

Tasks Driven by Perceptual Information Do Not Recruit Sustained BOLD Activity in Cingulo-Opercular Regions

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Sustained blood oxygen level dependent (BOLD) signal in the dorsal anterior cingulate cortex/medial superior frontal cortex (dACC/msFC) and bilateral anterior insula/frontal operculum (aI/FO) is found in a broad majority of tasks examined and is believed to function as a putative task set maintenance signal. For example, a meta-analysis investigating task-control signals identified the dorsal anterior cingulate cortex and anterior insula as exhibiting sustained activity across a variety of task types. Re-analysis of tasks included in that meta-analysis showed exceptions, suggesting that tasks where the information necessary to determine a response was present in the stimulus (i.e., perceptually driven) does not show strong sustained cingulo-opercular activity. In a new experiment, we tested the generality of this observation while addressing alternative explanations about sustained cingulo-opercular activity (including task difficulty and verbal vs. non-verbal task demands). A new, difficult, perceptually driven task was compared with 2 new tasks that depended on information beyond that provided by the stimulus. The perceptually driven task showed a lack of cingulo-opercular activity in contrast to the 2 newly constructed tasks. This finding supports the idea that sustained cingulo-opercular activity contributes to maintenance of task set in only a subset of tasks.

Keywords: cognitive control, fMRI, sustained BOLD, task-control signals, task set

Introduction

The human brain is a complex network of regions that interact to allow for performance of a vast array of tasks, often including accurate performance on relatively novel and difficult tasks. In order to perform a task, humans are presumed to adopt a task-specific cognitive set [e.g., Logan and Gordon (2001)]. A task set is a collection of cognitive processes that is maintained to allow task performance (Sakai 2008). Two task sets may be identical in stimulus inputs (e.g., visually presented words) and responses (e.g., button press) but differ in the rules of association that connect the stimulus and response (e.g., semantic vs. physical judgments; Rogers and Monsell 1995; Sakai and Passingham 2003, 2006; Sakai 2008; Koch et al. 2010). For example, a button-press response to the stimulus “ALLIGATOR” would be mapped differently for a Living/Nonliving judgment versus a Big/Small judgment.

The implementation of a task set presumably requires task-related control signals in the brain. Plausible task-control signals would include 1) task-initiation signals required to drive the starting of a task and the loading of the proper task set

“parameters” (Donaldson, Petersen, and Buckner 2001; Donaldson, Petersen, Ollinger, et al. 2001; Konishi et al. 2001; Fox et al. 2005); 2) task maintenance signals to sustain these parameters throughout task performance (Chawla et al. 1999; Donaldson, Petersen, and Buckner 2001; Donaldson, Petersen, Ollinger, et al. 2001; Dosenbach et al. 2006); 3) performance-related feedback signals (e.g., error- or conflict-related signals) that could be used to adjust task parameters when the task is performed incorrectly or with considerable effort. The development of the mixed block/event-related fMRI design (henceforth referred to as the mixed design) (Chawla et al. 1999; Donaldson, Petersen, and Buckner 2001; Donaldson, Petersen, Ollinger, et al. 2001; Visscher et al. 2003; Dosenbach et al. 2006; Petersen and Dubis 2012) allowed for each of these signal types to be extracted separately, with the putative task maintenance signal characterized as a sustained activation across the entirety of the task block (Chawla et al. 1999; Donaldson, Petersen, and Buckner 2001; Donaldson, Petersen, Ollinger, et al. 2001; Otten et al. 2002; Velanova et al. 2003).

A meta-analysis by Dosenbach et al. (2006) searched for commonalities of these task-control signals across mixed design studies of 10 tasks. The tasks were diverse in that they had a variety of input modalities, stimulus sets, task demands, and response modalities. They identified sets of regions that were commonly recruited for 1 or more of the task-control signals.

Three regions—the dorsal anterior cingulate cortex/medial superior frontal cortex (dACC/msFC) [−1, 10, 46 (Talairach and Tournoux 1988)] and bilateral anterior insula/frontal operculum (aI/FO) [−35, 14, 5 and 36, 16, 4 (Talairach and Tournoux 1988)] were found to exhibit all 3 task-control signals in several of the tasks and were unusual in that they exhibited strong sustained signals in a broad majority of tasks. These cingulo-opercular regions are shown on a positive fixed-effects analysis across these tasks (Fig. 1) (Dosenbach et al. 2007, 2008).

Of particular interest for this paper is the observation that these 3 regions exhibited a positive, sustained blood oxygen level dependent (BOLD) signal in many, but not all, tasks. Identifying task properties that produced exceptions might help to characterize the functional role of the sustained BOLD signal. Figure 2 depicts a modified reproduction of the sustained magnitudes for the dACC/msFC region across the diverse tasks included in Figure 7B of Dosenbach et al. (2006). Our version of this figure has been modified in 2 ways: First, we used 10-mm spheres centered at the coordinates instead of defined voxel patches, which allows for better uniformity across data sets, so that we could better compare the signals

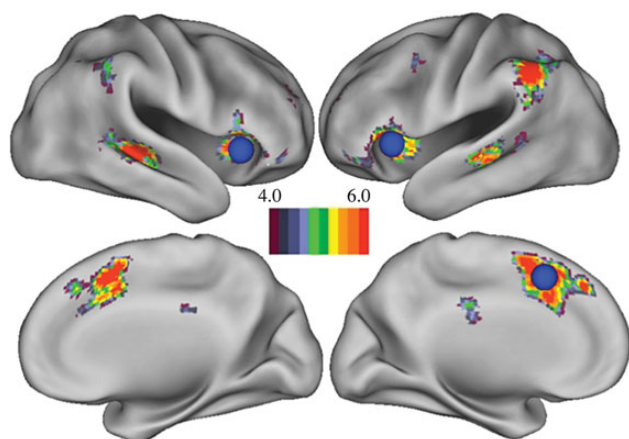


Figure 1. Meta-analytic positive sustained fixed-effects analysis conducted in Dosenbach et al. (2006) and *a priori* region identification. Dosenbach et al. (2006) summed the positive sustained BOLD signal from 10 contrasting tasks and then divided by square root of n to create fixed-effects map. Color scale reflects z -score calculated in fixed-effects analysis. The dorsal anterior cingulate cortex/medial superior frontal cortex and bilateral anterior insula/frontal operculum were identified as having all 3 control signals across tasks. The corresponding regions identified in the sustained BOLD signal meta-analysis were identified and indicated here with 10-mm-diameter spheres shown here on a Caret inflated surface (Van Essen et al. 2001). These regions are used in subsequent analyses as the *a priori* regions.

