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The cortical dynamics underlying effective switching of auditory spatial attention

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Abstract

Successful rapid deployment of attention to relevant sensory stimuli is critical for survival. In a complex environment, attention can be captured by salient events or be deployed volitionally. Furthermore, when multiple events are of interest concurrently, effective interaction with one's surroundings hinges on efficient top-down control of shifting attention. It has been hypothesized that two separate cortical networks coordinate attention shifts across multiple modalities. However, the cortical dynamics of these networks and their behavioral relevance to switching of auditory attention are unknown. Here we show that the strength of each subject's right temporal-parietal junction (RTPJ, part of the ventral network) activation was highly correlated with their behavioral performance in an auditory task. We also provide evidence that the recruitment of the RTPJ likely precedes the right frontal eye fields (FEF; participating in both the dorsal and ventral networks) and middle frontal gyrus (MFG) by around 100 ms when subjects switch their auditory spatial attention.

Keywords

auditory attention; frontal eye fields; temporoparietal junction; magnetoencephalography

1.Introduction

Effective verbal communication often requires directing auditory attention from one sound source to another. It has long been known that attentional allocation improves task performance in detecting relevant signals (Posner et al., 1980) and modulates visual and auditory cortical activity (Yantis et al., 2002; Petkov et al., 2004; Wu et al., 2007; Mesgarani and Chang, 2012). The focus of attention can be changed both endogenously (top-down) via conscious direction to a set of stimulus attributes, or exogenously (bottom-up) due to stimulus salience or subject vigilance. Neuroimaging studies suggest different cortical

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networks mediate these two attentional processes: endogenous switching engages a dorsal frontoparietal network consisting of bilateral intraparietal sulcus (IPS) and frontal eye fields (FEF), while exogenous switching involves a right-lateralized ventral network including the right (R)FEF and the right temporoparietal junction (RTPJ; Corbetta et al., 2008).

While behavioral tasks have been used to study endogenous attention orientation in vision (Kiesel et al., 2010), most studies of attention switching in audition have focused on exogenous attention (Shinn-Cunningham, 2008; but see Driver and Spence, 1998). One recent study found that voluntary attention switching costs were comparable in vision and audition (Koch et al., 2011), suggesting that attentional control may engage supra-modal mechanisms. Recent fMRI studies have found that several cortical regions including FEF are active in both visual and auditory tasks (Shomstein and Yantis, 2006; Wu et al., 2007), supporting the hypothesis that attentional control is mediated by a supra-modal network.

It is thought that RTPJ, operating within the exogenous attention network, acts as a "filter" of incoming stimuli, preventing attentional shifts to distractors (Shulman et al., 2007) and as "circuit breaker" to redirect attention to relevant stimuli outside the current focus of sensory processing (Corbetta and Shulman, 2002). It has also been postulated that exogenous network reorients the top-down dorsal frontoparietal network, which mediates spatial allocation of attention based on both endogenous and exogenous cues (Kincade et al., 2005), to the new stimuli of interest (Corbetta et al., 2008). In the auditory modality in particular, RTPJ has also been shown to be involved in top-down attention shifts (Salmi et al., 2009), and bilateral TPJ is involved in reorienting of attention following an invalid cue (Mayer et al., 2009). However, the timing underlying RTPJ's participation in attentional reorientation and its functional relationship to one's ability to switch attention are not well understood.

In this study, we visually cued subjects to either maintain or switch attention prior to the onset of two simultaneous spatially separated spoken digits, while simultaneously recording brain activity using magneto- and electro-encephalography (M-EEG). Temporally separating the preparatory visual cue from the auditory stimulus onset and combining the M-EEG data with individualized MRI anatomical constraints allowed us to determine the spatiotemporal dynamics and involvement of both RTPJ and RFEF in switching auditory attention on a millisecond time scale. Additionally, we observed that subject task performance was significantly correlated with the level of RTPJ activation on switch trials relative to standard trials, suggesting that RTPJ plays a critical role in enabling people to switch attention.

2. Materials and Methods

2.1 Subjects

Nine healthy, right-handed, normal-hearing subjects (ages 23–34, 1 female, mean Edinburgh handedness score of 72) participated in the experiment, each giving informed consent according to procedures approved by Massachusetts General Hospital.

