

Task-positive Functional Connectivity of the Default Mode Network Transcends Task Domain

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Abstract

■ The default mode network (DMN) was first recognized as a set of brain regions demonstrating consistently greater activity during rest than during a multitude of tasks. Originally, this network was believed to interfere with goal-directed behavior based on its decreased activity during many such tasks. More recently, however, the role of the DMN during goal-directed behavior was established for internally oriented tasks, in which the DMN demonstrated increased activity. However, the well-documented hub position and information-bridging potential of midline DMN regions indicate that there is more to uncover regarding its functional contributions to goal-directed tasks, which may be based on its functional interactions rather than its level of activation. An investigation of task-related changes in DMN functional connectivity during a series of both internal and external tasks would provide the requisite investigation for examining the role of the DMN during goal-directed task perfor-

mance. In this study, 20 participants underwent fMRI while performing six tasks spanning diverse internal and external domains in addition to a resting-state scan. We hypothesized that the DMN would demonstrate “task-positive” (i.e., positively contributing to task performance) changes in functional connectivity relative to rest regardless of the direction of task-related changes in activity. Indeed, our results demonstrate significant increases in DMN connectivity with task-promoting regions (e.g., anterior insula, inferior frontal gyrus, middle frontal gyrus) across all six tasks. Furthermore, canonical correlation analyses indicated that the observed task-related connectivity changes were significantly associated with individual differences in task performance. Our results indicate that the DMN may not only support a “default” mode but may play a greater role in both internal and external tasks through flexible coupling with task-relevant brain regions. ■

INTRODUCTION

The default mode network (DMN; Raichle et al., 2001) was originally identified based on an observation by Shulman, Fiez, Corbetta, Buckner, and Miezin (1997) that a common set of brain regions demonstrated decreased blood flow across a range of visual processing tasks. This finding led the authors to posit that this set of regions represents a “default mode of brain function.” Although originally considered a “task-negative” network and believed to interfere with goal-directed actions, theories of its functional roles have extended to include the support of internally based mentation processes (Kelly, Uddin, Biswal, Castellanos, & Milham, 2008; Sonuga-Barke & Castellanos, 2007; Weissman, Roberts, Visscher, & Woldorff, 2006; Fox et al., 2005) and general monitoring of the internal and/or external world (Gao, Gilmore, Alcauter, & Lin, 2013; Gilbert, Dumontheil, Simons, Frith, & Burgess, 2007; Hahn, Ross, & Stein, 2007; Gilbert, Simons, Frith, & Burgess, 2006; Wagner, Shannon, Kahn, & Buckner, 2005). Thus, the DMN may promote—rather than interfere with—certain “task-positive” processes. Nonetheless, the mechanisms by which this network contributes to behavior are not fully understood.

If the DMN is involved in general monitoring of the environment, the fulfillment of this function should encompass multimodal information processing including interactions with higher-order cognitive areas to make prompt decisions in response to internal and external stimuli. Indeed, numerous studies from both structural and functional connectivity perspectives have documented that midline DMN regions are among the most efficiently wired brain areas, serving as global “hubs” that bridge different functional systems across the brain (van den Heuvel & Sporns, 2013; Buckner et al., 2009; Hagmann et al., 2008). The behavioral relevance of such connections has been demonstrated by several studies showing that increased DMN connectivity with regions of other brain networks during goal-directed task states facilitates task performance. For example, both Gao and Lin (2012) and Spreng, Stevens, Chamberlain, Gilmore, and Schacter (2010) have shown that the DMN increases functional connectivity with a frontoparietal control system during “internally directed” tasks. However, DMN contributions to task performance may not be limited to internal tasks, as Gao et al. (2013) showed a similar enhancement of DMN interactions, particularly with regions of the salience network (Seeley et al., 2007), during an “externally directed” classification task. Thus, the current literature, composed of several independent

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reports, indicates that the DMN flexibly shifts its functional connections to contribute to the facilitation of task goals, which may particularly involve interactions with certain executive control (i.e., “task-positive”) brain regions/networks. Nonetheless, a comprehensive characterization of the task-related changes focusing on DMN functional connectivity across multiple task domains is currently lacking.

In this study, we tested the hypothesis that the DMN supports goal-directed tasks through changes in functional connectivity independent of whether DMN activity is increased or decreased. Specifically, we hypothesized that (1) the DMN would exhibit a dynamic reorganization of its functional connectivity pattern in a task-specific manner that would include enhanced interactions with regions traditionally considered to support task performance (i.e., “task-positive” regions: bilateral middle frontal gyrus, inferior frontal gyrus, anterior insula, anterior cingulate cortex; Gao et al., 2013) and (2) changes in functional connectivity would be positively associated with individual differences in measures of behavioral performance. Six tasks encompassing diverse functional domains were created to test this hypothesis including four “external” goal-directed tasks associated with decreased DMN activity, (i.e., working memory, inhibitory control, language, emotion processing), two “internal” tasks known to promote DMN activity (i.e., autobiographical memory, movie watching). Activity changes were detected using conventional general linear modeling, and task-related DMN connectivity was characterized using seed-based functional connectivity and supported with independent components analysis (ICA). Functional connectivity during each of these tasks was compared with that of a resting-state scan, and the relevance of the detected connectivity changes for behavioral performance was characterized. The study findings support our hypothesis and reveal new insights into the complex role of the DMN in normal brain functioning.

METHODS

Participants

Twenty participants (11 women) between the ages of 21 and 38 years (mean = 28.5 years) were included in this study, which was approved by the institutional review board of the University of North Carolina at Chapel Hill. All participants provided informed consent to participate after a thorough explanation of study procedures. All participants were healthy controls based on the absence of lifetime psychiatric or neurological disorders.