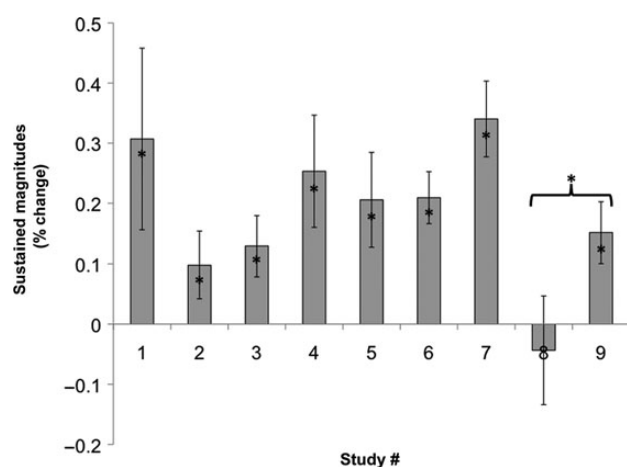


Figure 2. Sustained magnitudes from 9 studies included in Dosenbach et al. (2006) meta-analysis as measured in dorsal anterior cingulate cortex/medial superior frontal cortex region defined in Dosenbach et al. (2006) (tenth study (Verb Generation Task) included in Dosenbach et al. (2006) is excluded here because of quality of data). The studies include 1) Letter Identification, 2) Object Naming, 3) Reading, 4) Matching of Letters, 5) Living/Nonliving Judgment, 6) Physical and Semantic Judgments, 7) Motortiming Pattern Matching, 8) Visual Search, and 9) Abstract/Concrete Judgment. Studies #8 and #9 performed on within-subject basis. Significant levels (one-sample t -test against zero) as follows: * $P < 0.05$. Reliability analysis between studies #8 and #9 shown with bracket and reliability level: * $P < 0.05$.

across tasks. Second, we omitted the verb generation study [study #2 in Dosenbach et al. (2006)] because we have since discovered that these data include significant artifact. Despite sustained cingulo-opercular activity in the majority of the tasks analyzed, an apparent exception existed in study #8, a visual search paradigm task.

The visual search task was paired, on a within-subject basis and within a single experimental session, with an auditory abstract/concrete task (study #9), which appeared to elicit

sustained BOLD activity in *a priori* regions suggesting that this was not a subject effect. The 2 tasks were compared to determine how reliable the within-subject task difference was (only descriptive statistics are valid here as a result of previously observing the magnitude differences). The tasks showed reliable (two-tailed, paired t -test, $P < 0.05$) differences in the dACC/msFC and left aI/fO. The auditory task elicited significant (one-sample t -test against zero with one-tail, $P < 0.005$) sustained BOLD activity in each of the 3 regions. The visual task only elicited significant (one-sample t -test against zero with one-tail, $P < 0.05$) sustained BOLD activity in the right aI/fO region. This paper explores potential reasons for this apparent discrepancy.

So what might be the differences between the visual search and other tasks? Many of the other tasks have verbal (1, 2, 3, 5, 6, 9) or meta-linguistic (4, 5, 6, 9) processing demands. Only in the visual search task (8) does the stimulus contain all the information necessary to produce an accurate response. For instance, the auditory abstract/concrete task (9, performed by the same subject group) that does show strong cingulo-opercular activity requires the extraction of semantic information from the stimulus, making a meta-linguistic judgment of abstractness or concreteness to the word, along with responding with the appropriate button press. Perceptual attributes of the auditory stimulus alone do not provide the participant with enough information to make the correct response.

Similar claims that processing beyond stimulus information is necessary could be made for all tasks except task 8. This led us to the hypothesis that for tasks where the stimulus information is basically all that is needed (henceforth termed “perceptually driven”), little or no sustained involvement of cingulo-opercular regions is demanded. On the other hand, if further processing (creation of post-perceptual representations, abstract or arbitrary relations between stimulus and response, etc.) is demanded, sustained cingulo-opercular activity is recruited. Henceforth, these will be called “perceptual plus”.

This perceptually driven versus perceptual plus hypothesis is, however, susceptible to a number of alternative accounts. First, many of the tasks that show clear activity have obvious or potential verbal components. Thus, the difference may relate more generally to a distinction between verbal and non-verbal tasks. Second, these regions are often related to task difficulty or effort (Critchley et al. 2000, 2003, 2004; Critchley 2005; Marklund et al. 2007). Indeed, task 8, which does not elicit sustained signals, shows faster reaction times than other tasks (1225 ms for task 8 vs. 1350 ms for task 9). In order to dissociate between the different potential explanations mentioned earlier, the current experiment was designed to span a range of reaction times and accuracies, vary in apparent difficulty, vary in the verbal nature of the tasks, and vary in the perceptually driven versus perceptual plus demands of the tasks.

Experiment

Materials and Methods

The 3 tasks used in this experiment are described more completely later. A coherence discrimination task using concentric dot patterns was chosen as a difficult but perceptually driven task. A mental rotation task was chosen as a difficult, non-verbal “perceptual plus” task, meaning that the task requires more than solely perceptual information. A noun/verb judgment was chosen as a less difficult, verbal, perceptual plus

task. As a group, these tasks allowed leverage to test each of the alternative accounts described earlier.

Participants

Participants were 31 right-handed, native English speakers with normal or corrected-to-normal vision (17 male, average age 25.1 ± 1.8 years). Participants were recruited from the Washington University in St. Louis community and its surroundings. All were either college students or college graduates. Subjects were tested for IQ using a 2-subtest version of the Wechsler Abbreviated Scale of Intelligence (Wechsler 1999). All subjects had above average IQ (average 127). To guarantee participants had no past history of neurological or psychological diagnosis, a self-report telephone interview and pre-scanning questionnaire were administered. Participants provided informed written consent prior to participation and were reimbursed for their time per the Washington University Human Studies Committee approval. The Institutional Review Board at Washington University School of Medicine approved all aspects of the study. One participant was excluded for not completing the scanning session. One run from a single subject was excluded due to excessive movement.

