Auditory Gamma-Band Response to Modulated Tones:

Wavelet Analysis of MEG Data

Chris Rodgers, University of Maryland MERIT 2004

With Dr. Jonathan Simon, University of Maryland

Abstract.

The technique of magnetoencephalography (MEG) is a very powerful tool for the study of electrical impulses in the brain. Based on the detection of minute magnetic fields caused by those impulses, MEG measurements offer high temporal resolution, well-suited for understanding how the brain processes stimuli.

Tones, played in a subject's ear, are known to evoke responses in the brain with frequency in the gamma band (around 40 Hz). Generally these can be seen in MEG data approximately 100 ms after the stimulus, with consistent latency from trial to trial. However, previous work has shown that a so-called "induced" gamma response may also occur some 200 ms after the onset of the tone, though with relatively inconsistent latency. Because of this inconsistency and because of the high noise associated with MEG data, the induced response can be hard to detect.

In this paper we will use wavelets to analyze MEG data, which was collected using amplitude-modulated short tones as stimuli, and attempt to detect an induced response in the gamma band. We will also study the brain's steady state response to the same tones.

Introduction.

What is MEG?

Magnetoencephalography (MEG) is a powerful new technique for detecting neural activity in the brain. The University of Maryland system consists of 160 sensors, each of which is a tiny superconducting loop, placed around the subject's head. When enough neurons (around 10000) are activated synchronously in the same area of the brain, the resulting net ionic current induces a magnetic field, which in turn induces currents in the sensors. Maxwell's laws and the current in each sensor are, in theory, sufficient data to compute approximately the location, orientation, and strength of the ionic current. Figure 1 shows the locations of the channels around the head.

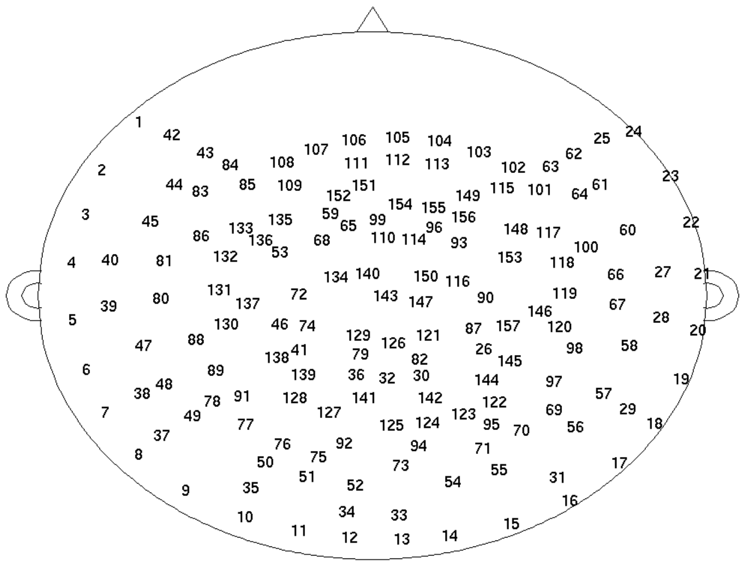

Figure 1 - A map of the 157 channel locations in the UM MEG system, looking down at the top of the head. The nose is pointing toward the top of the page. Channel numbers are marked to the right of the actual location.

These fields often amount to no more than a few femtoteslas[1]. In comparison, the ambient magnetic field from the Earth is approximately 10^{10} times stronger. Physical shielding is used to attenuate the noise, but nonetheless high noise background is a significant problem for analyzing MEG data.

What is wavelet analysis?

[1] Ahmar, Nayef E., Simon, Jonathan Z. "Periodic Noise Suppression for MEG Signals." Poster, 2004.

