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Resting-state networks predict individual differences in common and specific aspects of executive function

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ABSTRACT

The goal of the present study was to examine relationships between individual differences in resting state functional connectivity as ascertained by fMRI (rs-fcMRI) and performance on tasks of executive function (EF), broadly defined as the ability to regulate thoughts and actions. Unlike most previous research that focused on the relationship between rs-fcMRI and a single behavioral measure of EF, in the current study we examined the relationship of rs-fcMRI with individual differences in subcomponents of EF. Ninety-one adults completed a resting state fMRI scan and three separate EF tasks outside the magnet: inhibition of prepotent responses, task set shifting, and working memory updating. From these three measures, we derived estimates of common aspects of EF, as well as abilities specific to working memory updating and task shifting. Using Independent Components Analysis (ICA), we identified across the group of participants several networks of regions (Resting State Networks, RSNs) with temporally correlated time courses. We then used dual regression to explore how these RSNs covaried with individual differences in EF. Dual regression revealed that increased higher common EF was associated with connectivity of a) frontal pole with an attentional RSN, and b) Crus I and II of the cerebellum with the right frontoparietal RSN. Moreover, higher shifting-specific abilities were associated with increased connectivity of angular gyrus with a ventral attention RSN. The results of the current study suggest that the organization of the brain at rest may have important implications for individual differences in EF, and that individuals higher in EF may have expanded resting state networks as compared to individuals with lower EF.

Introduction

When individuals are not engaged in an experimentally-directed task (i.e., are in a “resting state”), distinct networks of widely separated brain regions can be identified as sharing similar temporal patterns of functional activity (Fox and Raichle, 2007) — a phenomenon often referred to as “resting state functional connectivity MRI” (rs-fcMRI). These “resting state networks” [RSNs] show strong correspondence with regions that tend to co-activate during performance of a class of tasks (e.g., language processing tasks; Smith et al., 2009). Moreover, the organization of such networks has been found to have behavioral and clinical relevance. A large body of literature indicates that RSNs are altered across a plethora of neurological and clinical populations, including Alzheimer's disease, schizophrenia, depression, attention deficit hyperactivity disorder, and others (for reviews see Greicius, 2008; Zhang and Raichle, 2010).

More recently, research has focused on how individual differences in abilities among neurologically normal individuals are related to the organization and extent of networks identified by rs-fcMRI. For example, patterns of rs-MRI are associated with fluid intelligence (Cole et al., 2012), attentional vigilance (Thompson et al., 2012), performance on the trail making test (Seeley et al., 2007), working memory (Hampson et al., 2006; Gordon et al., 2012), and the ability to maintain attentional control in the face of distracting information (Kelly et al., 2008). In general, however, there is a paucity of studies that examine the relationship between rs-fcMRI and individual differences in executive function (EF), the ability to engage in and guide goal-oriented behavior. Because EF is a broad umbrella term that encompasses a wide variety of specific functions and component processes (Miyake et al., 2000), our approach in the current study is to examine the relationship between RSNs and individual differences in both general and specific subcomponents of EF in a large sample of participants. Moreover, we take a novel approach of investigating this issue by embedding our research within the framework

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of a prominent and well-grounded theoretical model of EF, known as the unity and diversity model (for a review, see Miyake and Friedman, 2012). This model, based on intercorrelated patterns of performance across individuals on multiple measures of EF, suggests that many important aspects of EF can be reduced into at least three latent factors. The first is a common EF factor, representing the *unity* aspect of the model, on which all measured EF tasks load. This factor is thought to represent the general capacity to maintain a task goal, or "attentional set," and is thought to be a common feature of all EF tasks. The second two orthogonal factors represent the diversity aspect of the model and are more specific processes above and beyond common EF. Statistically speaking, these factors are residuals of the EF abilities once common EF has been taken into account. One factor, the shifting-specific factor, captures processes relating to flexibly shifting between different task or mental sets, while the other factor, the updating-specific factor, indexes the process of rapidly adding or deleting information from the contents of working memory.

Theoretical considerations, computational modeling, and empirical research by our group and others suggest that these three EF factors are likely to be supported by overlapping yet somewhat distinct brain systems (Miyake and Friedman, 2012; Herd et al., 2013). The ability to stably maintain a task goal is thought to rely on areas of lateral prefrontal cortex extending from BA 10 through mid-dorsolateral prefrontal cortex (Banich, 2009; Braver, 2012; Herd et al., 2006; Sakai, 2008), potentially including the anterior cingulate and frontal operculum as well (Dosenbach et al., 2008). Set shifting involves changes in the focus of attention and may engage more posterior regions of dorsolateral prefrontal cortex (e.g., inferior frontal junction) as well as parietal regions (e.g., intraparietal sulcus; Wager et al., 2004; Derrfuss et al., 2005). Working memory updating has been suggested to involve fronto-striatal connections and requires input from the basal ganglia (Braver et al., 1997; O'Reilly and Frank, 2006; McNab and Klingberg, 2008). Using task-related fMRI across multiple EF tasks, Collette et al. (2005) found that regions commonly activated across EF tasks include the left superior parietal gyrus and the right intraparietal sulcus, and to a lesser degree, mid- and inferior prefrontal regions. Moreover, left frontopolar cortex (BA 10) activity was specifically associated with updating-specific EF, while activity of the left intraparietal sulcus was associated with shifting-specific EF.