Behavioral Paradigms and Stimuli

Each subject performed 3 runs of each of the 3 tasks for a total of 9 runs. Each run consisted of 2 task blocks preceded and followed by 20 frames (50 s) of fixation. Tasks were performed in an intermixed, counterbalanced manner. Response handedness was counterbalanced by task across subjects. Prior to entering the scanner, participants were given instructions for each of the 3 tasks. They then performed 13 self-paced practice trials with feedback followed by 15 trials at the experimental pace without feedback.

For the noun/verb (verbal) task, 90 noun stimuli and 90 verb stimuli (present tense) were presented to the participant. Stimuli lists consisted of 6-letter, 2-syllable words, which were matched for frequency (Balota et al. 2002). Lists were chosen to minimize words with both common noun and verb definitions (e.g., shovel-verb: to dig or remove snow; shovel-noun: tool used to dig or remove snow). Task blocks consisted of 15 noun and 15 verb stimuli. Stimuli were presented in white, size 48 point (~ 3.75 visual degrees), Helvetica font on a black background. Example stimuli are shown in Supplementary Figure 1. Accuracy and reaction time were measured for each stimulus type.

For the non-verbal mental rotation task, white, 2D Tetris-like shapes made of 7 squares, similar to 3D shapes used by Shepard and Metzler (1971), were presented on a black screen. Two stimuli were presented on either side of a central, white fixation cross. Participants determined whether the 2 stimuli, rotated with respect to each other, had the same or mirror orientation. Eight different stimulus shapes were used. Orientation bins of 40° – 60° , 100° – 120° , and 150° – 170° were used. To shorten reaction times so as to fit in a single, 2.5-s MR frame, 1 of the 2 stimuli was always upright (0° rotation). Example stimuli are seen in Supplementary Figure 2. Accuracy and reaction time were measured for each stimulus type and degree of rotation. Due to concerns that sex differences may affect mental rotation capabilities (Metzler and Shepard 1974; Pertusic et al. 1978; Jones and Anuza 1982; Collins and Kimura 1997), data were also analyzed for differences between sexes.

For the coherence discrimination task, concentric Glass patterns, dot patterns created by dipoles related by a mathematical

equation (in this case, the equation for a circle) and diluted with randomly associated dot pairs (Glass 1969), were used. Patterns were white dots presented on a black background. Stimuli with 50%, 25%, 12.5% [at or below perceptual threshold (Wilson et al. 1997)], and 0% coherence were used. Participants judged whether or not the dots were coherent in this circular Glass pattern. Patterns were made using MATLAB and the psychophysics toolbox. Dots measured 0.04 degrees visual angle (1 pixel). Dot pair separation was 0.12 degrees visual angle. Dot density was 88 dot pairs/degree². Example stimuli are seen in Supplementary Figures 3 (50%), 4 (25%), 5 (12.5%), and 6 (0%). Accuracy and reaction time were measured for each stimulus type. For analyses, coherent stimuli were subdivided into 4 levels of coherence (0%, 12.5%, 25%, and 50%).

To compare across the 3 tasks, data from all trials for a given task were collapsed to determine average median reaction time and mean accuracy. Both behavioral measures were analyzed using one-way ANOVA with task as the group and subsequent post hoc two-tailed, paired *t*-tests using SPSS 16.0 for Mac (IBM).

All stimuli were presented using PsyScope Software (Cohen et al. 1993) using an iMac computer (Apple). Stimuli were projected to the participant using a CD715-X XGA DLP projector (Boxlight Belfair) onto a MRI-compatible rear-projection screen (CinePlex) at the head of the bore, which the participants viewed through a mirror attached to the coil. A PsyScope button box, linked to the iMac, with stimulus presentation synchronized to the timing of the MR scanner was used for all responses to measure reaction time and accuracy. Stimuli for each task were presented for 500 ms. Each trial lasted 1 frame of 2.5-s TR. For each task, 30 stimuli were intermixed with 32 null frames where only a fixation cross was present within a task block. Trials were jittered with 0, 1, or 2 frames between trials resulting in inter-stimulus interval of 2, 4.5, and 7 s, respectively. Trials are jittered to allow for the extraction of the event-related time course (Miezin et al. 2000). Because a mixed design was used, a uniform distribution of jitter intervals was used to enhance the modeling of the sustained signal (Petersen and Dubis 2012).

Task blocks began with a task-initiation cue, where the central fixation cross changed colors from white to green. Categories appeared to the left and right of the fixation cross identifying which hand button response corresponds to which response category (i.e., category presented to right of fixation cross requires right-handed response). Verbal task used “Noun” and “Verb” categories; mental rotation task used “Mirror” and “Same” categories; and coherence discrimination task used “Coherence” and “No Coherence” categories. The initiation cue was displayed for 1000 ms. At the end of a task block, the central fixation cross changed colors from white to red for 1000 ms, signaling to the participant that they should begin a trial-less block of fixation.

Task Difficulty Questionnaire

Following completion of all runs of the experiment and exit from the scanner, participants were given a questionnaire. The questionnaire included ratings of each task on the following topics: difficulty (1 easy–5 hard), level of attention (1 none–7 full), level of confidence in response (1 none–5 total), and rate of guessing (1 never–4 most of time). Lastly, participants made an absolute judgment as to which of the 3 tasks was most difficult. Questionnaire categories were analyzed using a one-way

ANOVA with task and subsequent post hoc two-tailed, paired *t*-tests using SPSS 16.0 for Mac (IBM). The questionnaire was also analyzed to determine whether sex differences existed in any of the tasks.

Scanning Procedures

Participants were given instructions to remain as still as possible while scanning. In order to maintain head position, a thermoplastic mask was fitted to the participant's face and attached to the head coil fixture. Headphones were provided to dampen scanner noise and allow for communication with participants.

MR Data Acquisition and Preprocessing

All anatomical and functional MR scans were collected using a Siemens 3T Trio scanner (Erlanger). One high-resolution, structural scan was collected using a sagittal magnetization-prepared rapid gradient echo (MP-RAGE) sequence (slice time echo = 3.08 ms, TR = 2.4 s, inversion time = 1 s, flip angle = 8 degrees, 176 slices, $1 \times 1 \times 1$ mm voxels). All functional MR runs were collected parallel to anterior–posterior commissure plane using an asymmetric spin-echo echo-planar pulse sequence (TR = 2.5 s, T2* evolution time 27 ms, flip angle 90 degrees). By collecting 32 contiguous, interleaved 4-mm axial slices (4×4 in-plane resolution), coverage of the entire brain was attained.