2.2 Stimuli and task

All subjects gave informed consent according to procedures approved by Massachusetts General Hospital. Visual stimuli were generated and presented using MATLAB (Mathworks Inc.) and PsychToolbox (Brainard, 1997). Stimuli were back-projected onto a screen 1 m in front of subjects using an InFocus 350 projector (Texas Instruments). Auditory stimuli (spoken digits 1–4, average duration roughly 400 ms) from the TIDIGIT database (Leonard, 1984) were resampled to 24.4 kHz, windowed with 10 ms \cos^2 envelopes, monotonized and pitch-shifted (100 Hz ± 3 semitones) using Pratt software (Boersma and Weenink, 2009), and processed by generic head-related transfer functions to simulate source locations ±30 degrees in the azimuthal plane (Shinn-Cunningham et al., 2005). Target locations (left

versus right) and pitches (high versus low) were both randomized across trials. Sounds were presented at 75 dB SPL (with constant 50 dB SPL Gaussian white noise to mask ambient noise; inverted at one ear to generate interaural differences that cause the noise to "fill the head," rather than coming from a distinct location) using digital-to-analog conversion and amplification (Tucker-Davis Technologies) to Tubal Insertion Earphones (Nicolet Biomedical Instruments).

Subjects performed a behavioral task that required attending to one of two simultaneous spoken digit auditory stimuli (Figure 1A). The two digits were simulated to originate from opposite hemifields and had different pitches. Subjects were first visually cued to covertly attend to one hemifield via a left or right arrow (at time t = -600 ms), then received a second visual cue (t = 0 ms). On 2/3 of the trials, it was a standard (diamond) cue indicating to maintain attention to the originally cued hemifield; on 1/3 of trials, it was a switch (opposite-direction arrow) cue indicating to attend to the opposite hemifield. Following digit presentation, subjects reported using a button box which digit was presented from the attended hemifield. A button-box press was used to reduce the effects of subject motion artifacts during digit presentation. Subjects performed six 6-min behavioral runs while in the MEG (432 trials total, with an equal distribution of left and right trials). Before scanning, subjects practiced the task and trained to respond only when the response circle appeared 1 sec after sound onset and maintain center fixation.

2.3 M-EEG and MRI data acquisition

During the behavioral task MEG and EEG data were recorded simultaneously. MEG and EEG data were collected simultaneously as combining these complementary measurements provides source localization that more precisely matches fMRI (Sharon et al., 2007; Molins et al., 2008). M-EEG data were recorded inside a magnetically shielded room (IMEDCO) using a 306-channel dc-SQUID VectorView system (Elekta-Neuromag). Four head-position indicator (HPI) coils were mounted on a 70-channel EEG cap (Brain Products), and a 3Space Fastrak (Polhemus) was used to record locations of cardinal landmarks (nasion, left/right periauriculars), EEG electrodes, HPI coils, and additional scalp points. These were used to co-register M-EEG sensors with individualized structural MRIs. At the start of each run, HPI coils reported the subject's head position relative to the MEG sensors.

In a separate session, brain anatomical information was obtained using three structural MRI scans. Structural MRI data were collected with a 1.5-T Avanto scanner (Siemens Medical Solutions). One standard structural multi-echo magnetization-prepared rapid gradient echo scan and two multi-echo multi-flip angle (5° and 30°) fast low-angle shot scans were acquired from subjects.

2. 4 Data processing and analysis

M-EEG data were analyzed using the MNE software suite (http://

www.nmr.mgh.harvard.edu/mne; see Lee et al., in press). Data were low-passed at 55Hz and signal space projection was used to exclude heartbeat and blink artifacts identified from recorded electro-cardiogram and electro-oculogram (EOG) data. Noisy M-EEG channels were excluded from subsequent processing. Trials were rejected for incorrect behavioral responses, eye movements / blinks (EOG > 150 μ V), supra-threshold EEG (75 μ V) or MEG (12 pT for magnetometers, 3.5 pT/cm for gradiometers) signals. For each subject, waveforms for each condition (standard versus switch, as well as attend-right versus attend-left) were averaged with trial counts equalized to avoid bias.

