d = 0.032, P < .001, 95\% \text{ CI}(0.02, 0.05)$], the control group did not found significant differences at pre- and posttraining [$d = 0.008, P = .293, 95\% \text{ CI}(-.01, 0.02)$] (Fig. 3b). In addition, our results also found significant interactions in training and control groups with the connections between the DMN and FPN [$F(1, 91) = 7.11, P = .009, \eta^2 = 0.07$]. Post hoc comparisons showed that connections between the DMN and FPN were decreased in the training group [$d = -0.061, P < .001, 95\% \text{ CI}(-.09, -0.03)$], while no significant alteration was found in control group [$d = -0.004, P = .784, 95\% \text{ CI}(-.03, 0.26)$] (Fig. 3c). These findings demonstrated that the training group had increased connectivity strength compared to controls between the DMN and FPN after task-switch training.

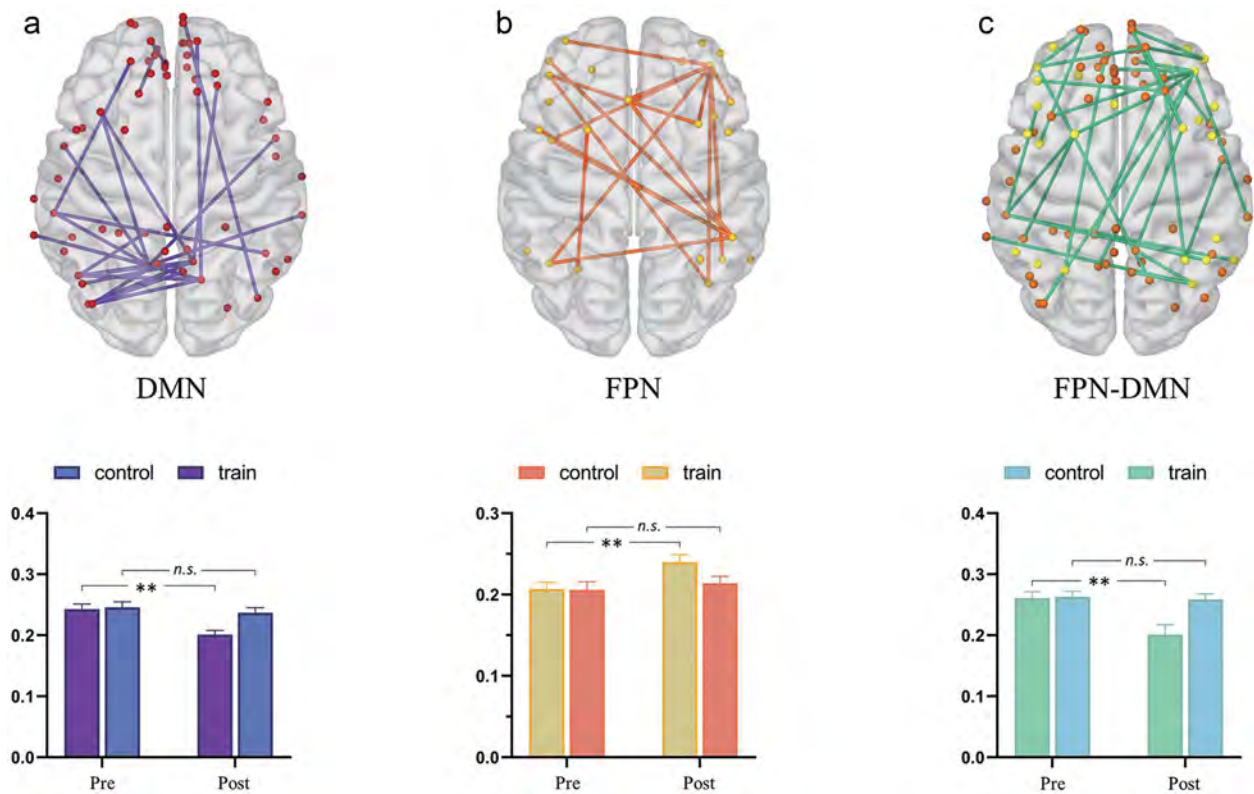


Figure 3. Significant interactions existed between the control and training group for the mean FC strength within DMN (a) and FPN (b), and the FC between FPN-DMN. Error bars indicate the SEM. Significant differences are marked with asterisks (* $P < .01$; ** $P < .001$).

Correlations of adaptiveness score with brain network measures

To explore the relationship between connections of brain networks and adaptiveness of ERF, z-transformed connectivity values were extracted from the DMN and FPN that showed significant training-related effects and the difference between the baseline and posttest was computed. Partial correlations were performed between the changes in resting-state FC and the pre- and post-training differences in the adaptiveness of ERF scores while controlling for age, gender, personality traits, and the use of ER strategies. The current result showed a significant relationship between the changes in connections (between the two fMRI sessions) and the improvements in adaptiveness of ERF scores ($r = -0.375, P = .009$). As shown in Fig. 4, we found that increased adaptiveness of ERF scores was significantly correlated to decreased FC of FPN and DMN in the training group (Fig. 3a). This result suggested the contribution of connections between the DMN and FPN to the adaptiveness of ERF by effective task-switch training. To correct for multiple comparisons in this study, we used Holm-Bonferroni multiple comparison for multiple testing ($\alpha = 0.05$, two-tailed) (Holm 1979).