Data Acquisition and Preprocessing

Participants performed a battery of tasks from six different domains (working memory, inhibitory control, emotion, language, autobiographical memory, and movie watching) while undergoing fMRI. Functional images were col-

lected with an EPI sequence on a Siemens Trio 3T MRI (Erlangen, Germany) and 32-channel head coil (repetition time = 1500 msec, echo time = 24 msec, flip angle = 70, matrix = $64 \times 64 \text{ mm}^2$, voxel size = $4 \times 4 \times 4 \text{ mm}^3$, 29 axial slices). In addition, a 5-min T1 MPRAGE scan provided anatomical data for each participant (matrix = $256 \times 256 \text{ mm}^2$, 192 sagittal slices, voxel size = $1 \times 1 \times 1 \text{ mm}^3$). Data preprocessing was conducted with Analysis of Functional Neuroimages (AFNI) software and included slice timing correction, deobliquing, motion correction, despiking of noise timepoints, alignment to the participant’s anatomical image, warping to an Montreal Neurological Institute (MNI) template, removal by regression of signal from white matter and cerebral spinal fluid as well as the six motion covariates, linear detrending, Gaussian smoothing at 8 mm FWHM and scaling to percent signal change and bandpass filtering (008–0.08 Hz). For BOLD activation detection, the bandpass filtering step was omitted. Any data sets for which greater than 10% of acquired volumes exhibited motion ($>0.5 \text{ mm}$ shift in head motion in addition to greater than a 0.5% change in BOLD signal from the previous repetition time) during a particular task were excluded from analyses of that task. Final analyses included 17 (emotion, inhibitory control), 16 (working memory, autobiographical memory, movie watching), or 15 (language) participants.

fMRI Tasks

To enable comparison of findings across tasks, we aimed to fix as many task design parameters as possible. Aside from the movie watching and resting-state scans, the five other scans included block design tasks in which five 40-sec experimental blocks alternated with five 40-sec control blocks. All tasks were visual in nature and utilized pictures rather than words/letters. For all tasks except the autobiographical memory task, blocks were preceded by a 2-sec cue indicating task instructions for that block and a 1-sec blank screen. For those four tasks, stimuli were displayed in color in the center of a black screen for 600 msec and followed by a fixed 1000 msec ISI, resulting in 25 trials per block. Thus, stimuli were presented in a rapid, continuous manner, allowing just enough time between stimuli for participants to make a button press response. On the other hand, because of the nature of the autobiographical memory task, each 40-sec block contained a single stimulus and was not preceded by a cue or ISI. Finally, all tasks included three 20-sec rest blocks presented at the beginning, middle, and end of the scan during which a fixation cross was displayed, producing a total scan duration of approximately 8 min for each task.

Autobiographical Memory

Each participant provided five photographs they had taken on different occasions and at different places to be displayed during the scanning session. Control stimuli

consisted of five unfamiliar photographs obtained from the Internet and loosely matched for content (people, scenes, buildings, etc.). Each photograph was displayed for 40 sec. During blocks in which the participant's own photographs were displayed, the instructions were to think about and remember in as much detail as possible the occasion depicted in the picture. Similarly, participants were instructed to imagine the event depicted in the unfamiliar photographs from the perspective of the hypothetical person who took the picture, creating hypothetical details related to that picture. At the completion of the scanning session, participants rated their ability to remember details related to each of their own pictures (memory strength) on a scale of 1–5, where 5 indicates a vivid memory with many details recalled. Additionally, participants reported on 5-point scales how recently the photographs were taken (i.e., 1 month, 2–12 months, 1–5 years, 5–10 years, 10+ years) and the emotional quality of the memory (very negative to very positive). All photographs for participants included in this study were rated 3 (*neutral*), 4 (*somewhat positive*), or 5 (*very positive*).

Emotion

An emotion judgment task required participants to determine the valence (“positive” or “negative”) of emotional facial expressions. Task stimuli were male and female faces obtained from the NimStim stimulus set (www.macbrain.org/resources.htm). Participants responded by pressing one button if the emotion was positive or another button if the emotion was negative. As a control task, participants judged the sex of the individual in the image (portraying a neutral facial expression) and responded by pressing one button for male and another for female. An equal number of each alternative stimulus was presented in a randomized order. Accuracy and RTs (for correct responses) were recorded for each trial.

Inhibitory Control

A go/no-go task was used to assess inhibitory control. Computer-rendered pictures of neutral objects downloaded from the Object Databank (Stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, www.tarrlab.org/) served as the task stimuli. Participants were instructed to respond by pressing a button as quickly as possible whenever a picture appeared on the screen but to withhold their response at the presentation of the no-go stimulus (a “chain”), which appeared in 24% (6/25) of trials. Go/no-go blocks alternated with control blocks in which participants were informed by the preceding cue that the no-go stimulus would not appear. Accuracy was based on inhibition trials: A nonresponse for no-go trials was considered cor-

rect, and errors of commission were incorrect. RT was measured for all responses on go trials.

Working Memory

Working memory was assessed with an *n*-back task, consisting of a 2-back task and a 0-back control task. Stimuli for the *n*-back task were the same as for the go/no-go task (above) with the exception of the “chain.” During the 2-back portion of the task, participants were to press a button if the picture on the screen matched the one presented two trials before it. The 0-back control task participants were instructed to respond to the appearance of the target picture (a kite). Button presses were required in 24% (6/25) of trials for each block. Correct responses, errors (omission or commission), and RTs for correct responses were recorded.

Language

For the language domain, we chose a covert (silent) object-naming task. Experimental stimuli consisted of 125 neutral object images obtained for the Object Databank. During the experimental blocks, participants were instructed to silently name the object depicted on the screen. Object naming blocks alternated with control blocks in which nonsense images (distorted versions of original images) were displayed and participants were instructed to not name the images. Because of the nature of the task, no behavioral measures were acquired during this task.

Movie

The movie watching scan consisted of an excerpt from the 1925 silent film, *Seven Chances*, edited to a length of approximately 7.5 min. The film largely depicts a series of social interactions that drive various comedic scenarios. All intertitles (i.e., dialogue text) were removed to avoid eliciting brain activity related to reading or a disruption in the visual flow of the film.

Task instructions were thoroughly explained to participants before the scan, and for the tasks requiring button presses (emotion judgment, *n*-back, go/no-go), participants were provided as much time as needed to practice the tasks before entering the scanner. The resting-state scan, during which participants were instructed to look at a white fixation cross on a black screen for 5 min, preceding all other scans, but otherwise the tasks were counterbalanced across participants using three different counterbalance orders.

Statistical Analyses

Following data preprocessing, general linear modeling of the task design, in which the experimental and control blocks were modeled as boxcar functions and the task

cues modeled as stick functions (where applicable), was used to detect task-related activity. Activation estimates from experimental blocks were contrasted with control blocks to isolate task-related activity in keeping with conventional fMRI task analytical procedures (Friston et al., 1994). Second-level group analyses of this contrast were calculated in one-sample mixed-effect meta-analyses using 3dMEMA in AFNI. Results were corrected for multiple comparisons ($\alpha = 0.05$) using a cluster level correction ($p < .05$, minimum cluster size = 128 voxels) based on Monte Carlo simulations conducted in 3dClustSim in AFNI.

