

NEUROPHYSIOLOGICAL CORRELATES OF METER PERCEPTION: EVOKED AND INDUCED GAMMA-BAND (20-60 HZ) ACTIVITY

Joel S. Snyder¹ & Edward W. Large²

¹*Department of Psychology, Cornell University*

²*Center for Complex Systems and Brain Sciences, Florida Atlantic University*

ABSTRACT

Meter plays an important role in coordinating action and perception among musical participants by generating precise temporal expectancies for sound events. We used electro-encephalography to understand the manifestations of auditory rhythmic anticipation in brain activity on a millisecond time-scale. Subjects listened to simple monotonic patterns based on a western duple meter, defined by alternating intensity accents, with occasional missing tones at the strong and weak beats within the metrical cycle. In addition subjects listened to a metronome pattern and a duple alternating accent pattern with no missing tones. Gamma-band oscillations (20-60 Hz) began prior to both missing and presented tones. Induced (non-phase-locked) activity was constantly present and increased prior to the onset of expected tones. Presentation of a tone resulted in the immediate activation of evoked (phase-locked) activity, suggesting phase resetting of gamma-band oscillations by tone onsets. The amplitude of gamma-band activity was larger for intensity-accented tones. We propose these phenomena as correlates of metrical processing, possibly revealing a direct representation of temporal expectancy in cortical activity. This approach to meter perception may prove particularly useful for studying populations without explicit musical knowledge or without sufficient motor capabilities to perform behavioral experiments.

1. INTRODUCTION

A fundamental aspect of music cognition is the perception of periodic structure, in particular pulse and meter. *Pulse* is the perception of equally spaced salient points in time that arise from a more or less periodic stimulus, such as performed music. Pulse typically has a period around 200-1000 ms, with a bias toward intermediate values in this range [5]. *Meter*, on the other hand, is the perception of multiple pulse trains that have simple period relations to each other [3,9,10]. Both pulse and meter play important roles in the human ability to listen to, perform, and dance with music. For example, the duple meter of a tango enables listeners, performers, and dancers to coordinate their perception and movement, thus creating a display of orderly, yet flexible rhythmic behavior.

A basic anticipatory mechanism must underlie the perception of metrical structure [8], as well as synchronization with music of considerable complexity [4,14], and simple forms of sensory-motor synchronization [11]. Without this anticipatory mechanism, a behavior as seemingly simple as synchronizing taps with a metronome, or tapping to a tango, would be reduced to reactionary taps following each tone. Clearly, such behavior would seem abnormal in the context of a music concert or a public dance.

Neurophysiological correlates of anticipatory behavior have appeared in two main forms, measured using electro-encephalography (EEG). The first is a response to the omission of an expected stimulus. So-called *emitted* potentials arise when a stimulus is omitted from an otherwise isochronous series of events. Emitted potentials are similar in form and topography to standard evoked potentials occurring 50-400 ms post-stimulus but they sometimes exhibit slightly later peaks. This phenomenon indicates that the nervous system can respond to the violation of temporal expectancies. Numerous experiments have shown that emitted potentials appear across different species, stimulus modalities, and sensory processing levels, thereby reflecting a basic aspect of sensory circuits [13]. Second, experiments have demonstrated a class of slowly evolving electrical potentials prior to expected sensory stimulation or planned movement [2].

Both emitted potentials and slow anticipatory potentials provide evidence of temporal expectancy in brain activity. However, neither appears to correlate directly with anticipation at a time scale relevant for pulse or meter. Emitted potentials, which operate on the relevant time scale, are post-stimulus events that reflect the violation of temporal expectancies, not expectancies themselves. Slow anticipatory potentials, which appear to correlate directly with temporal expectation, occur on a time-scale longer than that of pulse and meter. Thus, neurophysiological methods have not yet revealed brain activity that reflects precise, real-time expectancies for events unfolding on the time scale of musical pulse and meter.

