

Phase of low-frequency cortical oscillations encodes sound edges and sound-specific structure

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Natural sounds are rich in time-varying acoustical features. So far, little progress has been made towards understanding their cortical encoding, because of a predominant focus on low temporal resolution imaging methods, and because of the need to assume a stimulus-feature space whose nature is currently unknown. A good initial step is thus to investigate the ability of the auditory system to differentiate between natural sounds as a proxy for measuring the encoding of sound features, and to differentiate such sound-specific encoding from generic processing for the detection of sound against silence. We addressed these issues by combining MEG with information-theoretic methods for measuring time-varying information about the between-sounds and sound vs. silence differentiation.

Methods:

STIMULI: 3-s long recognizable natural sounds from a previous fMRI study (Giordano et al., 2012).
DESIGN: on each block of trials, supine participants (5) were presented in random order with each of the 32 sound stimuli, 10 3-s long silence stimuli, and the subsequent repetition of 2 randomly selected sounds (ISI: 2-4 s). They carried out a 1-back repetition detection task. MEG data were acquired with a 248-magnetometers whole-head system (MAGNES 3600 WH, 4-D Neuroimaging; s. rate = 1017 Hz).
PREPROCESSING: [1] low-pass forward-reverse (for.rev.) FIR filter (order: 11; cutoff: 50 Hz); [2] polynomial detrending of trial blocks; [3] trial segmentation (-1.75 s to 4.75 s from sound onset); [4] outliers detection; [5] time-shift regression removal of residual reference variance and 50 Hz component; [6] time-shift denoising source separation (de Cheveigné, 2010); [7] filtering with bank of order 508 for.rev. FIR filters (25 2-Hz bands in 0-50 Hz range); [8] computation of power and phase (Hilbert tr.) of the filtered data. For each participant, we computed the time-varying mutual information (MI) that differentiated between sounds (SOU), or between all sounds and silence (SIL) in the power and phase of each spectral band. Significance values for the MI were computed as described in Ince et al. (2012), and Bonferroni corrected. SIL and SOU MIs were scaled to the average of the pairwise MI in order to allow their comparison.

Results:

Significant information emerged predominantly for phase in the 0-8 Hz band (Fig. 1). Scalp topographies for power and phase coherence in this band appear consistent with a temporal-cortex origin (Fig. 2). Although phase coherence increased at sound onset in the 0-8 range, onset power appeared to increase significantly only in the 0-2 Hz band. A weaker offset-related increase in phase coherence also emerged in the 0-6 Hz range. Time-varying MIs (Fig. 3) revealed significant onset- and offset-related SIL information in the 0-2 Hz phase. For higher MEG frequencies, SIL information was limited to the onset and lower in magnitude. Phase in the 2-8 Hz band encoded predominantly SOU information, particularly at sound onset but also throughout the entire sound duration. MI scalp topographies appeared consistent with information encoding in the temporal cortex (although see 0.2 s 0-2 Hz SIL topography).