Wavelet analysis is a mathematical method for analyzing the frequency components in a signal. For example, the Morlet wavelet (shown in Figure 2) is the product of a Gaussian curve and a complex sinusoid. A sampled signal can be transformed with the Morlet wavelet over a specified range of frequencies. The square of the result is a power function defined on two dimensions which indicates the power of the signal at a given time and frequency. Abstractly:

$$\text{Signal}(t) \Rightarrow \text{Power}(f, t)$$

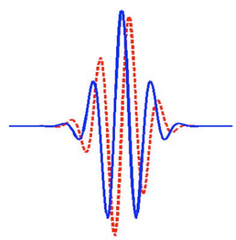

Figure 2 - The complex Morlet wavelet. The blue line is the real portion and the red line the imaginary.

However, it is not possible to calculate exactly the power of a specific frequency component at a specific instant in time; there is always a trade-off between resolution in the frequency domain and resolution in the time domain. This trade-off is governed by the width of the wavelet, which in this case is the width of the Gaussian. The wider the wavelet is in the time domain, the less temporal resolution and the more frequency resolution can be attained. In the limit, a Morlet wavelet of infinite width is simply a sinusoid, and wavelet analysis degenerates into Fourier analysis, with maximum frequency resolution and zero temporal.

Transforms using the complex Morlet wavelet, as implemented in this paper, do not preserve information about the phase of a signal.

What kind of neuronal response is expected?

Both a transient and a steady state response are expected. The steady state response is expected to be tightly phase-locked to the stimulus, and to be found at the frequency of modulation (Ahmar 2004). The transient response is expected to consist of frequency components in the gamma band (20-50 Hz).

However, the brain's transient response to auditory stimuli can be further divided into two categories: **evoked**, meaning phase-locked to the stimulus, and **induced**, meaning not phase-locked. Another way of saying this is that evoked responses always occur with fixed latency from the stimulus, while induced responses may have variable ("jittery") latency.

This means that if the same stimulus is repeated many times and the MEG signals are averaged together, the evoked responses will increase in strength relative to the noise background, while the induced responses will interfere destructively with each other and will not probably weaken with respect to the noise background. In other words, calculating the evoked response is much easier because the process of averaging tends to increase the SNR.

The induced response is harder to detect but it is important because it has been suggested that it indicates the formation of abstract structures in the mind[2].

[2] Tallon-Baudry, C., and Bertrand, O. "Oscillatory gamma activity in humans and its role in object representation." Trends in Cognitive Science 3.4 (1999): 151-62.

It has only rarely been observed in response to auditory stimuli[3]. But is this because it does not exist, or because it is not strong enough to be observed with current methods?

Methodology.

There were four stimuli in this experiment. Each was a one-second, pure sinusoidal tone at 400 Hz, but amplitude-modulated at 16, 32, 48, or 64 Hz. They were presented 100 times each, shuffled together, through headphones to a subject inside the MEG system. Data was sampled at 1000 Hz, beginning 400 ms before and ending 400 ms after the one-second stimulus, through 157 channels. (A block of data from all 157 channels for the entire 1.8 seconds is referred to as an **epoch**.) Three additional channels were used to measure and account for any magnetic fields originating outside the brain. A noise reduction algorithm developed by Nayef Ahmar of Dr. Jonathan Simon's lab was applied to the raw data to reduce narrow band noise, such as the 60 Hz noise generated by power lines (Ahmar 2004).[4]

To observe the steady state response, a long wavelet (width 15 ms) was used in order to increase the frequency resolution and to emphasize longer features. Since the SSR was expected to be phase-locked, the signal from each

---

[3] Knief, A., Schulte M., Bertrand, O., Pantev, C. "The perception of coherent and non-coherent auditory objects: a signature in gamma frequency band." Hearing Research 145 (2000): 161-8.

[4] In any MEG experiment, certain trials will inevitably be corrupted by artifacts such as eye-blink, swallowing, or even a metal cart rolling through the room, all of which have an incredibly damaging effect on data integrity. In this experiment, epochs with extremely high signal values and epochs with extremely high power at some frequency were identified as "bad" and were eliminated from future consideration. These usually amounted to around 10% of the total number of trials.

presentation was averaged and the result, one for each channel, was transformed. Recall that this procedure has the effect of reducing non-phase-locked activity (in this case, noise).[5]

To observe the transient response, a shorter wavelet (width 1 ms) was used. The evoked and induced responses were computed separately: the former, like the SSR, by averaging first and then transforming, while the latter was determined by transforming each individual presentation and then averaging the transforms. Since the wavelet transform does not preserve phase information, the latter method maintains non-phase-locked activity in the brain, which includes both the induced response and unfortunately the noise. This method is not ideal, but it is necessary.