Images underwent preliminary preprocessing to remove a single pixel spike caused by signal offset, to normalize whole-brain signal intensity across frames, to correct movement within and across runs, and to normalize slice-by-slice to correct for differences in signal intensity resulting for interleaving of slices. For detailed description, see [Miezin et al. \(2000\)](#).

After preprocessing, data were transformed into a common stereotactic space based on [Talairach and Tournoux \(1988\)](#) but adjusted using an in-house atlas composed of average anatomy of 12 healthy young adults aged 21–29 years and 12 healthy children aged 7–8 years [for methods, see [Lancaster et al. \(1995\)](#); [Snyder \(1996\)](#); [Brown et al. \(2005\)](#)]. The data were then resampled isotropically at $2 \times 2 \times 2$ mm. Data were registered using a 12 parameter affine warping of each individual's MP-RAGE to the atlas target using difference image variance minimization as the objective function. The atlas-transformed images were verified against a reference average to check for correct registration.

An analysis of head position based on rigid body translation and rotation was conducted to correct and quantify participant motion. In-scanner movement was low as a result of participant instruction to stay as still as possible while the scanner is running and presence of thermoplastic mask. Frame-by-frame movement correction data from rotation and translation in the x, y, and z planes were collected to guard against runs having an overall movement greater than 1.0-mm RMS. Across all subjects' data, a single run was removed for having 1.12-mm RMS movement. The minimum movement for a single run was 0.0619-mm RMS, and the average movement per run was 0.2764-mm RMS.

fMRI Processing and Data Analysis

The statistical analyses of fMRI data were based on use of the general linear model (GLM) using in-house software utilizing the interactive data language (IDL, Research Systems, Inc.) as previously detailed ([Miezin et al. 2000](#); [Ollinger, Corbetta, et al. 2001](#); [Ollinger, Shulman, et al. 2001](#); [Visscher et al. 2003](#);

[Dosenbach et al. 2006](#)). A mixed design was utilized to allow for simultaneous extraction of transient, trial-related activity and sustained, task-related activity. Events—task-initiation, trials, and task-termination—were modeled across 7 time points corresponding to 7 MR frames (17.5 s, 2.5 s/frame) following presentation of the stimulus. The sustained signal was modeled as a boxcar function beginning after the task-block initiation signal resolved (17.5 s) and terminating the frame prior to the task-termination signal. The boxcar had a length of 140 s (56 frames, 2.5 s/frame). Additional trend and baseline terms were coded into the GLM.

Trials were modeled independently for each task, and for different conditions within each task. In the verbal task, trials were modeled as “noun” or “verb”. In the mental rotation task, trials were modeled according to “mirror” or “same” and subdivided by bins of degree rotation 40° – 60° , 100° – 120° , and 150° – 170° . In the coherence discrimination task, trials were modeled as “coherence” and “no coherence.” “Coherence” trials were subdivided to reflect percent coherence—12.5%, 25%, and 50%. In all tasks, errors of commission and omission were modeled independently.

In order to remove motion effects as a result of slight head movements while scanning, we utilized a motion scrubbing technique ([Siegel et al. 2014](#)). Frame-wise displacement as a result of head motion was calculated. Those MR volumes exceeding a frame-wise displacement threshold (>0.6 mm) were marked to form a temporal mask. When calculating GLMs, the temporal mask was used to block marked frames during parameter estimation. On average, 78 frames per participant were excluded out of a total of 1692 total frames constituting an average removal of less than 4.67%. No participants were removed from the study because of excessive loss of frames.

Sustained BOLD activity was analyzed in previously mentioned, *a priori* regions of dACC/msFC and bilateral aI/FO, as well as experimentally defined regions proximal to the dACC and bilateral aI/FO. The experimental regions were defined using a contrast comparing the average of the sustained BOLD activity in the verbal task and mental rotation task against the sustained BOLD activity in the coherence judgment task. This was a planned contrast, which mirrored contrasts in the reliability analysis, comparing the task where all information is provided in the stimulus (perceptually driven) to the tasks where all information is not provided in the stimulus (perceptual plus). The contrast used a Monte Carlo correction for multiple comparisons (63 voxels, each $P < 0.05$, and total *z*-score of 2.25) followed by a peak finding algorithm. Regions were then investigated to ensure proximity of experimentally defined regions to the *a priori* regions.

Sustained cingulo-opercular activity for each task was first analyzed to determine whether significant activity was present using one-sample *t*-test against zero (one-tail) in both *a priori* and experimental regions. Next, a 3 (task: noun/verb, mental rotation, coherence discrimination) $\times$ 3 (region: left and right anterior insula and anterior cingulate) repeated-measures ANOVA was performed followed by post hoc paired *t*-tests in both *a priori* and experimental regions comparing each of the tasks to each other. The comparisons of the verbal task and mental rotation task, respectively, to the coherence discrimination task were hypothesis-driven resulting in the use of a one-tailed, paired *t*-test. The comparison between the 2 perceptual plus tasks (verbal and mental rotation) is not hypothesis-driven resulting in the use of a two-tailed, paired *t*-test.

Task Difficulty Comparison in Coherence Discrimination Task

A separate set of subjects was recruited to perform 2 versions of the coherence discrimination task described earlier. One version was the same as previously described using stimuli with 50%, 25%, 12.5%, and 0% and coherence (4-level version). This served as a difficult version of the task. A second version used only 50% and 0% stimuli (2-level version), which served as an easier version of the same task. A 2 (task version: 4-level, 2-level) $\times$ 3 (region: left and right anterior insula and anterior cingulate) repeated-measures ANOVA was performed followed by post hoc paired *t*-tests in *a priori* regions. For further description of materials and methods, see the Supplemental materials.

Results

Behavioral

Behavioral measures are summarized in Table 1.