For seed-based functional connectivity analyses, four different 8-mm radius spheres were placed in key nodes of the default node network using previously established coordinates (Vincent, Kahn, Snyder, Raichle, & Buckner, 2008) for the posterior cingulate cortex (PCC; MNI coordinates: $x = 1, y = -55, z = 17$), the ventromedial pFC (MNI coordinates: $x = 0, y = 51, z = -7$), the left posterior inferior parietal lobule (MNI coordinates: $x = -47, y = -71, z = 29$), and the right posterior inferior parietal lobule (MNI coordinates: $x = 50, y = -64, z = 27$). The mean time series of voxels within each sphere was calculated for each participant and concatenated across the experimental task blocks (or the entire scan in the case of the movie viewing scan) to serve as reference time series for seed-based functional connectivity analyses. Thus four seed-based functional connectivity maps were derived for each task. Task-based functional connectivity maps were compared with similarly derived connectivity maps for the resting-state scan for each of the four DMN seeds using a paired t test, consistent with other studies of task-related functional connectivity changes (Elton & Gao, 2014; Krienen, Yeo, & Buckner, 2014). Results were corrected for multiple comparisons ($p < .05$, minimum cluster size = 128). A composite map of significant voxels from the task-minus-rest contrast for all four seeds was calculated for each task.

To examine the similarities of DMN connectivity patterns across tasks, we examined the voxel-wise functional connectivity changes obtained from the seed-based connectivity analyses. Group mean functional connectivity differences between each task and rest for all voxels in the brain was vectorized for each ROI. Next, the voxel-wise correlation across the six tasks was computed and, following a Fisher z -transform, was then averaged across the four ROIs.

A secondary analysis, specifically focused on between-network connections derived from ICA, was conducted to provide an additional, network level approach to understand the results obtained from seed-based analyses. ICA is a data reduction method, which, when applied to fMRI data, is capable of providing independent components that closely correspond with brain networks identified by other functional connectivity methods (Calhoun, Adali, & Pekar, 2004). For the current study, the ICA was conducted using the Infomax algorithm in the GIFT

group ICA toolbox (v3.0a; Calhoun, Adali, Pearlson, & Pekar, 2001) implemented in Matlab R2011a. Each fMRI data set from all participants and all scans was included in a single group ICA to establish correspondence between identified components across both individuals and tasks. On the basis of estimates from 20 ICASSO iterations to test for the stability of the result, we solved for 15 independent components. The 15 component spatial maps were visually inspected to identify those representing obvious artifacts, resulting in the removal of one motion-related component in which peak values were around the outside of the brain. The remaining component spatial maps corresponded with identifiable neural networks.

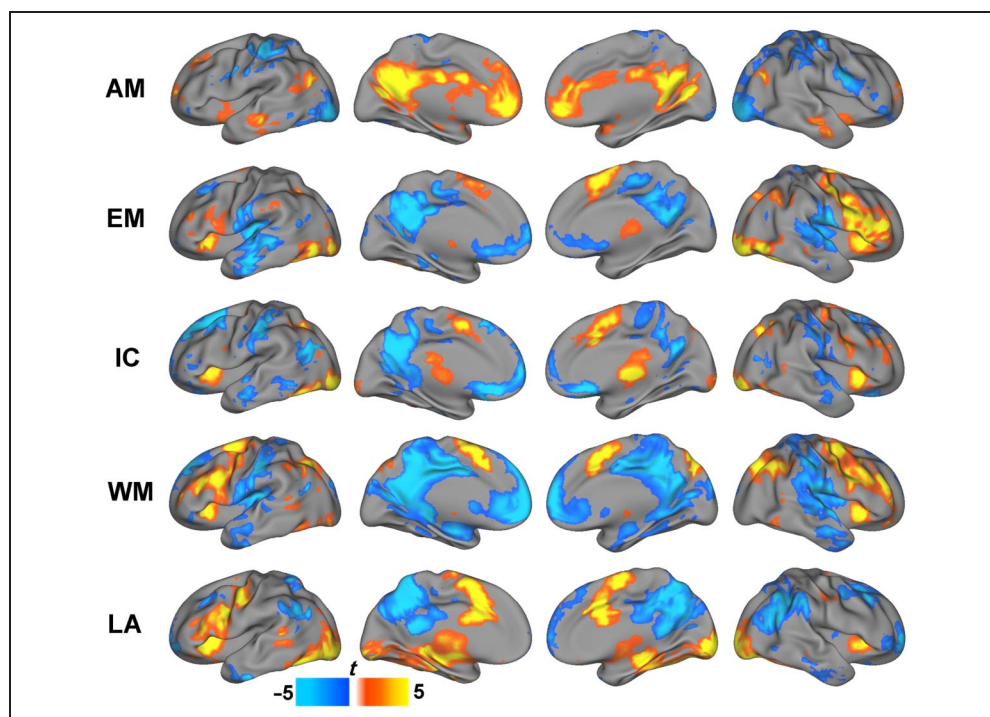
For each of the group component spatial maps, GIFT calculates time courses corresponding with each component for each scan entered into the analysis (i.e., for each participant and each task). Calculation of functional connectivity entailed the pairwise Pearson correlation of the 14 time courses, providing a 14-by-14 correlation matrix, for each participant and each task. The resulting correlation matrices were normalized with a Fisher z -transform. Task-related functional connectivity changes were calculated from paired t tests of each task and rest.

To calculate the canonical correlations between the seed-based functional connectivity changes and task performance, first, for each task, voxels demonstrating a convergence of significant task-dependent changes in connectivity across all four ROIs at the group level were identified for positive and negative regions. Then, for each task, each participant, and each ROI, the mean difference in connectivity between the task and resting-state scans within the intersecting voxels was calculated, producing a set of two functional connectivity variables (i.e., positive and negative changes) for each task and ROI. The second set of variables were behavioral measures, which varied by task: Mean postscan ratings of memory strength, distance, and emotion for the five photographs were calculated for the autobiographical memory task; mean RT, standard deviation of RT, and accuracy were calculated for the emotion, inhibitory control, and working memory tasks. The language task and movie watching did not provide behavioral output and were therefore not included in behavioral analyses. For this analysis, we consider behavior during the experimental task block only. For each task with behavioral measures, the two sets of variables (2 connectivity variables, 3 behavioral variables) were entered into a partial canonical correlation analysis controlling for ROI in SAS 9.3 software to examine the relationship between functional connectivity changes and task performance. Significance was defined as $p < .05$ after FDR correction (Benjamini & Yekutieli, 2001).

