Neuron

Article

# Short-Term Memory for Space and Time Flexibly Recruit Complementary Sensory-Biased Frontal Lobe Attention Networks

CrossMark

CellPress

(Tamber-Rosenau et al., 2013), prior human univariate functional magnetic resonance imaging (fMRI) studies of vision and audition either point to shared multisensory structures in lateral frontal cortex (Lewis et al., 2000; Johnson and Zatorre, 2006; Ivanoff et al., 2009; Karabanov et al., 2009; Tark and Curtis, 2009; Tombu et al., 2011; Braga et al., 2013) or report a lateral frontal cortical bias for only one modality (for example, see Crottaz-Herbette et al., 2004; Jantzen et al., 2005; Rämä and Courtney, 2005; Salmi et al., 2007), which could reflect differences in task difficulty rather than sensory modality. Studies in nonhuman primates have reported distinct areas in lateral frontal cortex that are biased toward audition or vision in anatomical connectivity and/or functional response (for example, see Barbas and Mesulam, 1981; Petrides and Pandya, 1999; Romanski and Goldman-Rakic, 2002; Romanski, 2007).

Our first two experiments investigate whether sensory modality is a determining factor in the functional organization of lateral frontal cortex. The first experiment manipulates attention to sensory modality and reveals two visual-biased regions interleaved with two auditory-biased regions in lateral frontal cortex. The second experiment confirms the observation of interleaved visual-biased and auditory-biased attention networks in lateral frontal cortex using resting-state functional connectivity. Our final two experiments investigate the domain recruitment hypothesis. In order to demonstrate flexible recruitment, the experiments focus on information in a single sensory modality at a time, contrasting high spatial and high temporal demands first within purely visual tasks and then within purely auditory tasks. The results of these experiments support the domain recruitment hypothesis, revealing strong recruitment of the auditory-biased frontal regions by the visual temporal task and strong recruitment of the visual-biased frontal areas by the auditory spatial task.

## RESULTS

We performed four fMRI experiments: (1) direct comparison of sustained visual and auditory spatial attention, (2) resting-state functional connectivity using regions of interest (ROIs) defined from Experiment 1, (3) two attentionally demanding visual short-term memory tasks differing in their spatial and temporal demands, and (4) two attentionally demanding auditory short-term memory tasks differing in their spatial and temporal demands. Together, Experiments 3 and 4 served as a two-by-two investigation to dissociate processing specific to sensory modality (visual/auditory) from that specific to information domain (spatial/temporal). Eleven participants completed all four experiments; however, one participant was excluded from analysis due to excessive head movements.

### Experiment 1: Sustained Visual and Auditory Spatial Attention

Participants were instructed to monitor one of four informational streams (visual left, visual right, auditory left, auditory right) and press a button when they detected a digit (a rare event among letters) in that stream while ignoring digits presented at all times in the competing streams (see Figure 1). Subjects performed at 84.1% ± 12.7% correct for visual attention blocks, and 79.9% ± 12.9% correct for auditory attention blocks with no significant difference in task performance ($t_9$ = 0.94, p = 0.37), indicating they successfully monitored the correct stream in both conditions.

In the caudal lateral frontal cortex of each hemisphere, a direct contrast of fMRI activation across the attended sensory modalities revealed two regions strongly biased for visual attention, interleaved with two regions strongly biased for auditory attention (see Figure 2A, Table 1, and Figure S1 available online). The superior precentral sulcus (sPCS) and inferior precentral sulcus (iPCS) exhibited a stronger blood-oxygen-level dependent (BOLD) response for visual compared to auditory sustained attention. This contrast identified the left sPCS in eight of ten subjects, the right sPCS in eight of ten subjects, and the iPCS in both the left and right hemispheres of nine of ten subjects. We consistently observed a gap between these two visual-biased areas; within this gap we observed a significant bias for sustained attention to auditory over visual stimuli. In humans,

the frontal ROIs de ned by a visual-attention bias, sPCS and control (passive viewing + button press; see Experimental Procedures and Table 2 for details). Conversely, for the visual-biased ROIs, the visual spatial task showed greater BOLD response in sPCS and iPCS compared to the visual temporal task, and both tasks showed a signi cant response relative to sensorimotor control. Using a xation baseline did not qualitatively change our results (see Figure S5 response versus sensorimotor control in sPCS and iPCS. Using a fixation baseline did not qualitatively change our results (see Figure S6). Although sPCS and iPCS can be driven by eye movements (e.g., Paus 1996; Corbetta et al., 1998), the observed functional differences cannot be attributed to eye movements or motor responses: eye-tracking during the auditory task revealed no difference in the number of eye movements between the spatial and temporal task ($t_6 = 0.35$, $p = 0.74$, see Figure S7 and Supplemental Experimental Methods) and motor responses were also equivalent across tasks. As a final analysis we combined the results from Experiments 3 and 4 into a single three-way ANOVA and observed a highly significant 3-way interaction between ROI, sensory modality, and information domain ($F_{3,24} = 60.02$, $p = 2.64e{-}11$). Taken together, the increased response for the visual temporal compared to the visual spatial task in auditory-biased frontal ROIs and the increased response for the auditory spatial compared to auditory temporal task in visual-biased frontal ROIs strongly support the domain recruitment hypothesis.