Results.

Part 1: The Transient Response

Recall that the transient response consists of two components: evoked (phase-locked) and induced (not phase-locked), and that it has been suggested that induced activity indicates higher-order processing. The induced response to one of the four stimuli are shown in Figure 3. [6] To save space, the other three are not shown, but they are described below.

[5] The SSR figures that are included in this paper were “baselined” to reduce the appearance of noise. In this case, baselining means dividing the power at every point in a wavelet transform by the average power at that frequency in the pre-stimulus period (from 200 ms before the onset of the stimulus until the onset). This power, since it is pre-onset, is presumed to be noise.

[6] Since there was a separate induced response returned from each of the 157 channels, it was necessary to choose the most relevant channels. This was done by choosing the ten that had the strongest signal at one of the peaks, and then averaging these ten channels

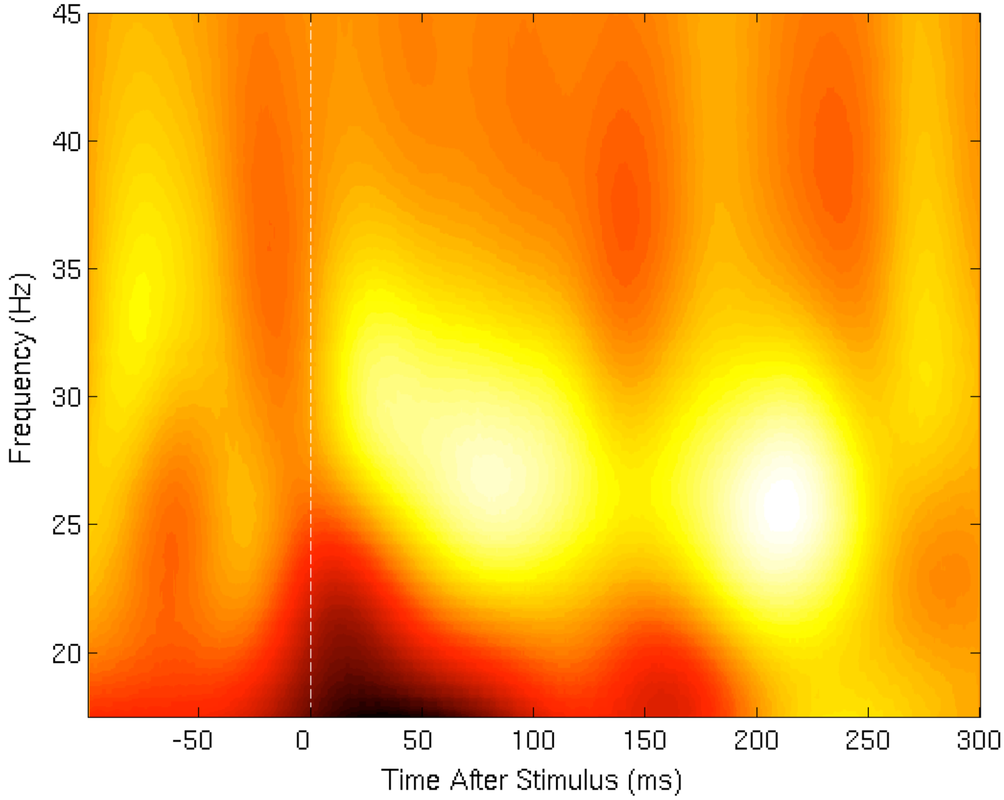

Figure 3 - The transient induced response to the 16 Hz stimulus.