RESULTS

The detected activations for each task were highly consistent with previous studies of autobiographical memory (Spreng, Mar, & Kim, 2009; Summerfield, Hassabis, &

Figure 1. Activity changes associated with five block design tasks. Both task-related activations (warm colors) and deactivations (cool colors) are shown. Significance was defined as cluster-size level corrected $p < .05$. AM = autobiographical memory; EM = emotion; IC = inhibitory control; WM = working memory; LA = language.



Maguire, 2009), emotion judgment (Phan, Wager, Taylor, & Liberzon, 2002), inhibitory control (Wager et al., 2005; Rubia et al., 2001), working memory (Owen, McMillan, Laird, & Bullmore, 2005), and language (Burgund, Lugar, Miezin, & Petersen, 2003; Figure 1). In particular, the emotion judgment, inhibitory control, working memory, and language tasks each exhibited decreased task-related activity in regions consistent with the DMN (i.e., PCC, precuneus, medial pFC, middle temporal gyrus). Conversely, the autobiographical memory task was characterized by task-related increases in activity in the same DMN regions. The continuous nature of the movie watching scan precluded an analysis of task-related activity.

Maps of the average functional connectivity of the four seeds for each task are presented in Figure 2. The network level composite map of the connectivity dynamics associated with the four DMN ROIs is presented in Figure 3. Despite similarities in functional connectivity across these seven brain states, consistent with prior work (Krienen et al., 2014), the task-related changes in functional connectivity relative to the resting state were extensive. Consistent with our hypothesis, differences in functional connectivity patterns during task blocks compared with the resting-state scan were observed for all defined DMN ROIs. Although each task demonstrated its own unique functional connectivity pattern, increased DMN connectivity was generally observed across the tasks within the middle and inferior frontal cortex and anterior insula, which are typically attributed to executive control functions and traditionally regarded as having positive contributions to task performance (Spreng, 2012). Furthermore, a pattern of increased anterior insula connectivity and decreased posterior cingulate connec-

tivity observed for each of these tasks is mirrored in the task-related activation maps for the four external tasks, further supporting the task-positive nature of these connectivity changes.

Certain functional connectivity patterns appeared to be consistent across all task domains, suggesting some commonalities across the tasks relative to rest. To examine these commonalities, Figure 3B presents regions showing task-related connectivity changes across at least three ROIs for all six tasks. Relative to the resting-state, DMN ROIs engaged a cluster centered in the right inferior frontal gyrus (MNI coordinates: $x = 48, y = 35, z = 0$; 97 voxels) during all six tasks. Similarly, there was overlap across all tasks for functional connectivity decreases in the PCC and medial visual cortex (MNI coordinates: $x = -1, y = -52, z = 19$; 356 voxels), brainstem (MNI coordinates: $x = -8, y = -24, z = -7$; 67 voxels), and cerebellum (MNI coordinates: $x = 4, y = -51, z = 019$; 47 voxels).

The correlations of the dynamic DMN functional connectivity patterns across the six tasks suggest certain similarities exist across the task domains (Figure 4). In particular, the calculated correlations support the classification of these tasks into at least two major categories, which seem to correspond with whether the task requires internally and externally focused cognitions. Specifically, the two internal tasks—movie watching and autobiographical memory—demonstrated highly similar patterns of connectivity ($r = .83, p < .001$). Similarly, high correlations were also detected among the emotion, inhibitory control, and working memory tasks, which ranged between $r = .79$ and $r = .83$. Although the emotion task exhibited a high degree of similarity to the

other tasks requiring external cognitions, there were also relatively high correlations between the emotion task and the two internal tasks (movie watching: $r = .79, p < .001$; autobiographical memory tasks: $r = .83, p < .001$), suggesting that this task may involve both internal and external cognitions. Functional connectivity changes during the language task were most closely associated with the emotion task ($r = .73, p < .001$).

For the ICA analysis, the DMN was represented by two independent components, corresponding with the posterior (pDM) and anterior (aDM) portions of the network consistent with prior reports (Di & Biswal, 2014; Uddin, Clare Kelly, Biswal, Castellanos, & Milham, 2009; Damoiseaux et al., 2006). For descriptive and visualization purposes, functional connectivity of the two DMN components was averaged to provide a single network level measure of DMN functional connectivity. However, changes in DMN connectivity were considered significant if either one of the two components demonstrated a significant effect. Within-DMN functional connectivity was represented by the connectivity between the two DMN components (i.e., pDM and aDM). Four components were identified as representing higher-order task-positive networks belonging to the so-called “control system” as reported in previous studies (Cole, Repovs, & Anticevic, 2014; Di & Biswal, 2014). These networks included the

dorsal attention network, salience network, right frontoparietal network, and left frontoparietal network. These selected networks are displayed in Figure 5A. Networks were identified and labeled based on visual inspection of their resemblance to resting-state networks reported in previous studies (Di & Biswal, 2014; Smith et al., 2009).

To illustrate the task-related dynamic patterns of DMN connectivity in relation to large-scale networks derived from ICA, spider plots of the functional connectivity changes of the DMN components with each of the other networks are displayed in Figure 5B with significant changes noted in Figure 5C. The patterns of functional connectivity changes in this network level analysis demonstrated both commonalities across tasks as well as task-specific features. Similar to the seed-based results, findings based on ICA time courses indicated decreased within-DMN functional connectivity (nonsignificant) for each of the tasks relative to rest except for the autobiographical memory task. Regarding functional connectivity with the designated task-positive networks, one notable commonality was that the DMN increased functional connectivity with the salience network for all six tasks compared with rest, which was statistically significant for pDM during the movie watching, emotion, and language tasks. The left frontoparietal network also demonstrated nonsignificant increases with the DMN during five of the

Figure 2. Average functional connectivity of the four DMN ROIs during each of the six tasks as well as the resting state. REST = resting state; MW = movie watching; AM = autobiographical memory; EM = emotion; IC = inhibitory control; WM = working memory; LA = language.