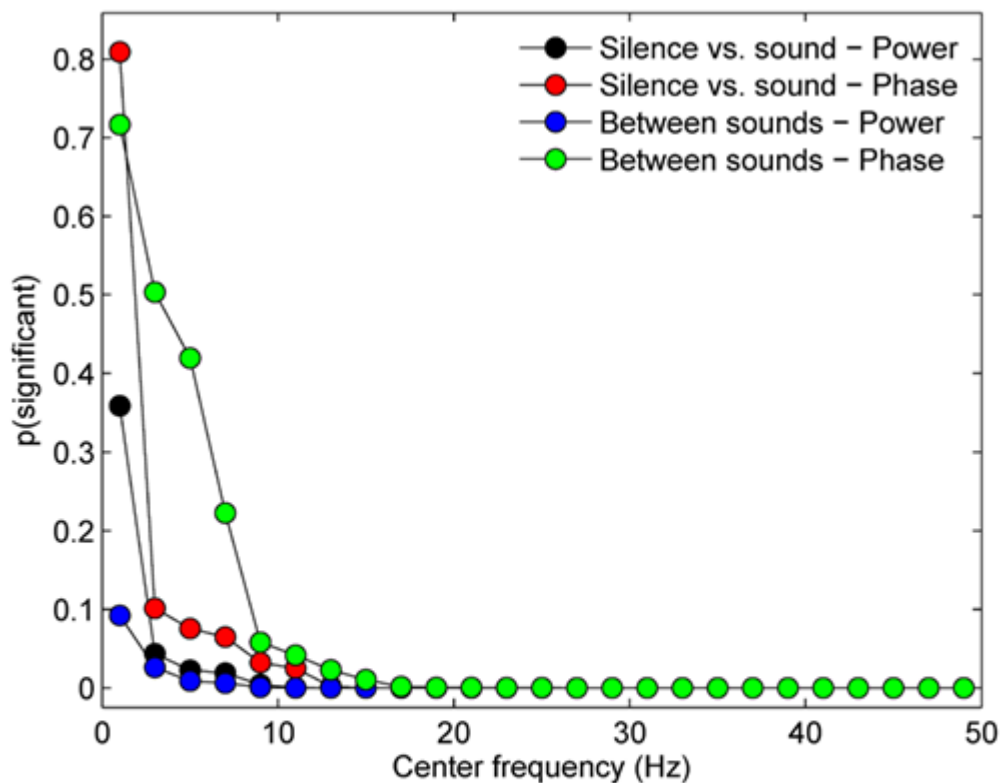


Figure 1. Proportion of significant MIs between 0-3 s from sound onset for each spectral band, averaged across participants and MEG sensors. $P < .05$ adjusted for multiple comparisons.

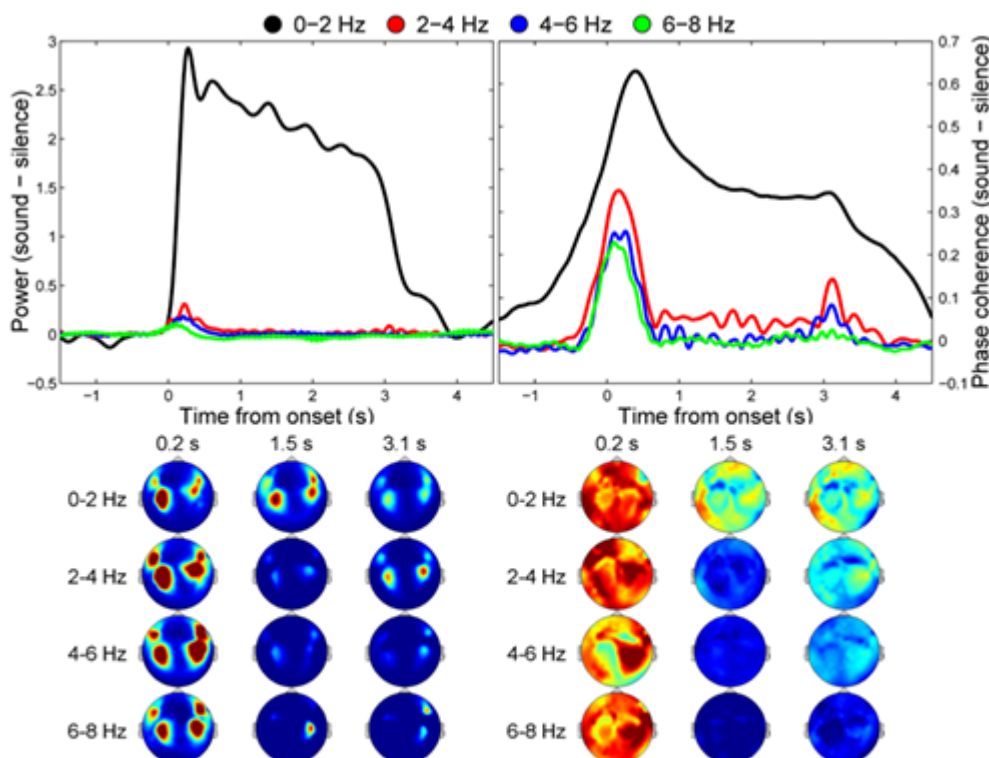


Figure 2. Top panels: difference between sound- and silence trials power (left) and phase coherence (length of average-phase vector; right) for spectral bands in the 0-8 Hz range, averaged across sensors and participants. Bottom panels: scalp topographies for the same sound-silence measures (power: right; phase coherence: left). For ease of comparison, color-scales were normalized within each spectral band (blue/red = min/max).

