A Neuronal Basis for Task-Negative Responses in the Human Brain

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Neuroimaging studies have revealed a number of brain regions that show a reduced blood oxygenation level-dependent (BOLD) signal during externally directed tasks compared with a resting baseline. These regions constitute a network whose operation has become known as the default mode. The source of functional magnetic resonance imaging (fMRI) signal reductions in the default mode during task performance has not been resolved, however. It may be attributable to neuronal effects (neuronal firing), physiological effects (e.g., task vs. rest differences in respiration rate), or even increases in neuronal activity with an atypical blood response. To establish the source of signal decreases in the default mode, we used the calibrated fMRI method to quantify changes in the cerebral metabolic rate of oxygen (CMRO₂) and cerebral blood flow (CBF) in those regions that typically show reductions in BOLD signal during a demanding cognitive task. CBF:CMRO₂ coupling during task-negative responses were linear, with a coupling constant similar to that in task-positive regions, indicating a neuronal source for signal reductions in multiple brain areas. We also identify, for the first time, two modes of neuronal activity in this network; one in which greater deactivation (characterized by metabolic rate reductions) is associated with more effort and one where it is associated with less effort.

Keywords: calibrated fMRI, default mode network, physiological artifacts, task-independent deactivation, task-negative BOLD response

Introduction

The default mode network (DMN) denotes a group of brain regions that show higher activity during rest (or nonspecific baseline conditions) than during a range of cognitive tasks (Shulman et al. 1997; Mazoyer et al. 2001; Raichle et al. 2001; McKiernan et al. 2003). Originally identified in a meta-analysis of positron emission tomography (PET) studies (Shulman et al. 1997), the network is observable both during task processing and the resting state (Beckmann et al. 2005; Damoiseaux et al. 2006; De Luca et al. 2006; Calhoun et al. 2008; Hasson et al. 2009). It is also reflected in anatomical connections (Greicius et al. 2009; van den Heuvel et al. 2009). The finding that the DMN is disrupted in Alzheimer’s disease and a number of other neurological conditions (Greicius et al. 2004; Buckner et al. 2008; Brody et al. 2009) has contributed to an explosion of interest into the function of this baseline brain activity. An enduring question underlying these investigations is whether the blood oxygenation level-dependent (BOLD) signal changes observed in the DMN during task performance are actually neuronal in origin or whether they reflect the contribution of various factors that are known to modulate the BOLD response, for example, respiration rate variations, signal related to heart rate, vascular effects, or activation with an atypical hemodynamic response.

The brain regions initially identified by Shulman et al. (1997) as showing consistent decreases in blood flow in PET during visual processing epochs relative to rest periods include an extended medial strip in frontal cortex and anterior cingulate cortex, the junction of the posterior cingulate cortex (PCC)/precuneus, and bilateral inferior parietal cortices and the amygda-hippocampal complex (Robinson et al. 2008). In addition to the generalized task-induced signal reductions observed in the DMN during task, several cases of negative BOLD responses have been documented for specific regions during the performance of particular tasks, including the occipital cortex for visual attention tasks (Tootell et al. 1998; Smith et al. 2000) and the ipsilateral primary sensorimotor cortex during sequential finger apposition (Allison et al. 2000). It has been postulated that the reduced activity could arise from a task-induced reduction in neuronal activation, neuronal inhibition, or redistribution of the blood supply during the visual task (Haxby et al. 1994; Shmuel et al. 2002). Using interleaved perfusion-BOLD measurements, Shmuel et al. (2002) showed that a reduction in task-specific neuronal activity is a significant contributor to the negative visual BOLD signal. Likewise, Stefanovic et al. (2004) used the calibrated functional magnetic resonance imaging (fMRI) approach to demonstrate that in motor regions, task-specific negative BOLD response is primarily attributable to neuronal deactivation. Considering baseline effects and applying calibrated fMRI, Pasley et al. (2007) showed that in the visual cortex, negative BOLD responses reflected decreases in activation rather than blood stealing or other hemodynamic artifacts.