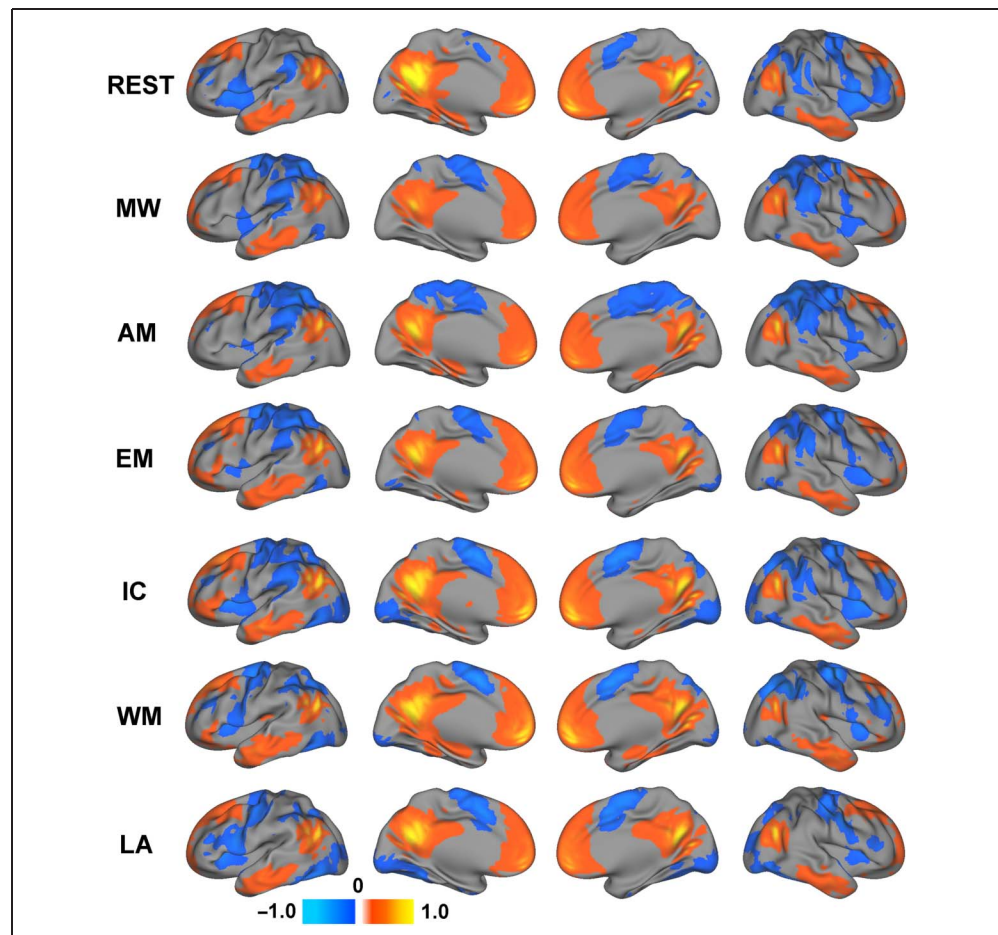
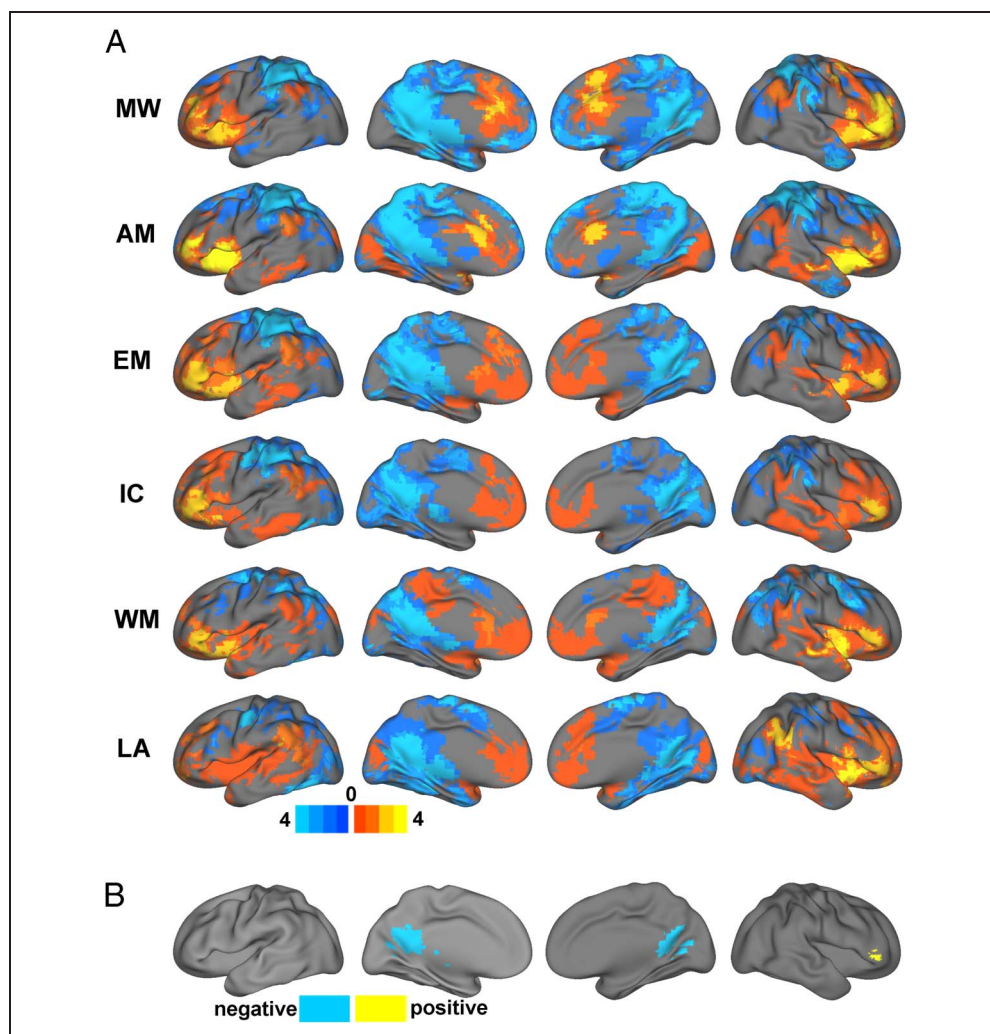


Figure 3. Functional connectivity of the DMN during six tasks contrasted with rest. (A) Overlap of DMN task-related connectivity changes versus rest across four ROIs. Brain maps represent the number of ROIs exhibiting significant positive (warm colors) or negative (cool colors) task-related functional connectivity changes at each voxel. (B) Overlap of DMN task-related connectivity changes versus rest across all six tasks. MW = movie watching; AM = autobiographical memory; EM = emotion; IC = inhibitory control; WM = working memory; LA = language.



tasks compared with rest with the exception of movie watching, which conversely demonstrated a significant increase with the right frontoparietal network ($t = 3.34$, $p = .002$). DMN connectivity changes with the dorsal attention network were also highly task dependent, demonstrating significant increases for the aDMN during the movie watching ($t = 3.40$, $p = .002$) and language tasks ($t = 4.10$, $p < .001$), but significant decreases during the

working memory ($t = -3.03$, $p = .005$), inhibitory control ($t = -2.59$, $p = .014$), and emotion ($t = -2.65$, $p = .012$) tasks. Thus, in support of findings from the seed-based analyses, these secondary analyses identified a number of “task-positive” increases in DMN functional connectivity during performance of various tasks relative to rest. Furthermore, the unique patterns of functional connectivity changes support the hypothesis that the DMN undergoes functional reorganization in a task-specific manner.