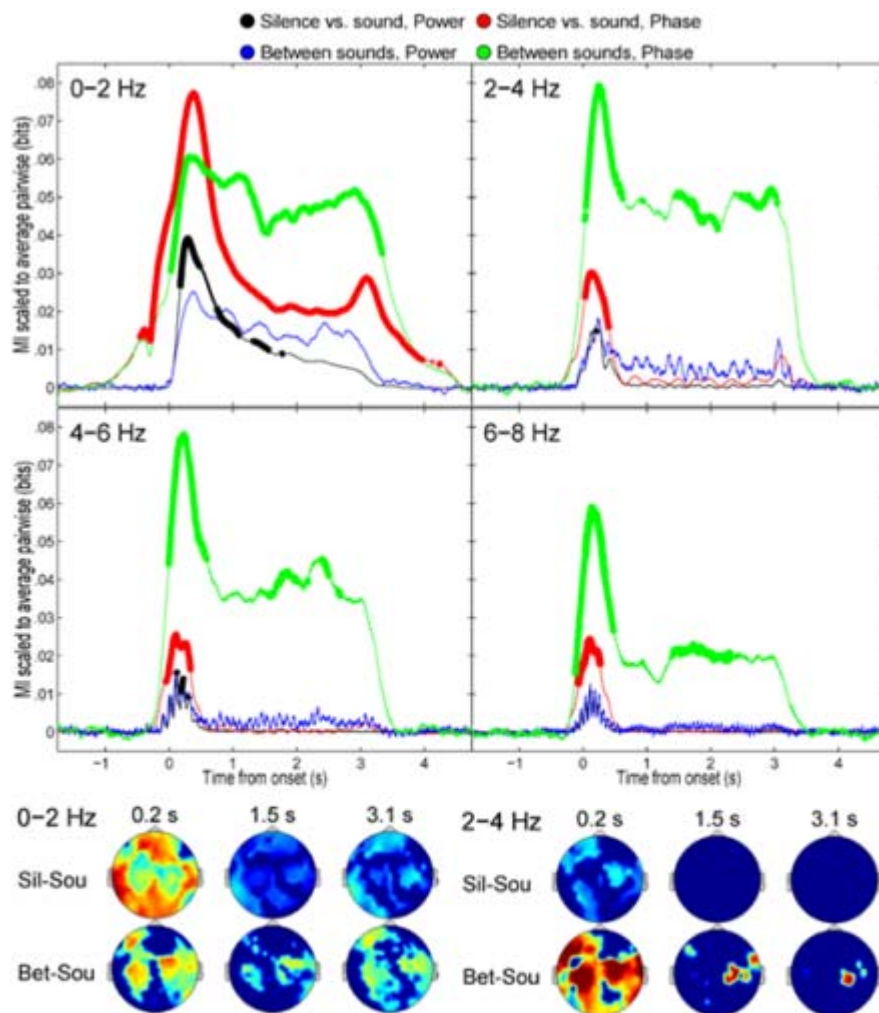


Figure 3. Top four panels: time varying mutual information in the MEG data about the silence vs. sound differentiation, and about the between-sounds differentiation in power and phase for spectral bands in the 0-8 Hz range, averaged across participants and across sensors with at least 10 consecutive time-points associated with a significant MI. MIs were scaled to the average value of MIs observed for all of the possible pairwise discriminations between pairs of sounds or between each sound and silence. Thick lines show those time-points where MI was significant for all of the experiment participants. Bottom panels: scalp topography for phase-related MIs in the 0-4 Hz range. Sil = silence; Sou = sound; Bet = between. Red/blue = max/min across all MIs and spectral bands, i.e., comparisons across MIs and spectral bands are meaningful.

Conclusions:

Confirming previous studies (e.g., Luo and Poeppel, 2007; Ng et al., 2012), sound-specific structure was encoded in the phase of oscillations up to 8 Hz. A functional dissociation emerged between 0-2 Hz oscillations and higher frequencies: whereas the former appeared to encode both sound-specific structure and information for differentiating between silence and sound edges (onset and offset), the latter appeared to encode predominantly sound-specific structure. Across spectral bands, encoding processes appeared to concentrate around sound onset, although they comprised the entire duration of the sound stimulus. Such encoding processes appeared to require a pure phase-reset mechanism only in the 2-8 Hz range, whereas in the 0-2 Hz band they involved both phase reset and onset-related power increase.

Perception and Attention:

Perception: Auditory/ Vestibular

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