While these studies have shown that task-dependent deactivation in visual and motor cortices is predominantly neuronal in origin and not driven by vascular steal (Shmuel et al. 2002; Hansen et al. 2004; Stefanovic et al. 2004; Pasley et al. 2007), the results cannot in principle be extrapolated as a general explanation for responses in the DMN. The reason for this is that the DMN is a network that is strongly responsive during performance of high-level cognitive tasks (as opposed to simply low-level visual and motor activity) and is a highly distributed network, the function of which has yet to be conclusively determined. In the absence of a calibrated fMRI study into deactivation of the DMN, it has been difficult to derive conclusions about the source of these task-negative responses.

There has also been a reemergence of controversy regarding deactivation in the DMN in the light of several studies showing that the distribution of DMN regions overlaps with the distribution of regions whose BOLD patterns show sensitivity to respiration- and cardiac-induced variation (Wise
demonstrated in the visual (Hoge et al. 1999a), sensorimotor engender large changes in CBF, with CMRO₂ remaining mostly different. Hypercapnia, for instance, is generally considered to BOLD changes caused by non-neuronal factors is quite

et al. 2007) and task-dependent deactivation (Shmuel et al. 2007; Chang et al. 2004; 23 ms, Chiarelli et al. 2007; 25 ms, Chen and Pike 2009; and 27 ms, Luh et al. 1999; at 4 T of 26 ms, Uludag et al. 2004). Additionally, we selected a design with long task blocks so that few data points were sampled during transition phases. Finally, we used sinc subtraction of images, in which estimates are generated of the labeled signal that would have been obtained if the labeled images were acquired at the same time as the control images. This is an
effective means of reducing BOLD contamination (Aguiire et al. 2002).

Data analysis was performed using AFNI (Cox 1996) and MATLAB software written in-house. The first 4 volumes of each functional run were excluded from analysis to allow for quasi-equilibrium in longitudinal magnetization to be achieved. Motion correction was performed using 3D rigid-body registration to the first retained image in each run. Images were spatially smoothed with a Gaussian kernel of 6 mm full-width at half-maximum (FWHM).

The perfusion image series was generated by sinc subtraction of the label and control images, followed by conversion to absolute CBF image series based on the kinetic model (Buxton et al. 1998). The BOLD signal was calculated by averaging adjacent tag and control images.

fMRI Data Analysis of BOLD and CBF Data

Single-subject functional activation and deactivation maps from BOLD and CBF time series were estimated using the General Linear Model. For the second-level (group) analysis, single-subject contrast maps were normalized to the Talairach coordinate reference system (Talairach and Tournoux 1988) using AFNI. Activated areas were identified using Talairach coordinates and human brain atlases (Talairach and Tournoux 1988). Multisession activation contrast maps were computed with 2-sided t-tests across subjects (a random effects analysis with participants as a random factor). Family-wise error (FWE) control for multiple comparisons was set at $P < 0.05$ and established using cluster-level thresholding. The single voxel level was set at $P < 0.001$ and simulations (following Forman et al. 1995 as implemented in AFNI's AlphaSim) indicated that a reliable cluster would need to exceed 5 connected voxels to be considered reliable at this FWE level.

Subject-specific regions of interest (ROIs) were defined to allow characterization of deactivations in the DMN as well as task-induced activation. ROIs defined on the basis of anatomy or BOLD activation results are liable to include draining veins that may affect the accuracy of coupling ratios, whereas CBF activation results are better localized in the parenchyma (Leontiev et al. 2007). To avoid contamination by draining veins, ROIs were defined via the overlap between supra- and infra-cortical regions. The magnitude of BOLD signal changes observed here (around ±1%) was similar to that observed in previous studies with sensory stimuli at 3 and 4 T (e.g., ~2% in visual areas in Leontiev et al. 2007, ~1% in Ances et al. 2008) and slightly higher than that observed elsewhere with cognitive stimuli (e.g., ~0.5% in a memory task in Restom et al. 2008).