Finally, to determine the behavioral relevance of task-dependent changes in connectivity, we investigated the association of DMN connectivity changes with task behavioral measures. Because both increases and decreases in functional connectivity could potentially contribute to enhanced task performance (Gao et al., 2013), we adopted a multivariate approach to test the association of the observed positive and negative functional connectivity changes with task performance variables using canonical correlation analysis, which finds the linear combination of two sets of variables that maximizes their correlation. Canonical correlations, as well as variable loadings and cross loadings for significant canonical variate pairs, are

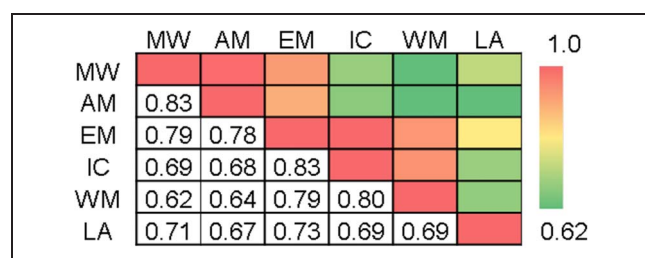


Figure 4. Correlation matrix representing the extent to which patterns of DMN connectivity (relative to rest) are similar across the six tasks. MW = movie watching; AM = autobiographical memory; EM = emotion; IC = inhibitory control; WM = working memory; LA = language.

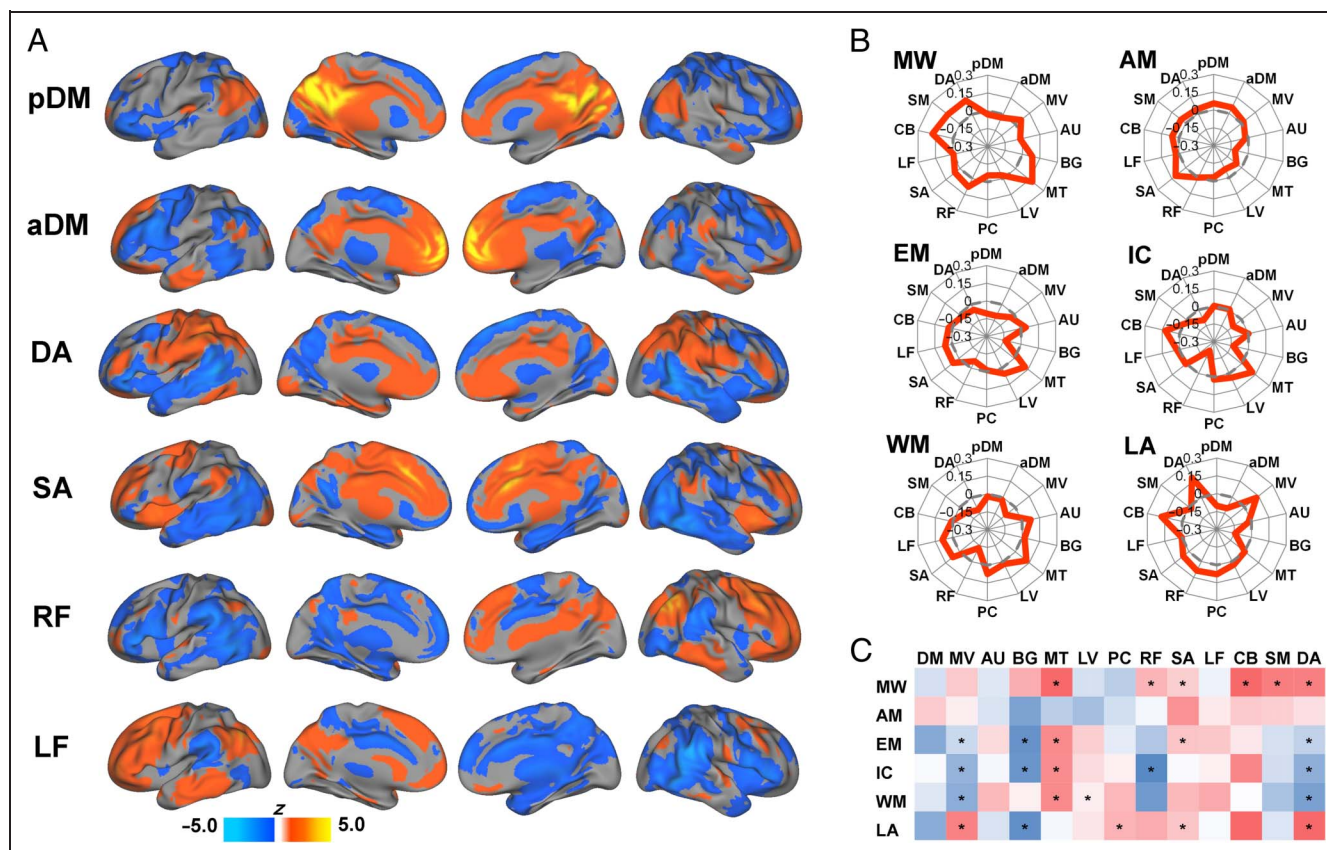


Figure 5. Results based on independent component analysis. (A) Mean values (z scores) for selected independent components. (B) Spider web plots depicting changes in DMN functional connectivity (between each task and rest) across all independent components. (C) Color chart depicting changes in DMN functional connectivity (between each task and rest) across all independent components. Red indicates degrees of positive change in connectivity, and blue indicates degrees of negative change in connectivity. Asterisks denote significant functional connectivity changes. MV = medial visual network; AU = auditory/language network; BG = basal ganglia network; MT = medial-temporal network; LV = lateral visual network; PC = precuneus network; RF = right frontoparietal network; SA = salience network; LF = left frontoparietal network; CB = cerebellar network; SM = sensorimotor network; DA = dorsal attention network; MW = movie watching; AM = autobiographical memory; EM = emotion; IC = inhibitory control; WM = working memory; LA = language.