Baseline noise covariance was estimated from 200 ms prior to the initial cue onset from each trial. A cortical M-EEG source space was constructed using dipoles with 7 mm spacing,

yielding ~3,000 dipoles per hemisphere, constrained to be normal to the cortical surface located along the gray/white matter boundary segmented from the structural MRI (Dale et al., 1999) using Freesurfer software (http://surfer.nmr.mgh.harvard.edu/). Dipole currents were estimated from the M-EEG sensor data using an anatomically constrained minimum-norm linear estimation approach (Hämäläinen and Sarvas, 1989; Dale and Sereno, 1993; Hämäläinen and Ilmoniemi, 1994), and temporally averaged using 10 ms non-overlapping windows. Source localization data were then mapped to an average brain using a non-linear spherical morphing procedure (20 smoothing steps) that optimally aligns individual sulcal-gyral patterns (Fischl et al., 1999).

During the secondary visual cue in the behavioral task (the diamond/arrow cue), in an orthogonal manipulation, a 60 dB SPL noise burst was played from the cued or opposite hemifield. Since subjects were presented with a 50 dB SPL masking noise throughout their time in the MEG room, this noise burst was designed to serve as a low-salience distractor (when coming from the non-cued side) or facilitator (when coming from the cued side). We found that (1) subjective post-behavioral-experiment polling of subjects indicated that all listeners were unaware of the noise burst, and (2) analyses of the M/EEG effects when analyzing trials where the noise was always played from the cued hemifield were consistent with those from trials where the noise burst came from the opposite hemifield, so here we only show results where the noise was presented from the cued side (facilitation condition). In Supplementary Material, we show that similar clusters are obtained when contrasting the standard condition (maintain-attention with facilitating noise) with the switch condition with a distracting noise (burst coming from the opposite hemifield), showing that analysis contrasting the standard condition with switch condition does not depend on whether the noise in switch trials was distracting or facilitating. Since the contrast of distracting versus facilitating noise (i.e., in maintain attention trials) is not the main focus of this investigation, we only show the results of that contrast in the Supplementary Material.

2.5 M-EEG statistics-spatiotemporal clustering

Spatiotemporal activations were analyzed using a non-parametric spatial clustering permutation test with a maximal statistic (Nichols and Holmes, 2002) extended to incorporate the temporal dimension. This method has the advantage of addressing multiple comparisons by controlling the family-wise error rate while identifying regions of large spatial and sustained temporal activation. First, a statistical map was produced from a paired t-test across subjects contrasting standard versus switch activations at each point in space (cortical dipoles) and time. Points putatively significant at a threshold of p < 0.05 were then clustered based on matching t-value sign, and geodesic spatial (5 mm along the cortical surface) and temporal (10 ms) proximity. Each cluster was scored by summing the t-value magnitudes of all cluster points. Second, this procedure was repeated under 512 permutations (with nine subjects, $2^9 = 512$) where the experimental conditions (standard or switch) were relabeled for a subset of subjects, clustering was performed, and the maximal cluster score under each permutation was recorded to form a maximal distribution. Finally, the corrected p-value for each cluster from the original labeling was obtained as the proportion of maximal distribution scores greater than or equal to that of the given cluster. We also use a time-of-interest to only consider clusters with significant activation on t > 0(following the switch/maintain-attention cue).

For each cluster, the spatial center of mass was calculated by weighing each cluster vertex by the sum of its significant t values across time. The temporal center of mass was similarly obtained by weighing each time point by the sum of significant t-values across vertices in the cluster.

2.6 Functional FEF and anatomical RTPJ ROI definition

We chose *a priori* L/RFEF as ROIs, constraining them both anatomically to the precentral sulcus and gyrus (Simó et al., 2005) defined by a standard automated surface-based parcellation (Fischl et al., 2004), and functionally using a "go" vs. "no-go" saccade contrast. In this task, subjects received a green (go) or red (no go) cue pointing either left or right, and 330 ms later a circle appeared in that direction. Subjects were instructed to move their eyes to the circle or maintain centered fixation for a green or red arrow, respectively. We contrasted go/no-go conditions during the preparatory period (50 – 400 ms after cue onset) using a repeated-measures ANOVA at each vertex, treating time as an experimental factor over consecutive 10-ms time frames. We used a conservative Greenhouse-Geisser non-sphericity correction and p < 0.05 (uncorrected) for activation greater in go than in no-go trials to constrain the ROI.

We also defined an anatomical ROI for RTPJ. Since estimates of RTPJ location reported in meta-analysis of attention-manipulating tasks vary by up to 22.7 mm (Mitchell, 2008), we constructed an ROI by first fitting the smallest possible sphere around previously reported MNI coordinates. We then selected the surface vertices from our average brain (from Freesurfer) that fell within that sphere (in MNI coordinates) to form the RTPJ ROI.