Estimation of Functional Changes in CMRO$_2$

Relative task-induced changes in CMRO$_2$ can be calculated from relative changes in BOLD and CBF using the following relation (see Davis et al. 1998 and Hoge et al. 1999b for a derivation):

$$\frac{\text{CMRO}_2}{\text{CMRO}_2} = \left(1 - \frac{(\text{BOLD}/\text{BOLD})_a}{M}\right)^2 \left(\frac{\text{CBF}}{\text{CBF}}\right)$$

where the subscripts "0" refer to the baseline values. The parameter $\alpha$ describes the relationship between CBV and CBF changes, and was taken to be 0.38 (Grubb et al. 1974). The parameter $\beta$ is a proportional constant related to the deoxyhemoglobin concentration in blood and was taken to be 1.3 (Buxton 2002). The parameter $M$ is a proportional constant related to BOLD, CBF, and CBV changes and represents the maximum possible BOLD signal change that can be measured in a particular region. $M$ has been estimated experimentally in hypercapnia studies at different field strengths (Table 1) and found to be within a range of 5.7-25 in the regions listed in the table (Uludag et al. 2004; Chiarello et al. 2007; Leontiev and Buxton 2007; Ances et al. 2008; Restom et al. 2008). Given inherently large errors in these iso-CMRO$_2$ measurements, we follow the practice of a number of recent studies in assessing CMRO$_2$/CBF coupling over a range of $M$ suggested by the literature (Shmuel et al. 2002; Uludag et al. 2004; Pasley et al. 2007; Lin et al. 2008; Qiu et al. 2008; Chen and Pike 2009; Wu et al. 2009). The CMRO$_2$/CBF ratio was calculated as the percent change in oxygen metabolism (ΔCMRO$_2$) to the percent blood flow change (ΔCBF).

Results

Active and Deactive Brain Regions during a Mathematical Task

Participants in the fMRI study completed blocks of mathematical tasks that were separated by rest periods. As a validation check, we first examined patterns of activation and deactivation relative to rest during the mathematical task. These analyses were conducted separately using the BOLD and CBF data. Establishing the validity of both measures was a necessary step as CMRO$_2$ measures were derived via an equation that takes both BOLD and CBF as parameters.

Activation maps (Fig. 1) based on BOLD or CBF data were quite similar, showing the involvement of regions known from previous studies to be associated with mathematical processing (Kawashima et al. 2004; Fehr et al. 2008). Deactivation was also present in areas commonly referred to as the "default mode network" (Binder et al. 1999; Mazoyer et al. 2001). Thus, the basic findings indicate the validity of measurements in relation to prior work and demonstrate that both CBF and BOLD provide robust group-level results. On the basis of these findings, we established ROIs for subsequent analyses (see Table 2 for Montreal Neurological Institute coordinates and labels). For each of the active and deactive region, BOLD, CBF, and CMRO$_2$ changes were calculated relative to rest.

Scatter plots of BOLD and CBF signal changes in each of the ROIs considered are shown in Supplementary Figure 1. Every combination of BOLD and perfusion value corresponds to a specific rate of oxygen consumption, allowing the evaluation of the dynamic ranges of these values for different brain regions. The magnitude of BOLD signal changes observed here (around ±1%) was similar to that observed in previous studies with sensory stimuli at 3 and 4 T (e.g., ~2% in visual areas in Leontiev et al. 2007, ~1% in Ances et al. 2008) and slightly higher than that observed elsewhere with cognitive stimuli (e.g., ~0.5% in a memory task in Restom et al. 2008).

Neurovascular Coupling in Deactive Regions: Linear and Same as in Task-Active Regions

CMRO$_2$ was estimated using a validated neurovascular coupling model (eq. 1) (Davis et al. 1998). The parameter $\alpha$ was taken to be 0.38 (Grubb et al. 1974), and $\beta$ was taken to be 1.3 (appropriate to the 4 T field strength of this study; Buxton 2002). The most suitable value of the model parameter $M$ for 4 T is 25% (Uludag et al. 2004). This value was also adopted by Pasley et al. (2007) for their 4 T study. The CMRO2/CBF coupling ratio was estimated separately for each of the task-activated areas (RMOG, LMOG, LIFG) and for each of the deactivated areas (PCC, LANG, RANG, and LMPFC) (see Figure 2; activated areas are in plotted in red, deactivated areas in blue).