reported in Table 1. Significant relationships between functional connectivity changes and task behavioral measures were detected for each task, demonstrating the behavioral relevance of the observed DMN dynamics. For the autobiographical memory task, the significant canonical variate pair indicated a particularly strong relationship of more distant memories with stronger task-dependent increases and decreases in connectivity (Wilks' Lambda = 0.79, $F(6, 112) = 2.39$, $p = .033$). For the emotion task, the significant canonical variate pair (Wilks' Lambda = 0.79, $F(6, 88) = 2.25$, $p = .046$) indicated that lesser task-related functional connectivity increases and decreases were associated with longer RTs. The significant canonical variate pair for the n -back working memory task (Wilks' Lambda = 0.78, $F(6, 112) = 2.48$, $p = .027$) suggested that lesser task-related connectivity decreases in negative regions were associated with both longer RTs and greater RT variability. Finally, the significant canonical variate pair for the go/no-go inhibitory control task (Wilks' Lambda = 0.69, $F(6, 88) = 2.95$, $p = .011$) demonstrated a

rather complex relationship that does not lend itself to a clear interpretation.

DISCUSSION

The current study provides strong evidence that, independent of the direction of activity changes, the DMN undergoes task-positive changes in functional connectivity, which was demonstrated by both task-dependent reorganization of functional connectivity as well as significant connectivity-behavior relationships. In fact, the study findings indicated that the DMN increases functional connectivity with certain regions/networks that are implicated in the executive control of task performance, casting further doubt on the notion that the DMN is solely associated with task-irrelevant thoughts or behaviors during external tasks. Thus, the discrepancy between activity changes and connectivity changes associated with the DMN emphasizes the need for future research to consider both channels of information to

provide a more thorough understanding of the functional roles of this and other networks.

The “tonically active” nature of DMN regions during unconstrained rest has led to the postulation that the DMN is involved in broadband monitoring of both the internal and external world to maintain self-consciousness and vigilance during this state (Gilbert et al., 2007; Raichle et al., 2001). This broadband monitoring function would likely require extensive interactions between the DMN and various specialized brain networks. Indeed, different studies have consistently documented the “hub” role of core DMN regions within the brain, based on both function and structure (van den Heuvel & Sporns, 2013; Buckner et al., 2009). Therefore, we would argue that just as the DMN may utilize multimodal information integration to support broadband monitoring of both the internal and external world during unconstrained rest, it may also utilize its vast functional connections to flexibly facilitate performance of diverse goals during various task states. The highly flexible and task-specific reorganization of DMN connectivity suggest that the DMN may act as a crossroad for multimodal integration across domain-specific regions to support the current task. Indeed, we observed positive coupling between the DMN and external

task-activated regions and uncoupling of external task-deactivated regions with the DMN ROIs (Figures 1 and 2), which was evident for both external and internal tasks. The region that showed the most consistent positive coupling with the DMN across all tasks was the right inferior frontal gyrus, a key region belonging to the salience network (Seeley et al., 2007), so-called for its role in detecting salient stimuli. Indeed, a secondary analysis based on ICA time series also suggested a task nonspecific role of functional connectivity between a component identified as the salience network and the DMN indicating a general role in goal-directed cognitions. We have previously described DMN increases with this network during a global/local task (Elton & Gao, 2014; Gao et al., 2013), which we have described as a mechanism to support the monitoring of the internal and external environment. It is likely that such monitoring is an important functional component of each of the tasks included in this study, particularly to identify the appearance of salient stimuli and/or to monitor performance. Furthermore, recent work suggests that the salience network may modulate DMN interactions with the other “task-positive” networks (Di & Biswal, 2014), highlighting the potential relevance of such interactions for task performance.

Table 1. Canonical Correlations and Variable Correlations and Cross-correlations with Canonical Variates for Functional Connectivity (FC) and Behavior

<i>Task</i>	<i>Canonical Correlation</i>	<i>p</i>	<i>Variable</i>	<i>FC</i>	<i>Behavior</i>
Autobiographical memory	0.44	.033	FC positive	0.64	0.28
			FC negative	-0.50	-0.22
			Strength of memory	-0.13	-0.28
			Distance of memory	0.39	0.89
			Emotional quality	-0.04	-0.09
Emotion	0.44	.046	FC positive	-0.36	-0.16
			FC negative	0.76	0.34
			Accuracy	0.18	0.39
			RT	0.35	0.79
			RT variability	0.20	0.45
Inhibitory control	0.52	.011	FC positive	0.44	0.22
			FC negative	1.00	0.52
			Accuracy	0.43	0.83
			RT	0.19	0.36
			RT variability	0.22	0.42
Working memory	0.44	.027	FC positive	-0.03	-0.02
			FC negative	0.95	0.42
			Accuracy	-0.02	-0.04
			RT	0.32	0.72
			RT variability	0.32	0.72

The patterns of functional connectivity also showed variations depending on the task (Figure 4). For example, the two internal tasks (i.e., autobiographical memory and movie watching) demonstrated highly similar patterns but less similarity with the external tasks. The emotion task showed high similarity to both the internal and external task categories in terms of its dynamic DMN connectivity patterns. Thus, the changes in DMN functional connectivity patterns appear to be task dependent, yet also demonstrate a high degree of consistency across tasks employing similar processes. The importance of this task-specific reorganization is further underscored by the association of these DMN connectivity changes with behavioral variables associated with each of the tasks (Table 1). As an example, during the emotion task, both the speed and accuracy for detecting emotional valence were positively related to DMN coupling with task-positive regions including the anterior insula and inferior frontal gyrus regions of the salience network. It is likely that such functional coupling fosters the rapid and accurate detection of the task-relevant feature (i.e., valence) of the task stimulus (i.e., face). Such functional interactions likely serve to positively influence goal-directed behaviors more generally, as the ability to identify salient stimuli and/or to monitor performance is an important functional component of goal-directed tasks. Overall, these findings suggest that the ability of the DMN to flexibly interact with extensive and distributed brain regions/networks may exist not only as a means for broadband monitoring during the resting state but also as an important functional mechanism to facilitate various behavioral goals during different explicit task states. Therefore, we argue that, although studies of task-evoked activity changes may have enabled mapping of specialized functions across the brain, the study of task-evoked connectivity reorganization may provide information regarding large-scale functional interactions related to multimodal integration and facilitation, as observed here for the DMN.