Given the relatively limited scope of prior research on rs-fcMRI and EF, the current study had a number of major objectives. First, we wanted to determine whether patterns of rs-fcMRI are associated with individual differences in both common and specific factors underlying EF. Second, given the research suggesting that these three EF factors may engage somewhat different brain regions, we wanted to ascertain whether different aspects of rs-fcMRI predicted individual differences for each of the three EF factors investigated (i.e., common EF, updating-specific EF, shifting-specific EF). Third, we wanted to disentangle whether individual differences in these three aspects of EF are associated with activity in RSNs that are composed of regions commonly activated across individuals when performing EF tasks (e.g., the fronto-parietal network), and/or whether they are influenced by activity in RSNs outside those traditionally thought to be engaged in EF (e.g., medial frontal/limbic network). Finally, we wanted to investigate how individual differences in EF might predict alterations in either the degree to which specific subregions coactivate as part of a particular RSNs (e.g., more intense connectivity of DLPFC within the fronto-parietal network) or the composition of particular RSNs (e.g., a greater spatial extent of the fronto-parietal network). Our hypothesis was that rs-fcMRI would be associated with individual differences in these three aspects of EF. However, based on the paucity of prior research, our investigation was more exploratory with regard to how exactly such individual differences would manifest. To investigate these questions, we utilized dual regression to extract subject-specific versions of classic RSNs and then performed statistical tests to determine how individual variation in these RSNs predicted EF as characterized by the unity and diversity model.

Material and methods

Participants

One hundred individuals aged 18 to 34 years ($M = 22.3$, $SD = 9.92$) from the University of Colorado Boulder participated for payment over two sessions. Participants were paid $25.00 per hour for the fMRI session and $10.00 per hour for the behavioral session. Session one involved the administration of behavioral tasks that measured EF ability. Session two involved the acquisition of anatomical and functional brain data via magnetic resonance imaging. The two sessions occurred within an average of 31.6 days of each other. Functional brain data from six participants were discarded due to excessive levels of movement during the scanning session (greater than 3 mm in a single dimension). Additionally, data from three participants were discarded due to failure to comply with rules on one of more of the behavioral tasks. All presented results are from analyses of data from the remaining 91 participants (48 females).

Procedures

In session one, three behavioral tasks were administered from the battery of nine tasks typically used in studies that have provided evidence for the unity and diversity model of EF (see Miyake et al., 2000; updated in Miyake and Friedman, 2012): antisaccade, category switching, and keep track. These three tasks were chosen because they load most highly on common EF, switching-specific, and updating-specific factors, respectively, in a prior large scale study in which the full battery of EF tasks was administered (Friedman et al., 2012). A variety of self-report questionnaires (e.g., emotion regulation style, trait rumination, worry, distractibility) and genetic data were acquired during session 1. Analyses of questionnaire data are outside the scope of the current study. Analyses of genetic data were not performed due to lack of a replication sample.

In session two, participants were scanned in a Siemens Tim Trio 3T scanner. During a 5.5 minute resting state scan, participants were instructed to relax and close their eyes.

Session 1: behavioral tasks

Antisaccade task (adapted from Roberts, Hager, & Heron, 1994)

This task measures a person's ability to inhibit an automatic process (an eye movement). Participants were instructed to focus on a centrally located fixation cross (lasting 1.5–3.5 s). When the fixation cross disappeared, an initial box cue flashed 10 cm either to the right or to the left of fixation. The cue disappeared after a fixed interval (233, 200, or 183 ms), after which the target (a digit, 1 through 9) appeared for 150 ms before being masked with gray cross-hatching. Participants named the number they saw aloud and the experimenter typed in their response, triggering the next trial to begin. For some trials, the cue was helpful in that it indicated the location at which the target appeared (prosaccade trials). In other trials – antisaccade trials – the cue appeared on the opposite side of the screen as the target. The task began with a block of 18 prosaccade trials in which the cue disappeared after 183 ms to establish that participants could perform the easy prosaccade trials within the most stringent time demands. Participants were then given three blocks of 36 antisaccade trials (with 233, 200, or 183 ms cue durations, respectively). Participants typically vary in their ability to identify the target on antisaccade trials because it is difficult to inhibit the automatic tendency to look towards an object, in this case the cue. The dependent measure was average accuracy for the three blocks of antisaccade trials.

Category switch task (adapted from Mayr and Kliegl, 2000)

This task measures a person's ability to quickly and accurately switch between different modes of categorization. Participants were asked to