All regions—both task active and deactivate—demonstrated a strong linear correlation between CMRO$_2$ and CBF ($R^2 = 0.99$). The coupling was found to be well described by a linear relationship, with similar slopes for all regions: 0.62 ± 0.02 (PCC), 0.60 ± 0.04 (RANG), 0.62 ± 0.05 (LANG), 0.59 ± 0.03 (LMPFC), 0.59 ± 0.02 (RMOG), 0.62 ± 0.01 (LMOG), and 0.62 ± 0.01 (LIFG). Taken together, these results show that
deactivated regions in the DMN demonstrate a CMRO$_2$/CBF coupling that is identical in nature to that found in task-active regions. These results therefore provide strong support for the hypothesis that these deactivations are grounded in neural sources.

We used the most appropriate parameters in estimation of CMRO$_2$ using the neurovascular model (eq. 1) but also conducted an additional parameter sweep to determine how reliant our findings were on the values of $\alpha$, $\beta$, and $M$, since these dictate the accuracy of CMRO$_2$ estimation (Leontiev et al. 2007). We found that the linear relationship between CMRO$_2$ and CBF and the highly similar slopes found for active and deactivate areas held under a wide range of parameters values adopted for the parameters $M$, $\alpha$, and $\beta$ in the neurovascular model (ranges: $\alpha = 0.15$–0.45, $\beta = 1.0$–1.6, and $M = 5.7$–25%) (see Supplementary Figure 2 and Table 1). The value of the coupling ratio seen for deactivation was not significantly different from that for activation, except for at low values of $M$.

**Table 1**

| CMRO$_2$/CBF coupling ratios and linear correlation | Task-dependent activation areas |
|----------------------------------------------------|--------------------------------|
| DMN deactivation areas                             | RMOG | LMOG | LIFG |
| PCC | 0.47 ± 0.12 | 0.43 ± 0.24 | 0.46 ± 0.13 | 0.47 ± 0.09 | 0.57 ± 0.06 | 0.58 ± 0.07 |
| RANG | 0.49 ± 0.11 | 0.45 ± 0.15 | 0.45 ± 0.22 | 0.47 ± 0.12 | 0.48 ± 0.08 | 0.58 ± 0.05 | 0.59 ± 0.06 |
| LANG | 0.52 ± 0.09 | 0.45 ± 0.13 | 0.49 ± 0.18 | 0.50 ± 0.10 | 0.50 ± 0.06 | 0.59 ± 0.04 | 0.59 ± 0.05 |
| LMPFC | 0.53 ± 0.08 | 0.47 ± 0.11 | 0.51 ± 0.16 | 0.51 ± 0.09 | 0.51 ± 0.06 | 0.59 ± 0.04 | 0.60 ± 0.05 |
| M = 5.7' | 0.52 ± 0.09 | 0.52 ± 0.15 | 0.52 ± 0.08 | 0.52 ± 0.05 | 0.59 ± 0.03 | 0.60 ± 0.04 | 0.60 ± 0.05 |
| M = 6.3' | 0.50 ± 0.08 | 0.47 ± 0.04 | 0.48 ± 0.07 | 0.48 ± 0.05 | 0.59 ± 0.02 | 0.60 ± 0.01 | 0.61 ± 0.03 |
| M = 7.5' | 0.49 ± 0.08 | 0.49 ± 0.07 | 0.52 ± 0.12 | 0.54 ± 0.06 | 0.54 ± 0.04 | 0.60 ± 0.03 | 0.61 ± 0.03 |
| M = 8.3' | 0.52 ± 0.09 | 0.52 ± 0.09 | 0.48 ± 0.07 | 0.48 ± 0.08 | 0.59 ± 0.02 | 0.62 ± 0.01 | 0.62 ± 0.01 |
| M = 9.2' | 0.49 ± 0.08 | 0.49 ± 0.07 | 0.52 ± 0.12 | 0.54 ± 0.06 | 0.54 ± 0.04 | 0.60 ± 0.03 | 0.61 ± 0.03 |
| M = 11.1' | 0.50 ± 0.08 | 0.49 ± 0.08 | 0.48 ± 0.07 | 0.48 ± 0.08 | 0.59 ± 0.02 | 0.62 ± 0.01 | 0.62 ± 0.01 |
| M = 25' | 0.49 ± 0.08 | 0.49 ± 0.07 | 0.52 ± 0.12 | 0.54 ± 0.06 | 0.54 ± 0.04 | 0.60 ± 0.03 | 0.61 ± 0.03 |