Discussion

The current study combined rs-fMRI measurements with behavioral experiments to investigate how changing brain network patterns impact individuals' adaptiveness of ERF by task-switch training. Firstly, behavioral results showed the effects of training and found a significant difference in adaptiveness scores between the two groups. Moreover, the result of brain network

analysis indicated that the training group exhibited a higher number of connectivity edges in comparison to the control group, suggesting a greater extent of whole-brain pattern changes. In addition, compared with the control group, the training group showed not only significant alteration of connections within the DMN and FPN but also increased connections between the two networks were negatively correlated to the improvement of adaptiveness scores after task-switch training. Together, these findings suggest that adaptiveness of ERF can be supported by altered patterns with the brain network through task-switch training, especially the increased connectivity within and between the DMN and FPN.

In previous research, the task-switching paradigm was used as an effective training method to enhance individuals' cognitive flexibility, which refers to an individual's ability to adapt to switching between different tasks, flexibly adjust attention, and engage in goal-driven behaviors (Meiran 2010, Koch et al. 2018). Previous theoretical frameworks proposed that the functions of cognitive flexibility (inhibition, maintenance, or switching) can assist individuals in coping with changing situations and goals, which are considered important aspects in promoting emotional regulation flexibility (Pruessner et al. 2020, Toh and Yang 2023). Moreover, several studies put forward that emotion regulation is a motivated process associated with goal-driven behaviors in changing situations, which benefit from the ability to pursue—and achieve—different goals and support an essential aspect of one's ability to interact successfully with the environment (Boudreaux and Ozer 2013, Millgram et al. 2020). Besides, recent studies have shown that lower cognitive flexibility is associated with impaired switch function, while higher cognitive flexibility can increase individuals' subjective well-being by facilitating the achievement

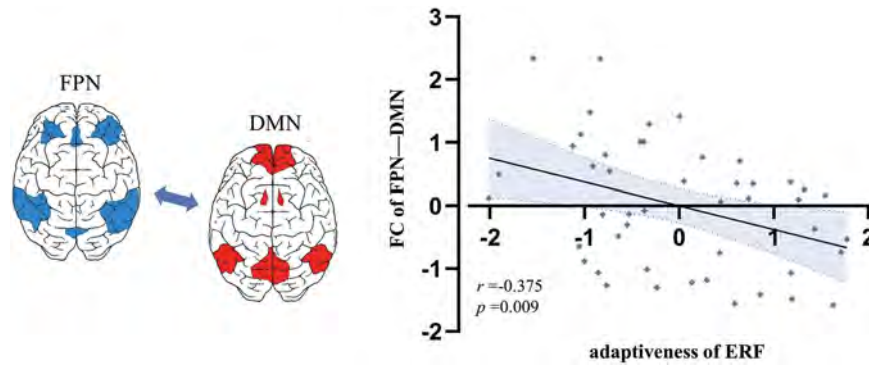


Figure 4. Scatter plots (with best-fitting regression lines) showing increased adaptiveness of ERF scores was significantly correlated to decreased FC of FPN and DMN in the training group (posttest score–pretest score).

of different goals (Thomsen 2016, Van Bost et al. 2022). Therefore, behavioral results demonstrated that the adaptiveness of ERF can be improved by enhancing cognitive flexibility.

The observed result of a higher number of connectivity edges in the training group could be attributed to the adaptive changes induced by the task-switch training. Firstly, task-switch training involves repeatedly engaging in tasks that require attentional control and goal-switching. This sustained practice likely leads to adaptive neuroplastic changes, such as functional network strengthening or reorganization, which enhance the connectivity between brain regions involved in these processes (Kelly and Garavan 2005, Demirakca et al. 2016). For example, several studies have demonstrated that cognitive control regions, such as the dlPFC, play a vital role in task switching and exhibit increased activation and connectivity following training (Erickson et al. 2007, Yin et al. 2018). Moreover, task-switch training may induce changes in functional connectivity by promoting the coordination and synchronization of neural activity across brain regions involved in cognitive flexibility (Cunillera et al. 2012, Rodríguez-Nieto et al. 2022). The repeated engagement in task-switching exercises may improve the efficiency of neural communication and information processing, as well as facilitate the efficient processing and integration of information across the brain network. For instance, research examining large-scale brain networks has revealed that individuals with higher cognitive control ability tend to exhibit higher global network efficiency, shorter path lengths, and increased modular organization within the whole-brain network, which may be associated with more robust and interconnected neural networks (Taya et al. 2015, Finc et al. 2017). Therefore, these changes in connectivity edges may involve the strengthening of existing connections and the formation of new connections, as well as the efficient processing and integration of information across the brain network that supports increased adaptiveness of ERF.