To compare the 3 tasks, all trials for a task were collapsed to determine median reaction time for correct trials and average accuracy as seen in Table 1. This analysis is different than simply averaging the category averages. One-way ANOVAs were performed indicating a significant effect of task on accuracy ($F_{2,87} = 77.29$, $P < 0.001$) and reaction time ($F_{2,87} = 158.04$, $P < 0.001$), such that the mental rotation task had significantly longer reaction times than the coherence discrimination and verbal tasks ($P < 0.001$), whereas there was no significant difference between the coherence discrimination and verbal task ($P > 0.2$). The coherence discrimination had significantly lower accuracy than the mental rotation task ($P < 0.05$), which had significantly lower accuracies than the verbal task ($P < 0.001$). In the mental rotation task, males and females showed no significant accuracy differences (P 's > 0.5), or reaction time differences (data not shown; P 's > 0.2).

Questionnaire

Results of the task difficulty questionnaire are detailed in Table 2.

Each category showed a significant effect of task (P 's < 0.001), such that both the mental rotation task and the coherence discrimination task were viewed as significantly more

difficult than the verbal task ($P < 0.001$) though no significant difference was seen between the former 2 tasks. The mental rotation task was viewed as requiring a significantly higher level of attention than the coherence discrimination task ($P < 0.001$), which required a significantly higher level of attention than the verbal task ($P < 0.005$). The verbal task was viewed as having the highest level of confidence with lowest rate of guessing ($P < 0.001$; two-tailed paired *t*-test). Finally, there were no significant differences between the sexes (data not shown) for any of the categories in any of the tasks ($P > 0.05$).

Imaging

A 3 (task: noun/verb, mental rotation, coherence discrimination) $\times$ 3 (region: left and right anterior insula and anterior cingulate) ANOVA showed a significant effect of task ($F_{2,58} = 3.62$, $P = 0.03$) but no significant effect of region ($F_{2,58} = 0.29$, $P > 0.7$) or interaction of task $\times$ region ($F_{4,116} = 0.54$, $P > 0.7$). Post hoc paired *t*-tests, seen in Figure 3, indicate that there was a significant difference ($P < 0.05$) between sustained BOLD activations for mental rotation and coherence discrimination

Table 2
Difficulty questionnaire ratings

Task condition	Difficulty	Level of attention	Level of confidence	Rate of guessing	Number of people who said task was most difficult
Verbal	1.15 (0.66)	4.77 (1.43)	4.69 (0.63)	3.77 (0.56)	0
Mental rotation	3.69 (0.89)	6.69 (0.68)	3.08 (0.74)	2.23 (0.61)	13
Coherence discrimination	3.92 (1.05)	5.92 (1.03)	2.77 (0.96)	1.69 (0.53)	17

Note: Values are means with SD in parentheses. Difficulty rating on Scale 1—Easy:5—Difficult. Attention rating on Scale of 1—None:7—Full. Confidence rating on Scale 1—None:5—Total. Guessing rating on Scale 1—Most of Time:4—Never.

Table 1
Behavioral measures of 3 tasks

Task condition	Stimulus type	RT (ms)	% Correct
Verbal	Noun	916.8 (139.0)	95 (5.2)
	Verb	897.3 (162.7)	93.9 (7.6)
	ALL	901.3 (142.0)	94.4 (6.0)
Mental rotation	Same: 40–60	1251.8 (150.9)	82.9 (8.1)
	Same: 100–120	1420.6 (180.0)	72.4 (12.2)
	Same: 150–170	1523.6 (212.8)	72.1 (18.2)
	Mirror: 40–60	1371.9 (185.1)	77.6 (12.0)
	Mirror: 100–120	1517.7 (149.9)	74.4 (14.2)
	Mirror: 150–170	1580.0 (179.5)	72.1 (15.4)
	ALL	1436.9 (150.7)	75.3 (10.7)
Coherence discrimination	No coherence (0%)	976.0 (112.7)	70.7 (12.2)
	Coherence: 12.5%	1022.8 (160.5)	46.7 (12.9)
	Coherence: 25%	897.2 (119.4)	68.8 (16.6)
	Coherence: 50%	810.0 (111.9)	90.1 (10.0)
	All	926.3 (95.7)	69.6 (7.1)

Note: Values are means with standard deviations (SD) in parentheses.

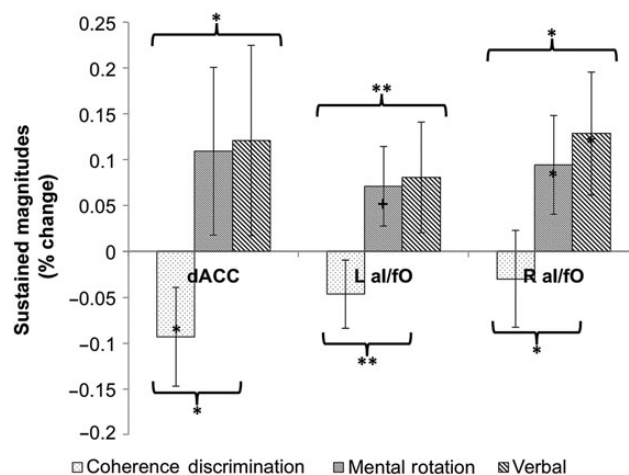


Figure 3. Sustained magnitude contrasts from hypothesis-driven experiment in *a priori* defined regions. Sustained magnitudes were extracted in each of the regions for each of the tasks. The coherence discrimination task is displayed in dots, the mental rotation task is displayed in light slash, and the verbal task is displayed in heavy slash. One-sample *t*-tests against zero with one-tail and one-tailed, paired *t*-tests were performed. Significance indicators below data reflect coherence discrimination-mental rotation paired *t*-test results. Significance indicators above data reflect coherence discrimination-verbal paired *t*-test results. Significance levels are as follows: * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