* M measured in visual cortex, 13 subjects, 21–56 years, 3 T (Ances et al. 2008).
* M measured in motor cortex, 6 subjects, 24–32 years, 3 T (Chiarelli et al. 2007).
* M measured in visual cortex, 6 subjects, 24–32 years, 3 T (Chiarelli et al. 2007).
* M measured in lentiform nuclei, 13 subjects, 21–56 years, 3 T (Ances et al. 2008).
* M measured in medial temporal lobe, 9 subjects, 21–29 years, 3 T (Restom et al. 2008).
* M measured in visual cortex, 10 subjects, 24–40 years, 3 T (Leontiev and Buxton 2007).
* M measured in visual cortex, 8 subjects, 4 T (Uludag et al. 2004).

Figure 1. Functional maps of task-induced changes in BOLD (left) and CBF (right) patterns, averaged over 12 subjects. The activation (red) and deactivation (blue) maps ($|r| < 0.001, r-values in color bars) are superimposed onto a T$_1$-weighted anatomical image in Talairach space.

Figure 2. Neurovascular coupling between CMRO$_2$ and CBF in task-active and task-deactive regions (12 subjects). Each data point depicts CMRO$_2$ and CBF signal changes during the mathematical task relative to the resting condition for a subject in 1 ROI. Coupling ratios quoted in the main text are the results of linear fits to results for each ROI. The linear fits in this figure are over all activated regions and (separately) all deactivation regions, and are very similar to the separate ROI results.
To examine this issue, we normalized participants' CMRO\textsubscript{2} changing transient states occurring in one run but not another. This was done to ensure that any differences in CMRO\textsubscript{2} values were not attributed to individual variance, but rather to rapidly changing transient states occurring in one run but not another. To this end, we first tested whether participants' CMRO\textsubscript{2} results were reproducible across the 3 task sessions. Large variations across sessions would point to substantial within-participant variance and would indicate in turn that there are no strong grounds for examining the relation between CMRO\textsubscript{2} and participant behavior. Specifically, if CMRO\textsubscript{2} measures were not consistent across the 3 sessions, weak CMRO\textsubscript{2}:behavior associations would not be meaningful, and reliable effects could not be attributed to individual variance, but rather to rapidly changing transient states occurring in one run but not another. To examine this issue, we normalized participants' CMRO\textsubscript{2} scores in each ROI, for each of the 3 sessions (resulting in distributions with standard deviation [SD] approximately equal to 1, by definition, for each region and session). For each participant, we calculated the SD of the Z scores in the 3 sessions (consistency $= \frac{\sigma(\bar{Z})}{\bar{Z}}$) and tested if this value differed from chance (i.e., consistency $< 1$) on the group level. In 4 of the 6 ROIs, participants demonstrated reliable consistency (LANG, LMPFC, RMOG, LMOG, $P < 0.01$). In PCC and RANG, consistency was lower than 1, though this difference was not significant at the group level ($P = 0.10$). Nonetheless, even in these regions, at least 6 participants demonstrated statistically reliable consistency across sessions ($P < 0.05$ for each of these 6 participants as determined by permutation tests), which is highly significant at the group level on a binomial test ($P < 0.00001$).

To conclude, CMRO\textsubscript{2} measures were consistent in task-active and task-deactive regions. Having established consistency, we examined whether changes in CMRO\textsubscript{2} predicted participant’s behavior during task performance. To assess the relation between CMRO\textsubscript{2} and behavior, we used a regression method that is robust against univariate outliers in the data, as implemented using a robust linear model procedure ($rlm$) of the R statistical language (R Development Core Team 2009). Such robust regression methods have been proposed for analysis of both behavioral data (Wilcox 1998) and neuroimaging data (Wager et al. 2005). We correlated participants' CMRO\textsubscript{2} values obtained in the 3 sessions ($N = 36$) against their behavioral measures during those sessions. We found significant CMRO\textsubscript{2}:behavior correlations in 3 areas showing deactivation (all $P$ values $< 0.05$ using robust regression, see Fig. 3). In the PCC and RANG, the association was negative: Metabolic activity decreases relative to rest were associated with greater task effort, as reflected by time on task and its stability. However, the LMPFC showed a positive correlation, with metabolic activity approaching that found at rest as task difficulty increased.

