Thinking About a Task Is Associated with Increased Connectivity in Regions Activated by Task Performance

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Abstract

We investigated whether functional neuroimaging of quiet “rest” can reveal the neural correlates of conscious thought. Using resting-state functional MRI, we measured functional connectivity during a resting scan that immediately followed performance of a finger tapping motor sequence task. Self-reports of the amount of time spent thinking about the task during the resting scan correlated with connectivity between regions of the motor network activated during task performance. Thus, thinking about a task is associated with coordinated activity in brain regions responsible for that task’s performance. More generally, this study demonstrates the feasibility of using the combination of functional connectivity MRI and self-reports to examine the neural correlates of thought.

Key words: conscious thought; functional connectivity; resting state; unconstrained thought

Introduction

A n essential goal of neuroscience is to understand how thinking is represented in the brain. Functional neuroimaging during wakeful rest has shown that brain activity is organized across multiple networks (Smith et al., 2009). The occurrence of spontaneous undirected thought is reflected in the activation of subsystems of the default network (Christoff et al., 2009). However, regions not thought to be part of the default network have also been associated with undirected thought, suggesting that examinations limited to the default network alone are not sufficient to capture the neurobiological underpinnings of thought (Fox et al., 2015). It has also been shown that the resting brain connectivity of task-specific networks is both modulated by learning (Albert et al., 2009; Stevens et al., 2010; Tambini et al., 2010) and associated with memory consolidation (Deuker et al., 2013) of the respective task. To our knowledge, however, no studies have attempted to identify the neural correlates of specific thoughts during wakeful rest. In this study, we used a postscan mentation questionnaire and functional connectivity MRI (Biswal et al., 1995) to examine the neural correlates of thinking about a just-completed task.

We previously reported that increased resting-state connectivity in the motor network, measured immediately after learning a finger tapping motor sequence task (MST) (Karni et al., 1998), predicts sleep-dependent performance improvement measured the following day (Gregory et al., 2014). Using the same data set, we now demonstrate that self-reports of the amount of time spent spontaneously thinking about the task during this post-training rest correlates with connectivity between a different set of brain regions—those that were activated during task training.

Materials and Methods

The study design and experimental methods are detailed in our previous publication (Gregory et al., 2014) and are summarized here. Fourteen healthy participants (age 24.6 ± 1.8 years, six males) provided written informed consent and completed the study. The study was approved by the Partners Human Research Committee. Participants completed a resting functional MRI (fMRI) scan immediately before and after training on the MST. The MST involves repeatedly typing a five-digit sequence displayed on the screen, with the fingers of the left hand, as quickly and as accurately as possible, for twelve 30-sec trials, separated by 30-sec rest periods (Walker et al., 2002). Immediately after the post-task rest scan, participants were informed as follows: “We’d like to...
ask you a few questions about what you were thinking during the last scan, so take a few moments now to try and remember what you were thinking.” After they were removed from the scanner, they were asked to divide a pie chart into a maximum of five slices to indicate the proportion of time during the post-MST rest scan they had spent thinking about (1) the past, (2) the future, (3) the MST, (4) other things, and (5) nothing. The percentage of the pie chart allocated to the “MST” was taken as the percentage of time spent thinking about the task.

**Image acquisition**

Participants were scanned using a Siemens 3T Trio MRI scanner (Siemens Medical Systems, Erlangen, Germany) and a 12-channel head coil. We first acquired a high-resolution structural scan using a 3D rf-spoiled magnetization prepared rapid gradient echo (MP-RAGE) sequence acquired in the sagittal plane (TR/TE/Flip = 2530 msec/1.64 msec/7°; FOV = 256 mm, 176 – 1 mm isotropic slices). This was followed by three functional scans—rest, task performance, and rest—that used gradient echo T2* weighted sequences and contiguous slices parallel to the intercommissural plane. Rest scans took 6’12” each (TR/TE/Flip = 3000 msec/30 msec/85°; FOV = 216 mm; 47 – 3 mm isotropic slices, acquired interleaved). The task performance scan took 12’42” (TR/TE/Flip = 3000 msec/30 msec/77°; FOV = 190 mm; 47 – 3 mm isotropic slices, acquired interleaved) and included prospective acquisition correction for head motion (Thesen et al., 2000).

**Functional image preprocessing**

All analyses were conducted using AFNI (Cox, 1996). The first four images of each functional run were removed, and the remaining images were slice time corrected and corrected for residual motion. Each participant’s functional images were aligned to their MP-RAGE scan and transformed to Montreal Neurological Institute (MNI) space. Functional data were spatially smoothed (6 mm FWHM), and a temporal band-pass filter was applied (0.008–0.10 Hz).