The current investigation examined brain processes that occur at the onset of an auditory event and recover quickly enough to respond to a stream of events occurring at rates typical of musical rhythm. In particular, we measured human EEG activity in the gamma-band (20-60 Hz) that is known to occur immediately (20-100 ms) after auditory stimulation in the form of oscillatory bursts, and is localized in auditory cortex [12]. These oscillations may play an important role by serving as a means by which spatially distant brain regions communicate with each other to perform integrative processing [1,7] and by limiting the temporal resolution of the auditory system in responding to successive stimuli [6]. Early gamma-band responses to sounds, in particular, may indicate transient phase resetting of ongoing oscillations. Such *phase resetting* within auditory cortex could play a crucial role in the propagation of signals by delivering short-latency synchronous input to other brain regions for further processing.

We sought to determine whether gamma-band activity (GBA) exhibited anticipatory properties when processing tones embed-

ded in metrical patterns. We examined both evoked and induced oscillatory brain activity in 15–100 Hz bandpass filtered EEG data [15]. *Evoked* GBA refers to oscillatory energy in the gamma-band whose fine structure is phase-locked to stimulus onsets. To calculate evoked GBA one performs stimulus triggered averaging (similar to calculating an event-related potential); gamma-band responses will be preserved only if the fine time structure is time locked to the stimulus. Another possibility is that the phase of GBA is uncorrelated with stimulus onset times, but changes in the amplitude of GBA are time locked to stimulus onsets. Such stimulus-locked amplitude modulation is known as *induced* GBA. To calculate induced GBA, one recovers the amplitude of oscillatory GBA prior to stimulus triggered averaging, thus disregarding the fine time structure of the waveforms.

We hypothesized that induced and evoked GBA elicited by rhythmic auditory stimulation may reveal a specific set of neural processes underlying meter perception. One possibility is that induced GBA will build prior to a predicted tone and that the onset will reset the oscillatory phase, resulting in the appearance of evoked GBA. In this scenario, only induced GBA should appear around missing expected tones. An alternative possibility is that anticipatory processes will begin resetting the phase of GBA prior to stimulation, resulting in evoked GBA that precedes tone onset. This also predicts that evoked GBA should also be present when expected tones are omitted. Finally, we hypothesized that intensity-accented tones in a metrical context would result in larger evoked GBA than non-accented tones. To test these hypotheses, we stimulated subjects with four pure-tone patterns while recording EEG activity: 1) an isochronous series of undifferentiated tones, 2) an isochronous series of alternating loud and soft tones, 3) an isochronous series of alternating loud and soft tones with the *loud* tone occasionally missing, and 4) an isochronous series of alternating loud and soft tones with the *soft* tone occasionally missing.

2. METHOD

2.1. SUBJECTS

We obtained written consent from eight adults from the Florida Atlantic University community for participation in this experiment (M = 3, F = 5). Two of our subjects were professors of music at Florida Atlantic University, while the others ranged from amateur musicians to novices.

2.2. STIMULI & MATERIALS

We delivered auditory stimuli using a custom graphical interface program written using MAX 3.6.2, running on a Macintosh G3 Powerbook. MAX sent musical instrument digital interface (MIDI) signals to an Akai S2000 MIDI synthesizer that converted the MIDI signals into tones. A Harmon/Kardon multimedia speaker system consisting of two speakers approximately three feet behind the subject's head delivered tones at a comfortable listening level.

Auditory stimuli consisted of 262 Hz sine tones (i.e. middle C) with a 10 ms rise time and 40 ms steady-state duration (50 ms total duration). Subjects listened to rhythmic auditory patterns in

four different conditions. In all conditions, subjects listened to multiple trials with 60 tones in each trial. In the *metronome control* condition, subjects listened to 300 uniform tones (5 trials) presented at a constant rate of 390 ms inter-onset interval (IOI) and with a constant MIDI velocity (proportional to loudness) of 70. In the *accent control* condition, subjects listened to 300 cycles (10 trials) of an alternating loud-soft accent pattern presented at the same IOI as the metronome condition. In this condition, the loud tones had a MIDI velocity of 100 and the soft tones had a MIDI velocity of 70, resulting in a duple accent pattern. In the *omit-loud* condition, subjects listened to 1020 cycles (34 trials) of the loud-soft accent pattern with occasional missing loud tones. Similarly, in the *omit-soft* condition, subjects listened to 1020 cycles (34 trials) of the loud-soft accent pattern with occasional missing soft tones. In the omission conditions, approximately 30% of the cycles contained omitted tones with two constraints: 1) the first two cycles of a trial could not contain omissions, and 2) no more than two cycles in a row could contain omissions. These constraints assured that subjects had ample opportunity to establish and maintain the percept of duple meter, and yielded about 300 omitted tones in each of the two omission conditions.