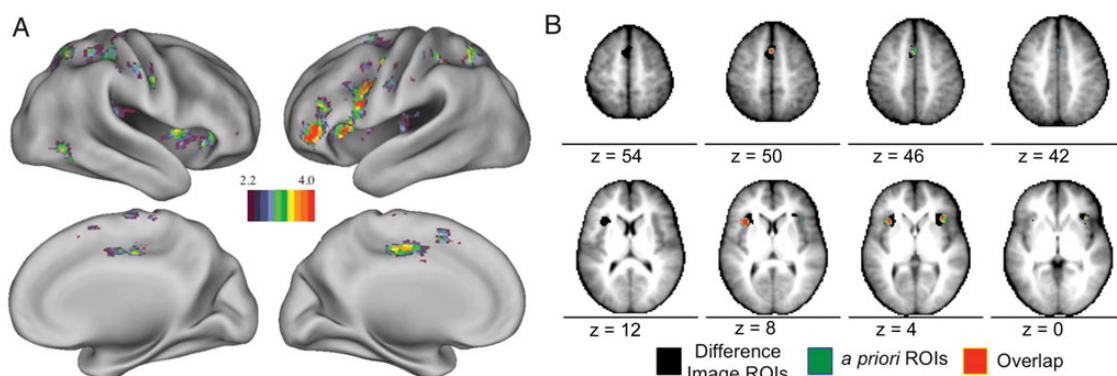


Figure 4. Experimental regions definition and comparison with *a priori* regions. (A) The hypothesis was tested comparing the task where stimuli contains all the information necessary (perceptually driven: coherence discrimination) versus the 2 tasks where additional processing is necessary (perceptual plus: mental rotation and noun/verb judgment). Contrast was corrected for multiple comparisons using a Monte Carlo correction (63 voxels, each $P < 0.05$, and total $z > 2.25$) shown on a Caret inflated surface (Van Essen et al. 2001). (B) Experimental regions (shown in black) closest anatomically to the *a priori* regions from Dosenbach et al. (2006) (shown in green) were overlapped (shown in red) with the *a priori* regions.

tasks, and between the verbal and coherence discrimination tasks, in all 3 regions. Moreover, there was no significant difference between the sustained activity in the verbal and mental rotation tasks ($P > 0.6$; two-tailed, paired t -test).

In the *a priori* dACC/msFC and bilateral aI/fO regions, positive, sustained BOLD activations were seen in the verbal task and the mental rotation task but not in the coherence discrimination task seen in Figure 3. The verbal task showed significant (one-sample t -test against zero with one-tail, $P < 0.05$) activation in right aI/fO. The mental rotation task showed significant activation in right aI/fO and trend level activation in left aI/fO. Deactivations in the coherence discrimination task were significant in the dACC/msFC.

To ensure that the *a priori* regions were representative of these subjects' experimental data, regions were defined using a hypothesis-driven contrast between the "perceptually driven" task and the other "perceptual plus" tasks. The contrast is seen in Figure 4A depicted on a Caret inflated surface (Van Essen et al. 2001). A peak finding algorithm identified regions of interest. Coordinates were compared with the *a priori* regions to find experimental regions located closest to the *a priori* regions. The following peaks of regions were identified: dACC/msFC ($-3, 8, 51$), left aI/fO ($-32, 15, 7$), and right aI/fO ($31, 17, 3$) (Talairach and Tournoux 1988). All 3 regions are within 6 mm of the peaks defined in Dosenbach et al. (2006). Similarity of the regions was visualized by overlapping the 2 region sets as seen in Figure 4B depicted on horizontal slices.

To characterize the nature of the differences in the experimental regions, the regions were analyzed similarly to the *a priori* regions. It is understood that there is an inherent bias in this overall analysis; this analysis is to confirm that the much lower sustained BOLD activations for the coherence discrimination task do not depend on the specific choice of voxels. The mental rotation and verbal tasks showed positive, sustained BOLD activations, but the coherence discrimination task did not, as seen in Figure 5. The mental rotation task showed reliable activations ($P < 0.05$) in the dACC/msFC and right aI/fO and trend level activation in the left aI/fO. The verbal task showed reliable activation in the dACC/msFC and trend-level activations in the left aI/fO. The deactivations in the coherence discrimination task reached reliability in bilateral aI/fO. Direct comparisons were made using a 3 (task: noun/verb, mental

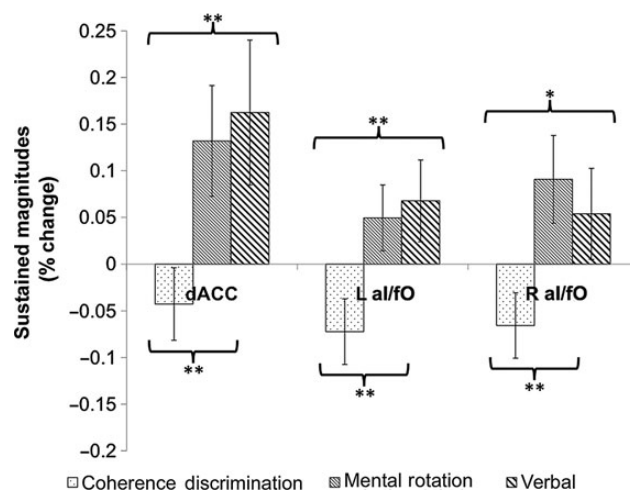


Figure 5. Sustained magnitude contrasts from hypothesis-driven experiment in experimentally defined regions. Sustained magnitudes were extracted in each of the regions for each of the tasks. The coherence discrimination task is displayed in dots, the mental rotation task is displayed in light slash, and the verbal task is displayed in heavy slash. One-sample t -tests against zero with one-tail and one-tailed, paired t -tests were performed. Significance indicators below data reflect coherence discrimination-mental rotation paired t -test results. Significance indicators above data reflect coherence discrimination-verbal paired t -test results. Significance levels are as follows: * $P < 0.10$; * $P < 0.05$; ** $P < 0.01$.

rotation, coherence discrimination) $\times$ 3 (experimental regions: left and right anterior insula and anterior cingulate) ANOVA. As with the *a priori* regions, a reliable effect of task ($F_{2,58} = 5.8$, $P = 0.005$) and interaction of task $\times$ region ($F_{4,116} = 1.01$, $P > 0.4$) were seen, such that the mental rotation task and verbal task were both significantly different from the coherence discrimination task ($P < 0.005$, one-tailed) in all 3 regions, but there was no difference between the former 2 tasks ($P > 0.6$, two-tailed). However, a significant effect of region ($F_{2,88} = 3.40$, $P = 0.04$) was also found.