## DISCUSSION

description that overlooks the important role of sensory modality in the functional organization of lateral frontal cortex. By analyzing data from individual subjects on their cortical surfaces, we were able to obtain a higher effective spatial resolution than is typically obtained with group-averaging methods. These methods may have been critical to resolving multiple distinct visual-biased and auditory-biased attention regions where prior studies found responses independent of sensory modality. Consistent with our ndings, a recent multivariate analysis study indicated that posterior lateral frontal cortex contains information about sensory modality, but this study did not identify speci c visual-biased and auditory-biased frontal cortical areas (Tamber-Rosenau et al., 2013).

Our ndings are largely orthogonal to reports of hierarchical organization in the LFC (e.g., Koechlin et al., 2003; Badre et al., 2010); however, we note that the two most caudal regions in these studies (i.e., PMD and pre-PMD) may align with sPCS and iPCS. Similar coordinates have been reported in studies of cognitive control (Brass et al., 2005) and salience detection (Corbetta and Shulman, 2002). Future studies will be needed to investigate their colocalization as well as the role of sensory modality in relation to the proposed hierarchical organization of frontal cortex.

The domain recruitment hypothesis is a neural hypothesis related to the modality appropriateness hypothesis, a perceptual hypothesis that describes the biased relationships among vision and audition and space and time when con icting sensory information arises (cf. Alais and Burr, 2004, for important exceptions). The domain recruitment hypothesis extends this concept to neural responses under higher cognitive demands. Several prior behavioral studies investigating short-term memory for spatial and/or temporal information presented in visual and/or auditory modalities have reported that the visual modality is superior for spatial STM and that the auditory modality is superior for temporal STM (e.g., Balch and Muscatelli, 1986; Glenberg et al., 1989; Collier and Logan, 2000; Guttman et al., 2005; McAuley and Henry, 2010O54 wh533-362.e(m529-305.3(informati54)-266.1(doma53)-300.6(536-405.2(t536-)-2ask(t530-215.4(533-36283(ory)]TJ 0 -1.2988 T‘)s)-26

Each subject participated in a minimum of ve sets of scans across multiple sessions and separate behavioral training sessions. In addition to the four fMRI experiments, high-resolution structural scans were collected to support anatomical reconstruction of the cortical hemispheric surfaces. Imaging was performed at the Center for Brain Science Neuroimaging Facility at Harvard University on a 3-T Siemens Tim Trio scanner with a 32-channel matrix coil. A high-resolution (1.0 3 1.0 3 1.3 mm) magnetization-prepared rapid gradient-echo sampling structural scan was acquired for each subject. The cortical surface of each hemisphere was computationally reconstructed from this anatomical volume using FreeSurfer software (http://surfer.nmr.mgh.harvard.edu/). For functional studies, T2*-weighted gradient echo, echo-planar images were collected using 42 3 mm slices (0% skip), oriented axially (time echo 30 ms, time repetition [TR] 2,600 ms, in-plane resolution 3.125 3 3.125 mm). In the visual spatial task, 7 of 11 subjects were scanned on an identically equipped Siemens Tim Trio scanner at the Martinos Center for Biomedical Imaging at Massachusetts General Hospital.

### Stimulus Presentation

Visual stimuli were presented using a liquid crystal display projector illuminating a screen within the scanner bore. The display extended across a visual angle of 14 radius horizontally and 11 radius vertically. The audio system (Sensimetrics, http://www.sens.com ) included an audio ampli er, S14 transformer, and MR-compatible earphones. Inside the MR scanner, subject responses were collected using an MR-compatible button box.

### Experiment 1: Sustained Visual and Auditory Attention

Participants monitored one of four (two auditory, two visual) rapid serial streams of distractor letters (“A,” “F,” “G,” “H,” “J,” “K,” “L,” “M,” “N,” “P,” “R,” “X,” and “Y”) for the presentation of any digit (1–4), while ignoring

Corbetta, M., and Shulman, G.L. (2002). Control of goal-directed and stimulus-