By comparing the mean connectivity strength of ROI networks between the training and control group, we identified contrasting patterns of altered connectivity in the DMN and FPN that have implications for understanding the neuroplastic processes in adaptiveness of ERF after the task-switch training. We observed a pattern of widespread hypoconnectivity across nodes of the DMN, especially the posterior cingulate cortex. The DMN is related to self-referential processing and is known to underlie the emotion dysregulation process (e.g. rumination), and it tends to be relatively suppressed during cognitive task execution (Smith et al. 2018, Yin et al. 2018). Task-switch training likely involves the suppression of internally focused cognition and introspection,

resulting in decreased functional connectivity within the DMN, especially involving the PCC, which is a key hub within the network (Sidlauskaite et al. 2016, Shaw et al. 2021). Moreover, we also observed a pattern of widespread hyperconnectivity within the FPN especially the dorsolateral prefrontal cortex after training. The FPN is typically activated during executive functions and its integrity is critical for the successful performance of planning goal-driven processes (Fassbender et al. 2006, Gulbinaite et al. 2014). The alteration pattern of connectivity within the FPN may reflect the neural adaptations associated with enhanced attentional control, cognitive flexibility, and goal-adaptiveness abilities after training (Woolgar et al. 2015, Lydon-Staley et al. 2019). Taken together, these findings suggest that task-switch training may facilitate increased adaptiveness through a shift away from self-referential processing and introspection towards externally focused cognitive processes, which benefit from different alterations in connectivity within the DMN and FPN respectively.

In addition to these results of connectivity within the brain network, we found a significant negative correlation between the adaptiveness and changed neural patterns with the interconnectivity of the DMN and FPN. Prior work suggests that FPN contributes to cognitive control by flexibly encoding goal-driven information, including task rules (e.g. stimulus-response mappings) and their relationship to expected behavioral outcomes (Brzezicka 2013, Parlatini et al. 2017). That is, rapid adjustments in the cognitive process may occur via flexible goal-relevant shifts in the FPN coupling patterns. In contrast, the DMN contributes to spontaneous cognition and introspective processes including mentalizing, autobiographical memory, as well as self-referential processing, which rarely involve widespread or excessive cognitive control involvement. Moreover, previous neuroimaging studies found that a failure of the FPN to effectively inhibit DMN activity may result in problems shifting cognitive resources away from internal thoughts to the external world (Cao et al. 2020, Dixon et al. 2022). In addition, an increased degree of segregation between the DMN and FPN was found after working memory training, which suggests that the altered interconnectivity of the DMN and FPN was relatively sensitive to cognitive training (Salmi et al. 2020, Lan et al. 2022). Therefore, the current result may reflect a higher adaptiveness of ERF benefit from increased segregation between the DMN and FPN through task-switch training. These findings suggested that the balance of activity in the FPN and DMN might control global metastability to brain networks, providing a mechanistic explanation of how cognitive resources are allocated and modulated across different task states.

There are some limitations to our study. First, although our study demonstrated the improved adaptiveness of ERF in subclinical depressive populations through task-switch training, future work needs to investigate whether these training effects can alleviate depressive symptoms in clinical samples. Second, the current study acknowledges the limitation associated with using a single measure to assess cognitive flexibility. A comprehensive measurement of cognitive flexibility should be used in future studies to confirm the validity and reliability of our findings. Third, we only calculated basic average functional connectivity strength as a brain network indicator, future studies should employ more specific graph theory metrics to compare the complex characteristics of different brain networks, as well as to determine if there are closer associations between the adaptiveness of ERF and other brain network indicators. Finally, we were not able to address whether the alteration in functional brain connectivity or the cognitive gains were maintained at a distant time point from the immediate training period, longitudinal work should be included in future studies to explore the persistent training effects.

Conclusion

In this study, we assessed the altered patterns of brain functional networks associated with increased adaptiveness of ERF after task-switch training. We found altered patterns of widespread hypoconnectivity within the DMN and hyperconnectivity within the FPN, which highlighted that task-switch training may facilitate increased adaptiveness of ERF through a shift away from self-referential processing and introspection towards externally focused cognitive processes. Furthermore, decreased interconnectivity of the DMN and FPN was negatively correlated with increased adaptiveness in ERF, which suggests that the segregation between the DMN and FPN contributes to shifting cognitive resources and controlling global metastability, as well as finally improving individuals' adaptiveness to the complex environment. In sum, these findings shed light on altered patterns of the DMN and FPN functional connectivity underlying the improved adaptiveness of ERF, which have potential implications for the remission of mood disorder.

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Supplementary data

Supplementary data is available at SCAN online.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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