There are two strong peaks in Figure 3, the response to the 16 Hz stimulus. One is at approximately 90 ms post-stimulus and 27 Hz, and the other is at approximately 200 ms post-stimulus and 25 Hz. Was this behavior also found in the responses to the other stimuli? Unfortunately the answer is not clear. The 64 Hz stimulus generated a response that also peaked twice, in approximately the same areas. But the 32 and 48 Hz responses contained only one of the two peaks, and in each case it was a different one! To sum up, the responses were somewhat consistent, but not impressively so.

---

together. This resulted in Figure 3. In most cases like this on, the exclusion of the other 147 channels did not significantly change the figure.

Where in the brain do these signals originate? Figure 4 shows a contour plot of the power of the signal from each channel at 613 ms and 25 Hz, in other words, during the second peak of Figure 3.

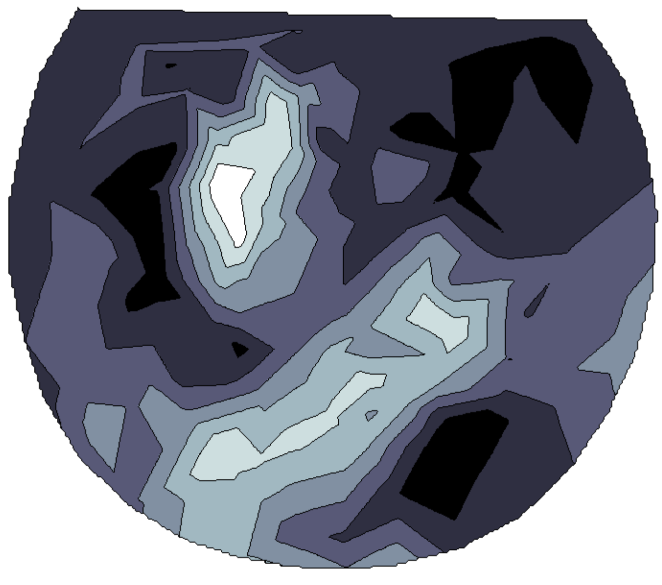

Figure 4 - A contour map of the MEG signals from each channel during the second peak of Figure 3, from the same reference point above the head as Figure 1. The nose points forward.

The strongest activity is found slightly to the left of the midline and slightly anterior. In almost every peak, in almost every response, this same area was the source of the strongest activity. Empirically it seems that this part of the brain plays a large role in interpreting AM tones. The other active areas were quite often also active in other responses, but usually less so than the first region.

The offset region, that is, the 400 ms after the offset of the stimulus, was also examined in exactly the same manner as the onset region. However, no consistent patterns were found in these data.

Part 2: The Steady State Response

Figure 5 shows the SSR for each stimulus. These figures were prepared by averaging together the responses from the ten channels that were most active at the modulation frequency, and the result is very encouraging. It is clear that the activity is very strong around the modulation frequency, and relatively weak at other frequencies. This result has been demonstrated previously with frequency analysis (Ahmar 2004), but the advantage of wavelet analysis is that it is possible to see the evolution of the SSR in time (at the cost of some frequency resolution).

The 48 Hz response appears to be the strongest signal, and it seems that the SSR in that case lasts from approximately 50 ms after onset until 50 ms after offset. This verifies earlier results.[7]

[7] Variation in strength between the different SSR is highly dependent on the noise background (Ahmar 2004). In general it is expected that the noise background decrease rapidly with increasing frequency, and therefore the SSR at 64 Hz should be the most clear. Unfortunately the noise reduction algorithm has to apply a notch filter at 60 Hz to remove power line noise, and the effect of this bleeds into the 64 Hz response. Similarly, noise sources near 16 and 32 Hz weaken the SSR at those frequencies.