We recorded electrical brain signals using 84 channels from an EEG cap (Electro-Cap International, Inc., Eaton, OH). A Micro-Amplifier amplified EEG signals before being digitized by a digital signal processor (Sam Technology, Inc., San Francisco, CA), sending the digitized signals to a Pentium III Dell Dimension XPS T450 computer running Manscan 4.1 which recorded the data at 256 Hz sample rate (1 sample period = 3.90625 ms). In addition, a custom-designed micro-controller device received MIDI events and triggered stimulus event marking on the computerized data record.

2.3. PROCEDURE

Each EEG recording session lasted 2-3 hours, including setup and recording. During recording, subjects sat in a comfortable chair and fixated on a cross in front of them. We instructed subjects to avoid eye and body movements, and eye-blinks during stimulation. Each subject served in each condition described above, and listened first to the metronome control pattern, then to the accent control pattern, and finally to the patterns in the omission conditions. The two omission conditions were each divided into two sets of 17 trials. These blocks of 17 trials were presented in a counter-balanced order, alternating the two omission conditions.

2.4. DATA ANALYSIS

The EEG data were analyzed using custom MATLAB programs (*MathWorks*, Natick, MA) running on a SunBlade 1000 Unix workstation. We first bandpass filtered each block of data with a 25-point finite impulse response filter (15–100 Hz passband), using a zero-phase algorithm. We then calculated a spectrogram for each EEG channel, using a 256 point fast Fourier transform applied to 32 point (125 ms) Hanning windowed data, with 30 point overlap. For detecting stimulus-locked responses, we averaged 780 ms sections of the spectrograms (each containing responses to two tone onsets) with intervals beginning 195 ms before the onset of first the tone and ending 195 ms after the

onset of the second tone. This enabled us to examine brain activity before and after each tone in the extracted interval.

To separately calculate evoked and induced oscillatory activity, we varied the order of the two final processing steps. *Evoked* activity contains fine oscillatory structure that is time-locked to the stimulus. Thus, to find evoked activity, we calculated a stimulus-triggered average of the time-varying complex spectra — preserving phase information — before calculating GBA power. This averaging procedure eliminated activity that was not phase-locked to tone onsets. *Induced* GBA, on the other hand, does not necessarily maintain a consistent phase relation to the stimulus. Therefore, for induced activity we calculated GBA power — eliminating phase information — before stimulus-triggered averaging. In this procedure all gamma-band activity was preserved, thus averaging uncovered amplitude modulations of GBA that were time-locked to stimulus onset, whether phase-locked or not.