2.7 ROI-based temporal exploration

To display the time course of the different significant spatiotemporal clusters (see 2.5 *M*-*EEG statistics*, above), trials were epoched (baseline-corrected) and projected onto the cortical surface, and the magnitude of the currents from each of the vertices in the cluster (significant at any point in time) were averaged. To compensate for differences in overall SNR across subjects, the resulting traces were normalized (divided by the mean value across time for each subject) before being averaged together for display, yielding arbitrary units (AUs) for the axes.

To explore the temporal dimension of the functional FEF and anatomical RTPJ ROIs (see 2.6 Functional FEF and anatomical RTPJ ROI definition, above), the magnitude of the current of each vertex within the derived ROI was averaged, and then the spatiotemporal clustering permutation-test procedure was performed with no spatial dimension (preliminary t-test threshold p < 0.05, non-parametric corrected permutation threshold p < 0.05). However, here we are not able directly compare the time courses of the L/RFEF functional ROI to the regions derived using the whole-brain statistical approach (2.5), since the ROI-based approach comparatively has different sensitivity and decreases the number of multiple comparisons. We report results from both the anatomical RTPJ ROI and functional FEF ROIs here with the caveats of difficulties in comparisons caused by differences in ROI size and signal-to-noise ratios.

3. Results

3.1 Attention switching task

Subjects performed a behavioral task that required attending to one of two simultaneous spoken digit auditory stimuli (Figure 1A; see *Stimuli and task* in **Methods**). At the start of the trial, subjects were visually cued to covertly attend to one hemifield via a left or right arrow (at time t = -600 ms), and then received a second visual cue (t = 0 ms), which was either a standard (diamond) cue indicating to maintain attention to the originally cued hemifield, or a switch (opposite-direction arrow) cue indicating to attend to the opposite hemifield. Subjects reported using a button box which digit was presented from the attended hemifield, obtaining performances on the standard task ($\mu = 92.48\%$, range 79.6–97.7%) and switch task ($\mu = 93.4\%$, range 77.8–100%) that were both well above chance level

(25%) and did not significantly differ from one another (paired t-test p = 0.633; Figure 1B). In the trials where listeners made errors, this was typically due to reporting the masking digit (accounting for 86% of listener errors; chance level for reporting the masker was 33%).

3.2 Cortical dynamics of switching attention

To examine cortical activation with high temporal resolution, during the behavioral task MEG and EEG data were recorded simultaneously. The combined M-EEG data were coregistered with the subject's anatomical information, and the sensor data were used to reconstruct cortical activation using a minimum norm estimate (Hämäläinen and Ilmoniemi, 1994), and a within-subjects comparison of standard and switch conditions was performed (see Methods). Analyzing the whole brain for times between initial cue onset and 300 ms post-digit onset (t = -600 - 900 ms), we found that RTPJ and RFEF (possibly extending to RMFG) were significantly more active during switch trials than standard trials (see Figure 2A). The RTPJ spatiotemporal cluster (p < 0.004) was more active from 160 to 640 ms, while two clusters anatomically proximal to RFEF (p < 0.004 and 0.04) were more active from 270–430 and 410–590 ms, respectively. Other significant clusters are listed in Table 1.

We also performed a functional ROI-based exploration using the L/RFEF ROIs derived from a go/no-go saccade task subjects performed (see 2.6, 2.7). Examining the left and right FEF activations, we confirmed the findings of the spatiotemporal clustering method, finding significantly greater RFEF (but not LFEF) activations occurring at times between 150 and 860 ms (p < 0.05 temporal clustering; not shown), with an expanded range of significant activations likely arising from increased sensitivity and reduced multiple comparisons in the time-only (collapsing space across the ROI) statistical analysis. The similar analysis performed on the anatomical RTPJ ROI (which shared a fair amount of overlap with the cluster ROI; see Figure 2) had significant temporal activations between 280 ms and 520 ms.