However, how do we reconcile the current findings with the fact that the DMN typically shows decreased activity during most externally oriented tasks? We might find an explanation from the dual nature of DMN functions. First, numerous studies have found that DMN regions show task-evoked activity increases during a range of self-referential cognitions including autobiographical memory retrieval, self-related planning, and mentalizing, indicating a specialized role of the DMN in self-related thinking processes (Andrews-Hanna, 2012; Spreng et al., 2009; Buckner & Carroll, 2007). During the unconstrained resting state, the DMN may support both self-related thinking (a specialized, domain-specific function) as well as broadband monitoring (generalized information integration across domains). However, after transitioning to external, goal-directed task performance, the information integration function may continue to support broadband monitoring, potentially shifting to support more task-specific multimodal integration/control, which

would likely entail a similar level of information processing and thus a similar level of activity expenditure. On the other hand, self-referential mental processes are likely suspended during such external tasks (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007), which would reduce the local processing needs that support such functions within the DMN. Therefore, the relatively stable cost of large-scale multimodal integration combined with decreased local processing within the DMN could explain the net decrease in activity within the DMN during external tasks. On the other hand, when the local processing needs of the DMN exceeds that of the resting state (i.e., during a dedicated internally focused task such as autobiographical memory), we observe a corresponding increase of DMN activity (Figure 1). Taken together, our findings seem to imply that brain functions during both resting and task states may be supported by two large processing domains: (1) large-scale network level information integration and coordination supported by the connectivity dynamics of different functional networks, including the DMN and likely certain “control” networks that require a high but relatively constant level of activity regardless of whether the brain is at rest or involved in a specific task and (2) local and specialized task-specific processes supported by a discrete set of regions, likely underlying the subtle activity changes that are captured by conventional task fMRI activation analyses. This dual-layer hypothesis provides a simple explanation for the brain’s high level of flexibility to adapt to different task states while exhibiting minimal (yet statistically detectable) activity changes.

Regardless of the underlying mechanisms, the observed task-positive connectivity changes of the DMN across a range of tasks and their association with behavior reinforce the perspective (Spreng, 2012; Hampson, Driesen, Skudlarski, Gore, & Constable, 2006) that this network may contribute a wide range of functional deficits spanning diverse domains. For instance, the view that the DMN is suppressed during most tasks could hardly reconcile the innumerable findings linking this network to diverse task-related functional abnormalities spanning both internal and external domains, including motor control deficits (e.g., Parkinson disease; Tessitore et al., 2012; Van Dijk et al., 2010), attention deficits (e.g., ADHD; Liddle et al., 2011; Uddin et al., 2008), social skill deficits (e.g., autism; Lynch et al., 2013; Washington et al., 2013; Murdaugh et al., 2012; Spencer et al., 2012), dysregulated mood (e.g., bipolar disorder, depression; Sambataro, Wolf, Pennuto, Vasic, & Wolf, 2013; Marchetti, Koster, Sonuga-Barke, & De Raedt, 2012; Ongur et al., 2010; Sheline et al., 2009), psychosis (e.g., schizophrenia; Guo et al., 2014; Jang et al., 2011; Ongur et al., 2010; Pomarol-Clotet et al., 2008), and memory loss/cognitive disabilities (e.g., Alzheimer’s disease and dementia; Qi et al., 2010; Greicius, Srivastava, Reiss, & Menon, 2004). Rather, in addition to the typically postulated role of the DMN in task-independent thoughts and processes, in

which impairments result from a failure to deactivate this network (Sonuga-Barke & Castellanos, 2007), our findings suggest that the DMN may also contribute to the neuropathology of different brain disorders through dysconnectivity with task-relevant regions that support active brain operations. For example, a previous study investigated altered task-dependent connectivity of the PCC and medial pFC in individuals with post-traumatic stress disorder (PTSD) versus healthy controls during a blocked working memory task (Daniels et al., 2010). The DMN seeds demonstrated greater task-related connectivity with task-positive regions in the control group versus the PTSD group, whereas greater task-dependent connectivity for the PTSD group was observed within DMN regions. The hyperconnectivity of the PTSD group within the DMN and reduced integration with other task-positive networks during the working memory task indicate a deficit in the appropriate engagement of task-related brain networks, rather than simply an inability to suppress DMN activity. Other evidence of deficits in multimodal integration of DMN structures contributing to disease comes from reports indicating that patients with schizophrenia exhibit decreased hub-like organization of cortical networks (Rubinov et al., 2009), particularly in the posterior cingulate/precuneus region (Lynall et al., 2010), suggesting reduced communication between this DMN region and other large-scale networks. Therefore, although prevailing theories typically lead to the interpretation that altered DMN connectivity contributes to deficits in self-related processes, emerging evidence also suggests that such abnormalities could impact numerous other functional domains through altered connectivity with relevant brain regions. Given the role of the DMN as a hub network in addition to the immense diversity of disorders in which the DMN has been implicated (Broyd et al., 2009), it is possible that certain brain disorders could be associated with multimodal integration deficits related to altered DMN dynamics. Indeed, the relationship of DMN connectivity dynamics to behavior demonstrated by the current study represents a promising model for understanding symptoms of mental health disorders.

Several study limitations deserve discussion. First, a seed-based approach was adopted to delineate the dynamic connectivity of the DMN network, limiting our conclusions to the specific seeds selected. However, our results showed a high degree of overlap across all four of the selected DMN seeds (Figure 3) supporting our network level conclusions regarding the DMN. Furthermore, our conclusions were supported by an ICA-based approach. However, a limitation of ICA is the optimization requirement of this approach, which can produce small variations in results when solving for a different number of components. Another limitation of the current study is that our sample size is moderate ($n = 15\text{--}17$ participants per task); thus, the brain-behavioral correlation analyses would be strengthened by future independent validation.

Overall, the current findings from six distinct task domains provide compelling evidence that the DMN does

not always operate under a “default” mode and may actively participate in both internal and external goal-directed tasks through dynamic connectivity. The functional relevance of such task-related connectivity changes was demonstrated by their association with behavioral measures for each task. The current investigation represents the first systematic investigation focusing on the task-dependent connectivity of this network and demonstrating its positive contributions to a range of explicit task states. A dual-layer functional mechanism may reconcile the seemingly discrepant activity and connectivity changes under different task states. The novel findings in this study provide a new perspective from which to understand DMN function and its contribution to various brain disorders.

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