Task Difficulty Comparison in Coherence Discrimination Task

Results of the task difficulty questionnaire for the 2-level and 4-level versions of the coherence discrimination task are

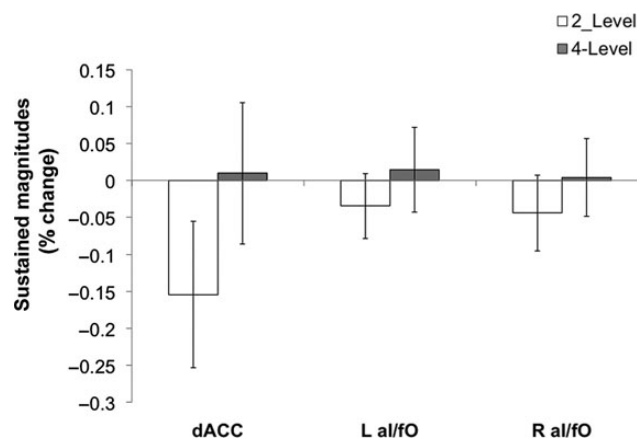


Figure 6. Sustained magnitude contrasts from 2 versions of the coherence discrimination task. Sustained magnitudes were extracted in each of the regions for each of the 2 task versions. The 2-level version is displayed in white; the 4-level version is displayed in gray. Neither task version showed significant sustained BOLD activity in any of the 3 *a priori* regions, and there was no significant interaction of task version $\times$ region.

shown in Supplementary Table 1. Each category showed a significant effect of task (P 's < 0.02), suggesting that the 4-level version was viewed as significantly more difficult than the 2-level version.

The performance measures for the 2-level and 4-level versions of the coherence discrimination task are shown in Supplementary Table 2. Participants performed the 2-level task version more accurately ($t_{19} = 14.6$; $P < 0.001$) and faster ($t_{19} = -6.0$; $P < 0.001$) than the 4-level task version when all trials are collapsed across coherence levels within the task version.

Neither task version showed significant positive sustained BOLD activity in any of the 3 *a priori* regions (based on 6 one-sample t -tests against zero, 1 for each region for each task version, with one-tail, $P > 0.05$). A 2 (task version: 2-level, 4-level) $\times$ 3 (region: left and right anterior insula and anterior cingulate) ANOVA showed no significant effect of task version ($F_{1,19} = 2.61$, $P > 0.1$), region ($F_{2,38} = 1.03$, $P > 0.3$), or interaction of task version $\times$ region ($F_{2,38} = 1.05$, $P > 0.3$) as seen in Figure 6.

Discussion

The target hypothesis of this experiment is that sustained BOLD signal in cingulo-opercular regions, as defined by Dosenbach et al. (2006), is absent or negligible when a task is driven only by perceptual information available in the presented stimuli. To put it another way, sustained cingulo-opercular activity is recruited only in tasks with processing demands or representations beyond those provided by the stimulus. We will try to address what this might mean below. The experiment was also designed to assess alternative accounts of previous data. These accounts include suggestions that sustained activity is primarily driven by the verbal nature of the task or by task difficulty or arousal. The present results are in frank agreement with the target hypothesis and in apparent disagreement with the alternative accounts.

For the purposes of this experiment, the coherence task was conceived to be a “difficult”, perceptually driven, non-verbal

task, the mental rotation task to be a “difficult” perceptual plus, non-verbal task, and the noun/verb task to be a less difficult, perceptual plus, verbal task. For our hypothesis to be confirmed, we should see strong sustained cingulo-opercular activity in the latter 2 tasks (perceptual plus), with minimal activity in the coherence task. These results were observed. Neither of the alternative accounts fits the data well.

Sustained Signals are not Driven by Verbal Task Demands

Of the 3 tasks included in the present experiment, only 1 relied on verbal task demands (noun/verb task). If the sustained BOLD signal reflected verbal task demands, the expectation would be that only the noun/verb task would exhibit sustained activity. However, the presence of significant sustained BOLD activity in dACC/msFC and bilateral ai/fo in both the noun/verb task and the mental rotation task (non-verbal) suggests that verbal task demands do not drive sustained BOLD activations in these regions.

Sustained Signals are Not Driven by Task Difficulty

In our study, “difficulty” was measured objectively via performance measures including reaction time and accuracy and subjectively using a questionnaire with several ratings of difficulty. If the sustained BOLD signal reflected difficulty, as measured objectively using reaction times, the expectation would be that only the mental rotation task would exhibit sustained activity, as it had longer reaction times than the coherence discrimination and verbal task, which did not differ from each other. If the sustained BOLD signal reflected difficulty, as measured objectively using accuracy, the mental rotation and coherence discrimination tasks would be predicted to have high sustained cingulo-opercular activity as they had more errors than the verbal task. If the sustained BOLD signal reflected difficulty, as measured subjectively, again, the expectation would be for the mental rotation and coherence discrimination tasks to have high sustained cingulo-opercular activity as they were viewed as significantly more difficult than the verbal task in the task difficulty questionnaire. Most tellingly, the presence of significant sustained BOLD activity in dACC/msFC and bilateral ai/fo in the “easier” noun/verb task but not in the coherence discrimination task indicates that difficulty, whether objective or subjective, does not drive sustained BOLD activations in these regions.

Our analysis thus far considers difficulty across 3 diverse tasks. We reasoned that difficulty was not impacting the sustained BOLD activity because the easy task had sustained activity whereas the difficult perceptually driven task did not. At first glance, one may want to go a step further and compare difficulty within a given task to see whether there is greater BOLD activity for “difficult” trials than “easy” trials. While possible, this comparison is very different from that being discussed here. Indeed, the type of control signals we are studying here are based on sustained activity across the entire task block, presumably related to task maintenance. In contrast, transient, trial-related activity is different from and operates on a different, more adaptive, timescale than the sustained signals (see Petersen and Dubis 2012).

As such, in order to compare difficulty within a task, the level of difficulty must be varied on a block-wise basis in order to properly extract a sustained magnitude. To that end, we

used 2 versions of a coherence discrimination task that varied in difficulty by block, where 1 version (half of the runs) had 4 levels of coherence (making the task difficult), and the other version (the other half of the runs) included only the 2 levels with the greatest contrast (0% and 50%) (making the task relatively easy). Modulating the level of difficulty had no significant effect on the sustained activity in the *a priori* regions. Therefore, task difficulty within a perceptually driven task does not instantiate sustained task-control signals.