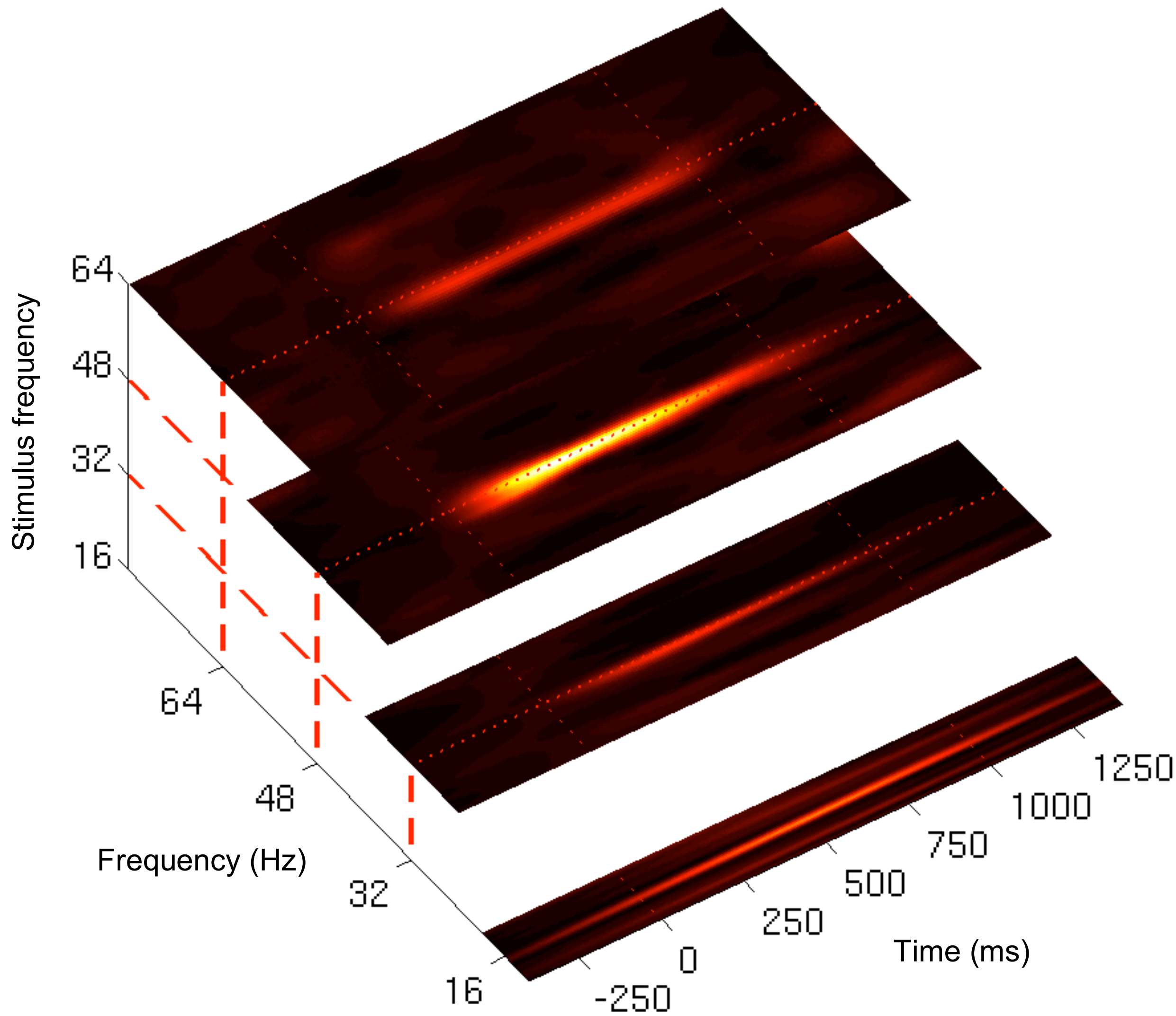

Figure 5 - An overlay of the SSR to each of the four stimuli. The vertical axis is the frequency of modulation and each level contains a wavelet transform of the SSR for that stimulus. The thick dashed lines emphasize the relative locations of the transforms. The thin vertical dotted line on top of each transform show the locations of 0 ms (onset) and 1000 ms (offset). The thin horizontal dashed lines show that the activity is centered close to the frequency of modulation for each stimulus.