These results show, for the first time using metabolic measures, evidence for different functional roles being played by frontal and posterior areas. Similar analyses using the BOLD measures revealed high consistency in BOLD data across sessions, but no correlations with behavioral measures. The use of robust regression methods allows reduction of the contribution of extreme data points in a data set. For this reason, it is difficult to judge whether correlations are significantly different (i.e., construct a sampling distribution for differences between correlation values), and we can therefore not determine whether the BOLD:behavior and CMRO\textsubscript{2}:behavior relations differed reliably.

Given that there was a positive correlation between CMRO\textsubscript{2} and task duration in LMPFC but this region was deactivated in all participants/sessions, we conducted a principal component analysis (PCA) to examine whether participants' CMRO\textsubscript{2} values in the LMPFC were more closely associated with activity patterns in task-active regions or task-deactive regions. To this end, we submitted all CMRO\textsubscript{2} values for each session and participant (36 sessions in all), in each of the 7 regions considered, to PCA (i.e., a 36-session $\times$ 7-region matrix). The procedure identified 2 factors with eigenvalues above 1, accounting for 66% of the variance in CMRO\textsubscript{2} values. The first factor (accounting for 40% of the variance) was positively correlated with CMRO\textsubscript{2} measures in the PCC, RANG, and LANG (0.4, 0.7, and 0.9, respectively), but negatively correlated with CMRO\textsubscript{2} measures in RMOG, LMOG, and LMPFC (-0.8, -0.6, and -0.3, respectively). Thus, this component strongly discriminated between task-active and task-deactive regions, as would be expected, but with the important exception of associating LMPFC with task-active regions in the solution (the second factor was not clearly interpretable and we do not discuss it here). The finding that activity in LMPFC is positively correlated with time on task is strongly corroborated by a recent analysis of BOLD data showing such positive correlation in a large group of subjects ($N = 252$; Yarkoni et al. 2009). Thus, even though this region is associated with reduced activity during task performance (vs. rest), its correlation pattern diverges from that found for other regions in the DMN. The PCA also implies that participants with lower CMRO\textsubscript{2} measures in "deactive" regions tended to have higher CMRO\textsubscript{2} values in active regions, with the exception of the LMPFC, which tended to cluster with active regions.

Interestingly, an identical PCA applied to the BOLD data in the 36 sessions communicated similar information, with an important caveat: This analysis (36 sessions $\times$ 7 regions) identified a first component that loaded positively and strongly on all regions. A second component loaded negatively on PCC, RANG, and LANG but positively on RMOG, LMOG, and LMPFC (jointly accounting for 60% of total variance). Thus, the second component found in the analysis of BOLD data resembles that identified in the analysis of CMRO\textsubscript{2} data. In contrast, the first highly general component identified in the BOLD data could be driven by systemic cross-subject differences in CBF, which may introduce strong correlations between BOLD data in all regions. Since CBF is partialed when deriving CMRO\textsubscript{2} values, this factor is not found in analyses of CMRO\textsubscript{2} data.

**Discussion**

We have investigated the sources of the common observation that large parts of the human brain appear to manifest lower
activity during task periods than during rest when assessed using BOLD fMRI. Our results challenge recent claims that the dominant source of these deactivations may be non-neural physiological effects such as vascular steal, abnormal neurovascular coupling (Villringer and Dirnagl 1995; Shmuel et al. 2002), or task-locked fluctuations in respiratory rate (Diamond et al. 2005; Brin et al. 2006). We used calibrated fMRI in healthy subjects to determine CMRO$_2$ changes in regions showing decreased CBF during a demanding cognitive task. CMRO$_2$ is more directly correlated with neural activity than BOLD and indexes regional oxygen consumption and metabolism. Across participants, deactive regions demonstrated a linear CMRO$_2$/CBF relation, characteristic of neuronal activity. CMRO$_2$/CBF ratios were identical to those found in task-active areas. Furthermore, task-negative regions corresponded well with the task-independent deactivation areas reported in meta-analyses of deactivation effects (Shulman et al. 1997) and more recent work (Binder et al. 1999; Hutchinson et al. 1999; Mazoyer et al. 2001; McKiernan et al. 2003; Fransson 2005). Taken together, our results demonstrate a neuronal basis for the task-independent deactivation network.