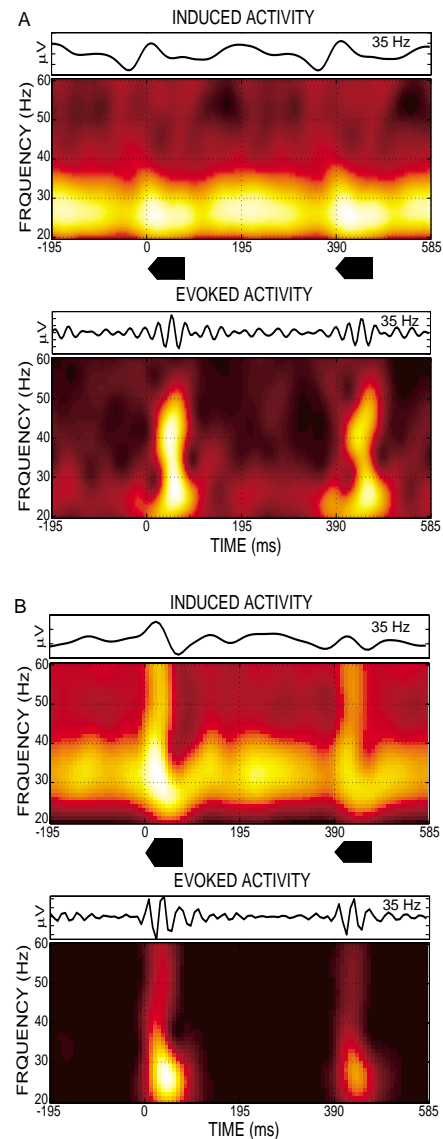
3. RESULTS AND DISCUSSION

Figure 1 shows spectrograms of GBA from individual subjects, averaged across EEG channels, for the average 780 ms interval in the metronome control condition (Figure 1A), the accent control condition (Figure 1B), and the omit-loud condition (Figure 1C). In addition, above each spectrogram is the time trace of the GBA amplitude taken from the spectrogram at a single frequency. The top of Figure 1A reveals induced GBA in the metronome condition that was present continuously in the 20-30 Hz range with amplification building before tone onsets, a consistent finding across subjects and conditions. In contrast, the bottom of Figure 1A indicates that evoked GBA showed little activation until tone onset, with peak power around 20 ms post-stimulus. This power was present in a relatively wide 25-50 Hz band. Subjects were consistent in showing transient evoked GBA, although the bandwidth of this power varied considerably from 10 Hz to as large as 25 Hz. Consistent with the phase resetting hypothesis, the induced GBA showed relatively constant amplitude with small increases before the tone, while evoked GBA showed transient power in a narrow time window after the tone.

For the accent control condition, Figure 1B again shows anticipatory activity in induced GBA and onset-triggered activity in evoked GBA across a wide frequency band. In addition, amplitude of the evoked and induced GBA was larger for loud versus soft tones, raising further questions. First, it is currently unclear how the GBA varies according to basic acoustic properties relevant to music such as pitch change, intensity, and inter-onset interval. Second, it is important to determine more generally whether GBA amplitude correlates with perceived accent arising from a wide range of features such as variations in melody, intensity, timing, and spectrum. Third, it is unclear whether the GBA is simply dependent on intensity or whether it requires the predictable alternation of loud and soft tones as in the current study.

In the omit-loud condition, Figure 1C shows an anticipatory building of induced GBA before the missing loud tone, and evoked GBA following the missing tone, again supporting the possibility that induced GBA reflects anticipation for tones in

metrical patterns. It is currently unclear how to interpret the finding of evoked GBA following a missing tone, although it is possible that this reflects an emitted oscillatory response. Further support for neural anticipation in GBA may come from a more thorough examination of tempo dependence in induced GBA. Particularly, as synchronization becomes more difficult for very fast and slow tempos, induced GBA should exhibit less anticipation [11]. Similarly, as the inter-onset interval becomes more variable, and hence less predictable, induced GBA should exhibit less anticipation. Assuming such experimental and behavioral support, future studies may extend the anticipatory nature of induced GBA to temporal expectancy in more complex signals such as performed music.