**MST analysis and identification of the seed region for functional connectivity analyses**

We used activation during the task scan to identify the seed region for functional connectivity analyses. Task activation was identified using a regression on the spatially normalized, averaged group data with condition (typing vs. rest) as the regressor of interest and the six directions of residual head motion from AFNI as nuisance regressors. The statistical map of task activation was corrected for multiple comparisons using a false discovery rate (Genovese et al., 2002) corrected threshold that set the overall probability to <0.01. The cortical voxel with the maximum T-statistic in the comparison of typing versus rest in the hand area of M1 on the right precentral gyrus, contralateral to the hand, used to perform the task. MNI coordinates (51, −24, 63) were used as the center of a 6 mm diameter spherical seed for resting-state functional connectivity analyses.

**Resting-state functional connectivity analyses**

Artifact Detection Tools (www.nitrc.org/projects/artifact_detect) were used to exclude time points corrupted by motion or other sources of spurious signal (Whitfield-Gabrieli and Nieto-Castanon, 2012), and anatomic component-based noise correction (Behzadi et al., 2007; Chai et al., 2012) was used to correct for spurious correlations in the data. Voxel-wise connectivity maps for each participant were derived from the post-training resting scan by computing Pearson correlations between the signal averaged over the motor seed region and the signal at each voxel in the entire brain.Correlation coefficients were transformed to z-score connectivity maps. The resulting connectivity maps were correlated with each participant’s report of the percent of time spent thinking about the MST.

Correction for multiple comparisons used a cluster threshold based on 10⁶ Monte Carlo simulations of synthesized white Gaussian noise with the smoothing and resampling parameters of the functional analyses and an uncorrected threshold of p < 0.01 (Nichols, 2012). This determined the likelihood that a cluster of a given size would be found by chance. A cluster threshold of 38 voxels set the corrected threshold to p ≤ 0.05 in the entire brain.

**Results**

MST performance was associated with activation in motor areas, including the bilateral cerebellum, bilateral pre- and postcentral gyri, and bilateral basal ganglia, consistent with prior reports of motor learning (Fig. 1 yellow areas and Table 1) (Hanakawa et al., 2003). The peak cortical activation region (right M1) was used as the center of a seed region for functional connectivity analyses.

Participants reported thinking about the MST during the postperformance resting-state scan 16% ± 21% (SD) of the time. This percentage significantly correlated with the strength of resting-state connectivity between the right M1 seed region and other motor regions activated by MST performance, including the bilateral cerebellum (lobes V and VIIIa), bilateral frontal operculum, bilateral supplementary motor area (SMA), and the left precentral gyrus (Fig. 1 green areas and Table 2). In addition, the right lingual gyrus (Fig. 1 blue area), which is not a motor region and did not show significant task-related changes in activation, was inversely correlated with time spent thinking about the MST.

**Table 1. Clusters Showing Significant Task Activation During the Motor Sequence Task**

<table>
<thead>
<tr>
<th>Location of maxima</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>T-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left cerebellum (lobe V)</td>
<td>−21</td>
<td>−51</td>
<td>−21</td>
<td>21.0</td>
</tr>
<tr>
<td>Right precentral gyrus (BA 4)</td>
<td>51</td>
<td>−24</td>
<td>63</td>
<td>14.6</td>
</tr>
<tr>
<td>Left SMA (BA 6)</td>
<td>−6</td>
<td>6</td>
<td>54</td>
<td>16.1</td>
</tr>
<tr>
<td>Right putamen</td>
<td>36</td>
<td>3</td>
<td>12</td>
<td>16.9</td>
</tr>
<tr>
<td>Right cerebellum (lobe VIIIb)</td>
<td>24</td>
<td>−57</td>
<td>−21</td>
<td>14.2</td>
</tr>
<tr>
<td>Left thalamus</td>
<td>−15</td>
<td>−12</td>
<td>12</td>
<td>11.0</td>
</tr>
<tr>
<td>Left putamen</td>
<td>−24</td>
<td>0</td>
<td>12</td>
<td>8.8</td>
</tr>
<tr>
<td>Left middle frontal gyrus (BA 46)</td>
<td>−27</td>
<td>42</td>
<td>21</td>
<td>5.0</td>
</tr>
<tr>
<td>Left middle temporal gyrus (BA 37)</td>
<td>−48</td>
<td>−66</td>
<td>12</td>
<td>4.4</td>
</tr>
</tbody>
</table>

List of maxima locations, MNI coordinates and peak T-score for clusters with false discovery rate probability values q < 0.01. MNI, Montreal Neurological Institute; SMA, supplementary motor area.
Correlations of task-related post-training thought with connectivity in task-activated regions were seen only in the post-task resting scan. No such correlations were found between task-related thought and connectivity in task-related regions during the pretask scan, suggesting that the correlations with thinking about the task do not reflect trait-like patterns of functional connectivity. We have previously shown that connectivity of these regions did not correlate with learning of the task, as measured by either MST performance improvement during training or subsequent sleep-dependent improvement (Gregory et al., 2014). Post-training thought also did not correlate with task-related activation seen during MST training, either in any of the significant regions identified in the primary analysis (Fig. 1, green) or in the MST seed region (all p’s > 0.1).