To our knowledge, this is the first fMRI study to characterize sources of task-independent deactivation with perfusion MRI, and the first to use the calibrated fMRI approach to investigate the default mode. Prior work using calibrated fMRI has examined functional connectivity in resting-state networks based on CMRO$_2$ synchronization (Wu et al. 2009), or characterized CMRO$_2$/CBF neurovascular coupling in task-active regions (Hoge et al. 1999a) or in sensory regions that show deactivation under particular task contexts, but not related to the DMN (Shmuel et al. 2002; Stefanovic et al. 2004; Uludag et al. 2004; Restom et al. 2008). Our calibrated fMRI procedure was designed to compare the neurovascular coupling in task-specific activated areas with that found in DMN areas that tend to be deactive independent of particular tasks. We find that the CMRO$_2$/CBF coupling ratio in deactivated regions is essentially identical to that found in active regions, with the numeric values for the slope of the relationship (~0.6) falling within the range reported for other areas in other studies (Hoge et al. 1999a; Atkinson et al. 2000; Kastrup et al. 2002; Stefanovic et al. 2004, 2005).

The quantitative model we used to calculate CMRO$_2$ (Davis et al. 1998) incorporates parameters determined by hypercapnia studies under the assumption that carbogen breathing does not modify neuronal activity or CMRO$_2$. A recent study indicates that while neural activity is reduced during hypercapnia with 6% CO$_2$, it is not significantly affected by a more moderate 3% hypercapnia in the anaesthetized monkey (Zappe et al. 2008). This confirms the validity of the Davis model for the range of ΔBOLD and ΔCBF changes investigated here.

In our study, we used Grubb’s equation to model the relationship between CBV and CBF ($\gamma = \text{CBV}/\text{CBF}$), where $\gamma$ was assumed to have a constant value in space and in time. Despite the fact that we evaluated and confirmed our results...
for a range of possible values of $\alpha$ (0.15–0.45, covering human measurements reported in the literature), in using this model there are 2 important assumptions: spatial uniformity and temporal stability. Recent human MRI (Chen and Pike 2009) and PET studies (Rostrup et al. 2005) do not reveal significant spatial variability in $\alpha$, although a finer scale spatial non-uniformity might be present (as observed in animal studies; Wu et al. 2002; Jin and Kim 2008). Similarly, dynamic changes of $\alpha$ have recently been reported in the somatosensory cortex of anaesthetized rats studied with magnetic resonance contrast agents and single-slice fMRI during fast dynamic resolution during forepaw stimulation of different duration periods (Kida et al. 2007). These findings show that estimates of $\alpha$ can vary significantly between the phases of CBF rise, plateau, and decline (depending on stimulation duration). It is not yet clear whether $\alpha$ differs between rest, plateau, and activation (let alone during deactivation) in humans, but the study of Kida et al. shows that further work is needed to validate this aspect of the calibrated fMRI approach.

Recent studies have shown that inaccuracies can be introduced into the estimation of CMRO$_2$/CBF coupling by the parameters used to describe the neurovascular model, including the calibration constant $M$ (Chiarelli et al. 2007). For this reason, and following the approach used in other studies, we tested the sensitivity of our results to the parameters chosen for the neurovascular model (Shmuel et al. 2002; Uludag et al. 2004; Lin et al. 2008; Schridde et al. 2008; Wu et al. 2009). We found that CMRO$_2$/CBF coupling was linear for active and deactive areas over the entire parameter space.