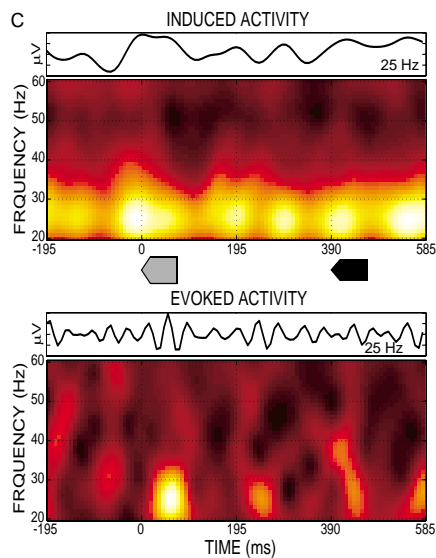


Figure 1. Spectrograms of channel-averaged induced (top) and evoked (bottom) gamma-band activity (GBA). Above the spectrograms for each type of activity is an amplitude trace of the GBA taken from the spectrogram at a single frequency. The presence of tones are indicated by black shapes representing the amplitude envelope, and the missing tone is represented by a shaded amplitude envelope. (A) Metronome control condition from subject 2 with identical tones presented at 0 and 390 ms. (B) Accent control condition from subject 4 with a loud tone presented at 0 ms and a soft tone presented at 390 ms. (C) Omit-loud condition from subject 3 with a missing loud tone at 0 ms and a soft tone presented at 390 ms.

4. SUMMARY AND CONCLUSIONS

Using EEG, we demonstrated the existence of high frequency oscillatory brain activity in the gamma-band (20-60 Hz) that increased before expected tones, and was transiently phase-reset immediately after tone onsets embedded in metrical patterns. The increase in non-phase locked activity suggested a role for anticipation in activating oscillatory brain activity preceding expected tones. In addition, the amplitude of the brain activity showed a dependence on intensity for predictably alternating loud and soft tones. We propose these phenomena as possible correlates to temporal expectancy on the time-scale of human sensory-motor anticipation in general [11] and of musical pulse, meter, and accent in particular [3,4,5,9,10,14]. Further experimentation using neurophysiological and behavioral techniques will clarify the nature of the correspondences we propose. In addition, these methods may serve a particularly useful role in allowing the detailed study of metrical processing in populations, such as children and non-musicians, from whom it can be difficult to obtain behavioral data using complex stimuli or difficult tasks.

5. ACKNOWLEDGMENT

This research was supported by NSF grant BCS-0094229, awarded to EWL.

6. REFERENCES

1. Bhattacharya, J., Petsche, H., & Pereda, E. (2001). Long-range synchrony in the γ band: Role in music perception. *J. Neurosci.*, *21*, 6329-6337.
2. Brunia, C. H. M. (1999). Neural aspects of anticipatory behavior. *Acta Psychol.*, *101*, 213-242.
3. Cooper, G., & Meyer, L. B. (1960). *The rhythmic structure of music*. Chicago: University of Chicago Press.
4. Drake, C., Penel, A., & Bigand, E. (2000). Tapping in time with mechanically and expressively performed music. *Music Percept.*, *18*, 1-23.
5. Fraisse, P. (1982). Rhythm and tempo. In Deutsch, D. (Ed.), *Psychology of music* (pp. 149-180). New York: Academic Press.
6. Joliot, M., Ribary, U., & Llinás, R. (1994). Human oscillatory brain activity near 40 Hz coexists with cognitive temporal binding. *Proc. Natl. Acad. Sci. USA*, *91*, 11748-11751.
7. Knief, A., Schulte, M., Bertrand, O., & Pantev, C. (2000). The perception of coherent and non-coherent auditory objects: A signature in gamma frequency band. *Hear. Res.*, *145*, 161-168.
8. Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychol. Rev.*, *106*, 119-159.
9. Large, E. W., & Kolen, J. F. (1994). Resonance and the perception of musical meter. *Connect. Sci.*, *6*, 177-208.
10. Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.
11. Mates, J., Radil, T., Müller, U., & Pöppel, E. (1994). Temporal integration in sensorimotor synchronization. *J. Cognit. Neurosci.*, *6*, 332-340.
12. Pantev, C., Makeig, S., Hoke, M., Galambos, R., Hampson, S., & Gallen, C. (1991). Human auditory evoked gamma-band magnetic fields. *Proc. Natl. Acad. Sci. USA*, *88*, 8996-9000.
13. Prechtl, J. C., & Bullock, T. H. (1994). Event-related potentials to omitted visual stimuli in a reptile. *EEG Clin. Neurophysiol.*, *91*, 54-66.
14. Snyder, J., & Krumhansl, C. L. (2001). Tapping to ragtime: Cues to pulse finding. *Music Percept.*, *18*, 455-489.
15. Tallon-Baudry, C., & Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends Cognit. Sci.*, *3*, 151-162.