Once the significant spatiotemporal clusters were identified using our whole-brain approach, we examined their relationship to each subject's behavioral performance. We averaged the cortical current observed across all vertices in each cluster during that cluster's significant time span, and correlated the normalized cortical activation differences with the normalized behavioral differences in switch versus standard trials ([switch – standard]/standard). To conservatively correct for multiple comparisons (across 12 significant clusters), we used a Bonferroni-corrected correlation significance threshold of p < 0.05/12 = 0.004, and found that greater RTPJ activation correlated with better subject behavioral performance on switch trials (R = 0.88, p = 0.002; Figure 2B); to conservatively compensate for a potential outlier subject (shaded gray in Figure 2B), we additionally performed a Spearman ranks correlation which remained significant (R = 0.93; p = 0.0008).

4. Discussion

We found that, despite no significant difference in behavioral performance in maintaining versus switching attention between two upcoming simultaneous auditory streams, cortical areas previously hypothesized to behave as part of an attentional "circuit breaker" (Corbetta and Shulman, 2002) were significantly active. Specifically, RTPJ and RFEF/MFG were significantly more active roughly 150–650 and 300–600 ms following the reorientation cue, respectively. We also observed a correlation between differential RTPJ activation and behavioral performance in switch versus maintain attention trials. This suggests RTPJ as a potential source of the individual performance variability in reorienting auditory spatial attention in healthy subjects—not dissimilar to the lesion studies of spatial neglect in humans (Vallar and Perani, 1986; Mort et al., 2003). This suggests that RTPJ, as part of the ventral (typically exogenous) attention network, can function as an attentional circuit breaker to drive endogenous attention switching prior to stimulus onset. While we observe

that the RTPJ cluster is larger than typically observed using fMRI studies and extends to include a region that may correspond to human MT+, this is likely due to the slightly reduced spatial sensitivity of M-EEG relative to fMRI (Sharon et al., 2007). Moreover, the time-weighted spatial MNI center of mass differs from typical reports of five previous attentional RTPJ activation locations (see Mitchell, 2008) only by an average of 13.7mm— similar to differences observed between these previous studies—and falls within the ROI sphere defined by these previous studies (see Methods), suggesting that most of the observed significant activation originates from RTPJ. Nonetheless, given the broad nature of the activation patterns we observed, it could prove useful to perform additional studies to establish an even clearer correspondence between the regions discovered by fMRI and the underlying temporal dynamics, as the FEF and RTPJ activations from fMRI tend to be more focal.

Previously, bilateral TPJ has been implicated in evoking P300s in visual and auditory oddball tasks (Linden et al., 1999), has been shown to be sensitive to target but not distractor oddballs (Clark et al., 2000), and has been observed to activate when reorienting auditory attention following an invalid cue (Mayer et al., 2009). The right TPJ in particular, however, has been shown to be involved in active visual search (Himmelbach et al., 2006; Shulman et al., 2007) as well as detecting targets in auditory and visual tasks (Downar et al., 2000), especially those in unattended locations, and RTPJ's activation upon detection of incongruent sensory percepts (Balslev et al., 2005; Papeo et al., 2010) suggests a possible role in multisensory integration. Moreover, a recent study found that RTPJ activation occurred when orienting attention based on top-down cues in an auditory task (Salmi et al., 2009). We observe activation in only right TPJ, suggesting that here it acts specifically in using visual cues to reorient auditory spatial attention, as opposed to simply detecting deviations in the stimuli (as left/right visual cues were conserved). This is consistent with previous studies reporting a right-hemisphere bias when using auditory (Krumbholz et al., 2009) and visual cues (Kelley et al., 2008; Shulman et al., 2009, 2010) to switch attention. A related auditory attention switching study did not observe this type of RTPJ activation (Shomstein and Yantis, 2006), but this is likely because the ventral attention network is not recruited when subjects regularly switch from one task to another over short time periods (e.g., in task-switching paradigms; Corbetta et al., 2008).

Recent studies have suggested that RFEF is important for covert visual spatial attention (Taylor et al., 2007), switching between pro- and anti-saccade tasks (Astle et al., 2012), and shifting attention based on location, object attributes, or task rules (Wager et al., 2004). Here we observe that RFEF/MFG is important for covert switching of spatial attention, not just in vision but also for audition (Wu et al., 2007). While it is difficult to differentiate activity in RFEF from activity in RMFG from the large RFEF/MFG cluster obtained from our wholebrain M/EEG spatiotemporal clustering, the observed significant activity from the RFEF ROI analysis suggests that some the activity of the large RFEF/MFG cluster most likely originates in RFEF. In addition, the encroachment upon RMFG could be a result of RMFG linking the dorsal and ventral attentional networks, as suggested by recent resting state MRI work (Fox et al., 2006). Moreover, in our additional temporal ROI-based exploration, the finding that the anatomical RFEF ROI time-course was significantly active at 150 ms suggests that it might be involved in attention switching very early, possibly at the same time or prior to RTPJ. While there were additional significant regions discovered in our analysis (and listed in Table I), the involvement of these areas remains unclear since they lack clear correlates in previous work, and further studies will be necessary to clarify the roles of these areas in switching auditory spatial attention.