In considering these findings, we have used the term “deactivation” as it has been used by prior researchers who have examined task-induced signal changes in sensory (visual and motor) cortices to denote task-negative responses (Allison et al. 2000; Lustig et al. 2003; Greicius and Menon 2004; Stefanovic et al. 2004; Pasley et al. 2007). In general, the negative response we have documented may reflect decreased excitatory input or a reduction in CBF and metabolism caused by synaptic inhibition due to the interaction of $\gamma$-aminobutyric acid with its receptors (Lauritzen 2001; Gold and Lauritzen 2002). However, studies to date have used the term deactivation without implying that the processes causing task-negative responses are different from those causing task-positive responses. The DMN shows lower BOLD signal during high-demand tasks than during low-demand tasks or rest. This has, for consistency with the above convention, often been labeled TID, used as an abbreviation for both “task-induced deactivation” (McKiernan et al. 2003; Thomason et al. 2008) and “task-independent deactivation” (Shulman et al. 1997; Meyer-Lindenberg et al. 2001; Raichle et al. 2001; Laufs et al. 2003; Minzenberg et al. 2008; Yan et al. 2009). Because fMRI only offers relative measures, one cannot conclude, on the basis of fMRI information alone, whether the task state or the active state represents the “baseline” state for DMN processes. In the PET study of Raichle et al. (2001), however, absolute oxygen extraction fraction measurements indicated that localized activity decreases reflect a decrease from baseline, rather than a return to it. This would support the tendency to denote these as “task-negative” responses (i.e., deactivation). Others have chosen to see these signal changes as rest-specific activity increases (Buckner et al. 2008). In the current work, we do not make any presumptions about the nature of the underlying neuronal processes, or try to distinguish between “task-negative BOLD responses” and “rest-positive BOLD responses.” Our aim was restricted to determining whether these signal changes arise due to neuronal or other causes.

Our results show that in several deactive regions, CMRO$_2$ values were associated with behavioral measures indicating more effortful task performance. In PCC and RANG, greater effort was associated with greater deactivation, supporting prior work suggesting that greater attention to task is associated with a reduced BOLD signal in these areas (McKiernan et al. 2003). Instead, the opposite pattern was observed in the medial prefrontal cortex, which was deactive for all participants but showed “reduced deactivation” (i.e., greater activation, though below baseline) for more effortful processing. In other words, as the time spent processing a task increased, CMRO$_2$ values became more similar to those at rest. This singular pattern in medial prefrontal cortex corroborates recent suggestions that it constitutes a unique node within the deactivation network. Several resting-state studies show an anterior-posterior division in the task-independent deactivation networks when the temporal characteristics of the responses are evaluated (Beckmann et al. 2005; Damoiseaux et al. 2006, 2008; Calhoun et al. 2008). In addition, recent sleep studies with simultaneous electroencephalography-fMRI show that during deep sleep there is a decoupling of frontal areas from the DMN (Horovitz et al. 2009). In another work, a middle prefrontal region overlapping with the medial region identified here showed unique connectivity measures with DMN seed regions (Hasson et al. 2009): As opposed to other regions, it demonstrated stronger connectivity during task than rest, particularly for participants performing well on the task. These results suggest that medial prefrontal cortex may regulate the degree of deactivation in other regions as function of task involvement or task demands.

Finally, we note that the analyses we performed, which were based on conventional acquisitions, sensitive to the BOLD contrast, revealed similar patterns of activation and deactivation as well as strong within-participant consistency in activity across sessions. However, the BOLD data failed to reveal brain-behavior correlation patterns. Overall, our calibrated fMRI results show that deactivations patterns, when assessed via CMRO$_2$, do change as a function of interindividual differences, but the nature of these changes is nonhomogenous in the DMN, indicating functional variability among its nodes.

Taken together, our findings indicate a neuronal source for deactivation in multiple brain areas and identify for the first time two modes of neuronal activity in the DMN: one in which greater deactivation (characterized by larger metabolic rate reductions relative to rest) is associated with more effort and one where it is associated with less effort. Our results also suggest that the assessment of CMRO$_2$ or comparable indexes of neuronal activity during task and rest is important for quantifying and understanding deactivation patterns in the human brain and their implications for both healthy and clinical populations.

**Funding**

Government of the Provincia Autonoma di Trento, Italy, Project PAT Post-doc 2006; Fondazione Cassa di Risparmio di Trento e Rovereto; and University of Trento, Italy.
Supplementary Material

Supplementary material can be found at: http://www.cercor.oxfordjournals.org/

Notes

Conflict of Interest: None declared.

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