**Introduction**

Natural sounds, like speech, contain multiple levels and multiple types of modulations. However, the brain’s neural representation of such complex modulations is largely unknown.

**Methods**

**Stimuli**

A 550 Hz pure tone is simultaneously amplitude modulated (AM) and frequency modulated (FM). FM rate is fixed at 37.7 Hz. AM rate is investigated at 0.3, 0.7, 1.7, 3.1, 4.9, 9.0, and 13.8 Hz.

**MEG Recording**

The neural signal is recorded using a 157-channel whole head MEG system, sampled at 1 kHz. 10 right-handed adult subjects were scanned.

**Denoising source separation (DSS)**

Neural activities from the auditory cortex are extracted using DSS, which simultaneously diagonalizes the spatial correlation matrix and a (suitably) biased spatial correlation matrix of the MEG signal.

**Modeling the Dynamics of 40-Hz aSSR**

2 temporal integration systems and a static nonlinearity model the auditory steady state response (aSSR).

\[
\begin{align*}
\tau_{\text{fast}} & \; r_{\text{fast}}(t) = -r_{\text{fast}}(t) + \lambda s(t) \\
\tau_{\text{slow}} & \; r_{\text{slow}}(t) = -r_{\text{slow}}(t) + \lambda s(t) \\
r(t) & = g \left( r_{\text{fast}}(t) + r_{\text{slow}}(t) \right)
\end{align*}
\]

The two time constants are set to 200 and 25 ms. \(g(.)\) is a static nonlinear function, i.e. half-wave rectification.

**Results**

**Neural source localization**

The sources of the neural responses are localized to both left and right auditory cortices.

![Distribution of the magnetic field over the head (flattened for illustration). (subject R1170)](image)

**aSSR at modulation frequencies**

Both the AM and FM of the stimulus are simultaneously encoded in the auditory cortex by neural oscillations at the modulation frequencies.

- 3.1Hz
- 6.2Hz
- 37.7Hz

![Power spectrum of neural responses (subject R1170)](image)

**Technical Summary**

- Both the fast FM and slow AM are encoded by a precise temporal code in the human auditory cortex.
- Slow AM has a (robust) dual neural representation.
- Spatial correlation in the MEG recording can be used to separate the auditory response from other stimulus irrelevant neural activities.

**Applications**

- Understanding the brain’s neural encoding of sounds can help the development of audio processing techniques.
- aSSR is widely used in hearing assessment.