The weak evidence previously reported for spatial selectivity in the ventral network that includes RTPJ suggests that spatial reorienting is not mediated solely by that network but

involves joint activation of dorsal (e.g., bilateral IPS and FEF) and ventral regions (Corbetta et al., 2008). Although the ventral network is often responsible for reorienting attention due to exogenous cues, we suggest that here it operates as a generalized "circuit-breaker" to switch the listener's attention. Additionally, there is evidence that short-latency responses in the ventral attention network precede those in dorsal areas, suggesting that the ventral network triggers a reorienting response. EEG studies have shown parietal activation followed by frontal activation around 200-400 and 400-500 ms, respectively, in covert attention tasks (Talsma et al., 2005; van der Lubbe et al., 2006). Our observed activation timings are consistent with this, and suggest that RTPJ participates in the switching of attention prior to the region in both the ventral and dorsal networks (RFEF). Furthermore, we undertook a supplemental behavioral experiment (see Supplemental material) demonstrating that subject's performance significantly dropped when they only had < 200ms to prepare for switching of attention (compared to 400 and 600 ms), mirroring our current neuroimaging results. Taken in the context of prior fMRI Granger causality analysis (Sridharan et al., 2007), our work suggests that ventral activation precedes dorsal activation, providing a coherent link between spatial distributions previously observed with fMRI and temporal evolutions previously observed using EEG. Along with previous studies, our results also suggest that the ventral attention network (Corbetta et al., 2008) functions similarly in both vision and audition (Shomstein and Yantis, 2006; Wu et al., 2007), and thus RTPJ and RFEF (and possibly RMFG) operate within a supra-modal cortical attention system. Alongside results from a visual search study (Shulman et al., 2007), our results suggest that activity levels in the ventral network (and at RTPJ in particular) correlate with successful attentional modulation.

Our behavioral task utilized two visual cues 1200 and 600 ms prior to digit onset to direct listeners' auditory attention. While listener's auditory attention did not definitively need to be deployed prior to the second (diamond or switch arrow) cue, the frequent validity of the initial cue (on 2/3 of trials) likely caused listeners to shift their attention to the cued hemisphere. It is unlikely that the observed activity is due to shifting attention from the visual modality (hemifield cues) to attending to auditory space (attending to a side to listen for digits), as this was performed by subjects in both the maintain- and switch-attention conditions that we contrasted. These results suggest that these mechanisms are involved in redirecting attention to a particular auditory spatial location, as following the second cue, it was necessary for listeners to deploy auditory spatial attention to the proper hemisphere in order to perform the task successfully. Although most listener errors were due to reporting the masking digit, these errors were likely due to listeners mistakenly attending to the incorrect side as opposed to attending to both sides and reporting the incorrect digit. For example, in one divided attention study where listeners had to attend to two simultaneous talkers with the same ± 30 -degree spatial separation that we used here (Best et al., 2006), average performance reporting a color and number from each talker was under 30%, while performance reporting the color and number of only one of the two talkers (i.e. in a selective attention task like the one used here) averaged over 80%. This suggests that a dividedattention listening requires substantially more effort and produces lower performance levels than attending to one of two simultaneous sources, which decreases the likelihood subjects employed such a strategy. Nonetheless, we cannot definitively rule out the possibility that the activations we observed were due to subjects employing an alternative strategy of preparing to attend to both streams and then report one digit, as opposed to selectively attending to the cued stream alone. Also, although subjects reported not noticing the lowsalience noise burst during the second visual (switch/maintain) cue and additional analyses of trials where the noise burst was from the opposite (distracting) side were consistent with the data shown here (comparing Supplementary Material with Figure 2), we cannot completely rule out the possibility that some of the activations may be due to interactions with the low-salience noise burst.