“Perceptual Plus” Task Demands Appear to Recruit Sustained Signals

We understand that, up to this point, the hypothesis is not deeply theoretical. Rather, it is about delineating a set of situations that appear to relate to the perceptually driven nature of tasks, which do not elicit sustained cingulo-opercular activity. These findings appear to place contingencies on when sustained cingulo-opercular activity is recruited. Would there not be a need to adopt a task set for perceptually driven coherence judgments or visual search tasks? At first blush, this seems somewhat odd: Why would there be such a distinction between perceptually driven and perceptual plus tasks?

These task-type distinctions align somewhat with 2 other task-type dichotomies. The first is the data-limited/resource-limited distinction, described by Norman and Bobrow (1975). In this dichotomy, data-limited tasks are defined by limitations on (i.e., are made difficult by) the quality and/or nature of the stimulus. Resource-limited tasks are defined by limitations resulting from demands on the organization of the attentional resources, in terms of sequencing operations, or the demand for complex or abstract representations. In other words, a resource-limited task may require a simple judgment (e.g., name the color of a word), but can be made difficult by inducing conflict (e.g., the word “BLUE” written in red ink), or modulating attentional resources (e.g., simultaneously computing arithmetic).

The second categorization is that of perceptual versus conceptual processing as studied in memory (Jacoby 1983; Hashtroudi et al. 1988; Roediger et al. 1989; Weldon 1991). Here, perceptual processing is identified as processing related to analyzing the representations and physical features of the stimuli (Jacoby 1983; Blaxton 1989). Conceptual processing includes the processing of meaning (Hashtroudi et al. 1988; Blaxton 1989).

A previous report links these 2 categorization schemes (Weldon 1991). Both of these categorizations appear to represent fundamental distinctions between perceptual demands and other, more abstract demands, that produce separable processing effects (Norman and Bobrow 1975; Jacoby and Dallas 1981; Roediger et al. 1989; Weldon 1991). These previously observed behavioral distinctions bolster the probability that processing differences between perceptually driven tasks versus other tasks may entail separate neural hardware.

Searching for a Functional Explanation for Sustained Signals

What we have described thus far does not address what the sustained cingulo-opercular activity is “for.” Frankly, in spite of the constraints provided by this manuscript, we believe there are many possible descriptions of what these sustained signals are for, *per se*. We will present our current speculations in that

light. We believe that the sustained nature of the signals suggests that they are providing top-down information related to task set. We also believe that its absence in perceptually driven tasks suggests that the top-down information is quite likely not involved in the selection of sensory or perceptual processing mechanisms. The location of the dACC region adjacent to pre-SMA and SMA suggests that it may be more involved in configuring regions late in processing streams, but we do not currently feel confident in making this claim. The opercular/anterior insula location provides even less constraint. Nonetheless, the common, if contingent, activation of these regions across studies suggests their general importance.

The present work provides preliminary evidence to describe what task parameters might drive sustained cingulo-opercular involvement. Two of the possibilities include the following:

- A. Use of abstracted representations beyond perceptual ones (e.g., extracting conceptual, or meta-linguistic information from the stimulus). This possibility appears to explain several of the tasks. These include the need for:
 1. Letter Identification—extraction of name code for letter
 2. Object Naming—extraction of name code for line drawing
 3. Reading—extraction of name code for letter string
 4. Matching of Letters—extraction of name code for name matching (and physical matching)
 5. Living/Nonliving Judgment—extraction of conceptual animacy information
 6. Physical and Semantic Judgments—extraction of meta-linguistic information for semantic judgment
 7. Motor timing/Pattern Matching—rhythmic pattern learning of 7 tone sequences
 8. Visual Search—not clear
 9. Abstract/Concrete Judgment—extraction of meta-linguistic information and applying definitions of “abstractness” and “concreteness.”

This criterion would also apply to the meta-linguistic judgments in the noun/verb task of the current experiment, where the meaning of each word stimulus must be compared with a definition of “noun” and “verb” and potentially to the imagery information in the mental rotation task, where the shape stimuli need to be manipulated in imagery space in order to be compared (for more details, see below).

- B. The need to sequence operations including the need to apply abstract decision rules. This would apply to the:
 - (4) Letter Matching—extraction of letter identification and matching characters,
 - (7) Motor Timing—rhythmic pattern learning of 7 tone sequences.

Again, this criterion would also apply to some of the more abstract meta-linguistic judgments in the noun/verb task of the current experiment, where, again, participants must come up with a criteria for what defines a noun versus a verb, then identify the semantic meaning of each word stimulus, and finally to compare each definition to the criteria in order to classify each word as a noun or verb. It also would apply to the mental rotation task, which requires participants to manipulate each shape in 2D space in order to determine whether the 2 shapes match or not.

This analysis and discussion of abstract representations and manipulations necessary to complete a task is not meant to indicate that it is impossible to find additional “steps” in the processing of a perceptually driven task. Indeed, it is likely that, in

order to perform the coherence task, an individual compares the stimulus to an internal standard in some form of criterion judgment (e.g., internal standard circle). However, we do not believe that this sort of stimulus matching or comparison (e.g., making a criterion judgment) is of the same nature as the type of abstract representation and manipulation that occurs in the other tasks (as described earlier). Indeed, we believe that the other tasks require, beyond matching a stimulus to a criterion, participants to create a symbolic (e.g., shapes that can be manipulated in space) or semantic (e.g., characterization of nouns and verbs) representation that, only then can be compared with a criterion. In other words, it is not enough to represent the shapes presented in the mental rotation task and compare them visually; the participant must be able to manipulate those shapes in 2D space in order to determine whether they might be the same or mirror images. Also, it is not enough to know what a noun is in the noun/verb task; one must also define the word presented on the screen and determine whether that definition fits under the rubric of what classifies a noun or verb. In contrast, the glass pattern task does not recruit any additional processes other than comparing a stimulus to an internal criterion. Indeed, one can likely make an argument for some form of criterion judgment in response to any type of task or decision process, and thus, this sort of criterion judgment will not likely be useful in distinguishing between tasks.

There may be other possible explanations as well, but those discussed here seem the most obvious. We do not mean to imply that these are mutually exclusive. Other parameters that may be affecting, or further modulating, the sustained BOLD signal, and may be investigated in the future, include task load and the effect of practice on performing a task. Investigating such parameters and task demands would highlight the functional role of the cingulo-opercular network in maintaining task performance.

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