It appears that the 16 Hz SSR lasts much longer than the other responses; in fact, it appears to begin long before onset of the stimulus! In all likelihood, this is due to a phenomenon of wavelet transforms: at lower frequencies, resolution in the time domain is low. Thus the 16 Hz SSR is much longer, but also much narrower in frequency than the other SSR.

Figure 6 shows a contour plot of the strength of the SSR at each channel. These were calculated by averaging the power at the modulation frequency for each channel over the entire epoch of 1.8 seconds.

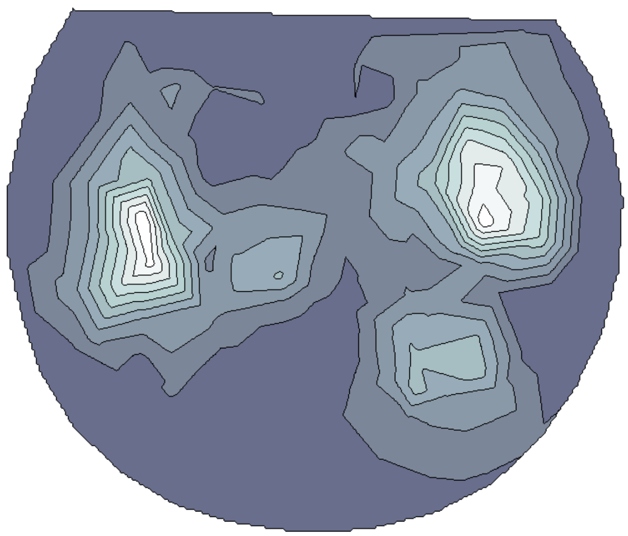

Figure 6 - A contour plot of the SSR strength at each channel, in the same orientation as Figure 1. The stimulus is the 48 Hz modulated tone.

Only a contour plot for the 48 Hz response is shown, because the 48 Hz response was the strongest. Plots for the other stimuli are very similar: each has the same three main areas of activity, although the relative strength of these areas varies greatly from stimulus to stimulus.[8]

[8] As discussed earlier, in Figure 5 the transforms were baselined to reduce the importance of noise. However, a side effect of this baselining is that the relative strength of each channel is affected greatly by the noise background of that channel, which is random. Therefore the contour plot was prepared based on the pre-baselined (thus, noisy) data. This is probably why there is so much variation between stimuli.

This kind of contour is similar to the results obtained with frequency analysis in previous research. The two anterior areas are presumed to be originating from the auditory cortices in the brain, where low-level processing of tones takes place.

Discussion.

For all of the data considered in this paper, the presence of noise was a large and sometimes overwhelming factor. Even in the case of perfect shielding from external sources, the researcher must still contend with MEG data that is contaminated by the ubiquitous non-auditory signals from the brain. Attempts to convince the subject to limit such distractions were not well received.

In the transient response, a possible induced response consisting of two peaks around 26 Hz was found; however, variation between stimuli was large. Why would this be? The first possibility is that this induced response is present, but obscured by noise. In this case, better algorithms for identifying artifacts in trials should be applied to the data to make the induced response more clear.

The second possibility is that no higher-order processing is necessary when the brain interprets AM tones, in which case there should be no reason to expect an induced response. Without further investigation, the results presented here are not sufficient to prove either of these possibilities; but hopefully they will be helpful in guiding the focus of future researchers.

The steady state response demonstrated a very clear pattern of activity, tightly banded around the modulation frequency and lasting from 50 ms postonset until 50 ms post-offset (approximately). This response was strongest in the channels near the auditory cortices in the brain.

Conclusions.

Wavelet analysis has proved to be very useful in interpreting data from MEG experiments, but it is limited by the experimenter's ability to identify and eliminate noise from the data.

Further research should focus on computing the ionic currents in the brain that are producing both the transient and steady-state responses. This will require new dipole fitting software that has recently been developed in this lab. The investigation should shed light on the link between external auditory stimuli and the actual neurochemical mechanics behind the brain's interpretation of sounds.

Many thanks to Dr. Yadong Wang for his help with processing, Nayef Ahmar and Juanjuan Xiang for their advice and suggestions, and Jeff Walker for generating the original MEG data.