Future studies could utilize functional connectivity analyses to further understand the interactions between these cortical regions, and possibly identify attentional modulations that do not manifest as raw activity level changes. For example, resting-state fMRI connectivity analyses have identified different cortical attention networks (Fox et al., 2006; Sridharan et al., 2007) and separate sub-regions of RTPJ that could serve different functions (Mars et al., 2011). Functional connectivity analyses on the millisecond timescale provided by M-EEG could be used to infer the connectivity of regions such as RTPJ or RFEF / RMFG explicitly during the periods of transient activation that are involved in attentional reorientation, which could imply the extent to which each region participates in the observed modulation of auditory and visual cortical responses during attentional tasks (Yantis et al., 2002; Petkov et al., 2004; Wu et al., 2007).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

(TPJ)	Temporoparietal junction
(FEF)	frontal eye fields
(MFG)	middle frontal gyrus
(MEG and EEG)	magneto- and electro-encephalography

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Highlights

M-EEG combined with MRI used to reveal cortical dynam ics in switching of attention

RTPJ followed by RFEF/MFG are more engaged in switched than non-switched trials

Strong correlation between behavioral performance and RTPJ activation

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Figure 1. Subjects attended to one of two simultaneous digits simulated to originate from opposite hemifields

A: Subjects stared at a fixation dot (t = -800 ms) until a cue arrow appeared (t = -600 ms) instructing them to attend to either the left or right hemifield. At t = 0 ms, on 1/3 of the trials an arrow pointed toward the opposite hemifield (switch condition), and thereby instructing the subject to attend to the opposite hemifield; on the other 2/3 of the trials a diamond (standard condition) instructed them to maintain attention to the original hemifield. Digits were then played from the left and right hemifields simultaneously (t = 600 ms), and the subject reported the number of digits heard. *B*. Subject behavioral performance did not significantly differ between the standard and switch conditions.



Figure 2. Switching auditory attention based on a visual cue evoked stronger responses from RTPJ and RFEF (and possibly RMFG), with RTPJ activation correlating with subject behavioral performance

A: Three spatiotemporal cortical activation clusters are shown corresponding to RTPJ, RFEF/MFG, and RFEF, with the functional RFEF ROI and anatomical RTPJ ROI overlaid in green. The duration each vertex in the cluster was significant is shown as a heat map in the top row alongside the multiple-comparisons corrected cluster p-value. In the bottom row, the time course of the normalized cortical current (arbitrary units; see Methods) averaged across all cluster vertices is shown, providing visualization of the temporal dimension of the significant spatiotemporal activation. The significant time span of the cluster vertices significant at each time point. We find that both RTPJ and RFEF/MFG both show activation differences prior to digit onset (at 600 ms). *B*: The normalized behavioral performance difference ([switch-standard]/standard) was highly correlated with the normalized RTPJ activation difference across subjects (with correlations persisting when the potential outlier subject, shaded in gray, is taken into account; see Results).

Swatermark-text

Table 1

normalized activity with normalized behavioral performance. RTPJ was significantly correlated following a Bonferroni correction (p < 0.05/12 = 0.004), Significant spatiotemporal clusters comparing switching versus maintaining attention, with the multiple-comparisons corrected p-value, approximate anatomical region, time span of activation (temporal center of mass in parentheses), spatial center of mass (MNI coordinates), and correlation of while a RFEF correlation did not survive this conservative correction.

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p-value	Region	Time range (ms)	MNI co	ords. (m)	(m	Corr. (p. R)
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0.0039	RTPJ	160 - 640 (410)	43.7	-53.2	23.3	0.002 (0.88)
0.0039	RFEF/MFG	270 - 430 (350)	39.4	2.5	40.7	0.25
0.0313°	RFEF	410 - 590 (510)	22.1	-7.2	51.1	0.01 (0.80)
0.0390	RVisual	340 - 400 (390)	20.5	-56.4	17.5	0.78
		Standard $>$ Sv	vitch			
0.0039	RParacentral	560 - 890 (730)	4.1	-35.1	63.6	0.72
0.0039	LVisual	30 - 130~(100)	-12.3	-86.6	7.8	0.66
0.0078	LPrecentral	440 - 610 (550)	-58.4	2.8	13.7	69.0
0.0313	LCirc Insula Inf	760 - 870 (800)	-35.7	-17.0	-7.2	0.57

 $\overset{7}{\Gamma}$ Clusters that are plotted in Figure 2 are shown by next to p-values.