**Discussion**

In conclusion, thinking about a recently learned motor task was associated with increased functional connectivity between motor brain areas that were activated during training. Control analyses demonstrated that there was no correlation (1) between post-training thought and either pretraining resting-state connectivity, task-related fMRI activation, or training task performance or (2) between the post-training connectivity of these regions and subsequent sleep-dependent task improvement.

Hence, the association of this connectivity pattern and thinking about the task are unlikely to be secondary to (1) a trait-like pattern of connectivity, (2) simple maintenance of connectivity patterns present during task training, or (3) tagging of the memory for subsequent sleep-dependent task improvement.

**Table 2. Regions in Which M1 Connectivity Is Significantly and Positively Associated with Thinking About the Task**

<table>
<thead>
<tr>
<th>Region</th>
<th>No. of Voxels</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>T-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left cerebellum (lobe V)</td>
<td>99</td>
<td>-12</td>
<td>-45</td>
<td>-18</td>
<td>5.29</td>
</tr>
<tr>
<td>Right frontal operculum (BA 44)</td>
<td>76</td>
<td>39</td>
<td>27</td>
<td>12</td>
<td>5.32</td>
</tr>
<tr>
<td>Left precentral gyrus (BA 6)</td>
<td>71</td>
<td>-30</td>
<td>-6</td>
<td>63</td>
<td>6.02</td>
</tr>
<tr>
<td>Left frontal operculum (BA 44)</td>
<td>58</td>
<td>-51</td>
<td>9</td>
<td>3</td>
<td>6.07</td>
</tr>
<tr>
<td>Right frontal operculum (BA 4)</td>
<td>58</td>
<td>57</td>
<td>9</td>
<td>15</td>
<td>6.45</td>
</tr>
<tr>
<td>Bilateral SMA (BA 6)</td>
<td>58</td>
<td>-6</td>
<td>0</td>
<td>60</td>
<td>5.85</td>
</tr>
<tr>
<td>Right cerebellum (lobe VIIIa)</td>
<td>45</td>
<td>15</td>
<td>-69</td>
<td>-45</td>
<td>5.67</td>
</tr>
</tbody>
</table>

Note that all regions show overlap with task-activation.
Several of the regions identified in our primary analysis play important roles in the conscious control of hand movements: the SMA (Roland et al., 1980) and frontal operculum (Tunik et al., 2008) are involved in planning of hand movements and the frontal operculum is involved in “mental ownership” in the rubber hand illusion (Ehrsson et al., 2004). In addition, the cerebellar regions (areas V and area VIIIa) are involved in sensorimotor processing (Stoodley and Schmahmann, 2009). The SMA is also involved in the temporal sequencing of hand movements (Roland et al., 1980; Shima and Tanji, 1998). Together, these earlier findings offer face validity for the conclusion that connectivity within this network can reflect thinking about the MST.

Obviously, thinking about any topic must be reflected in specific brain activity. However, it has been unclear how such activity can be measured. One approach has been through multivoxel pattern recognition (Norman et al., 2006), in which the subject consciously attends to specific sensory stimuli presented repeatedly. Our findings suggest another possible approach, as spontaneously thinking about prior actions is reflected in measurable changes in patterns of brain activity, specifically altering functional connectivity within circuits critical to the performance of those actions. Furthermore, they demonstrate that resting-state functional connectivity can be combined with a self-reported mentation questionnaire to investigate how thoughts alter activity in specific circuits within the human brain.

In this study, we used a remarkably simple self-report technique to probe conscious thought. The self-reporting occurred after the resting scan, and participants were not aware of the self-report requirement during the scanning session. We chose to collect the reports retrospectively, to avoid confounds associated with participants reporting their thoughts during scanning. Such reporting would also introduce a metacognitive task and thereby further alter patterns of brain connectivity.

In summary, we identified brain regions active during training on a motor task whose functional connectivity during a subsequent period of quiet rest correlated with retrospective self-reports of thinking about the task during that rest. This demonstrates the feasibility of using a combination of self-reports and functional connectivity analyses to study neural correlates of conscious thought.

Future work could apply a similar methodology to other domains, to determine patterns of functional connectivity associated with thinking about a wide range of cognitive and affective tasks. This may bring us closer to understanding the neural representations of conscious thought, both in experimental settings and in the natural environment.

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Author Disclosure Statement

The authors declare no competing financial interests.

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