Effects of Single Cycle Binaural Beat Duration on Auditory Evoked Potentials

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Abstract—**Binaural beat (BB) illusions are experienced as continuous central pulsations when two sounds with slightly different frequencies are delivered to each ear. It has been shown that steady-state auditory evoked potentials (AEPs) to BBs can be captured and investigated. The authors recently developed a new method of evoking transient AEPs to binaural beats using frequency modulated stimuli. This methodology was able to create single BBs in predetermined intervals with varying carrier frequencies. This study examines the effects of the BB duration and the frequency modulating component of the stimulus on the binaural beats and their evoked potentials. Normal hearing subjects were tested with a set of four durations (25, 50, 100, and 200ms) with two stimulation configurations, binaural dichotic (binaural beats) and diotic (frequency modulation). The results obtained from the study showed that out of the given durations, the 100ms beat, was capable of evoking the largest amplitude responses. The frequency modulation effect showed a decrease in peak amplitudes with increasing beat duration until their complete disappearance at 200ms. Even though, at 200ms, the frequency modulation effects were not present, the binaural beats were still perceived and captured as evoked potentials.**

I. Introduction

Central auditory binaural beats (BB) occur as a response to dichotic stimuli with slightly different frequencies are presented to each ear, e.g. 399Hz, to one ear and 401Hz to the other. The acoustic sum of the two tones will result in a 400Hz tone with a sinusoidal amplitude modulation (AM) of 2Hz. However, when these two tones (2T method) are presented to each ear seperately, even though each ear hears continuus tones, the continuous beating effect is still present indicating that there is a central interaction between the two ears. BB typically occurs if the frequency (carrier) of the left and right stimulus is no larger than 1500Hz and the difference of the two is less than 50Hz [1, 2].

In a previous study [3], the authors introduced a new method of creating BB using frequency modulating (FM) stimuli. Instead of using two continuous sinusoids with slightly different frequencies to create the continuous beats, the new three tone (3T) method used two stimuli with the same base frequency (f_b) which was modulated at a specific time to one above ($f_b+\Delta f$) and the other below ($f_b-\Delta f$) resulting in a frequency difference between the two ears which in turn generated a single cycle BB.

In the previous study [3], the effects of the base frequency with constant duration FM modulation on the BB and its auditory evoked potentials (AEPs) were investigated. Seven base frequencies were tested between 250 and 2000Hz modulated at constant duration (20.8ms) and presented at 1 s. The results showed that 400Hz dichotic stimuli evoked beat AEPs with the largest amplitudes. Stimuli with FM have been shown to evoke AEP when presented monoaurally [4]. For this reason the BB AEP obtained previously were a combination of BB and FM responses.

The goal of this new study was to further investigate the effects of the new stimuli and find a combination of parameters that will reduce the effects of the FM while preserving the BB. So, the next logical step was to fix the carrier frequency and vary the duration of the beat. However, due to the stimulus design process, the duration of the beat is inversely proportional to the FM frequency, meaning that doubling the duration of the beat will halve the FM frequency. Two stimulation configurations were tested for each beat duration. The first was dichotic configuration where the stimuli to each ear were modulated above and below the carrier frequency and was labeled as BB. The second was diotic stimulation where the stimuli in both ears were modulated below the carrier frequency, thus, generating binaural FM responses only.

II. Methods

The study was performed according to the Institutional Review Board of the University of Miami policies and regulations. Five young volunteers participated in the study, with ages from 22 to 29, all males and right handed. All participants were tested with pure-tone audiometry to confirm normal hearing (thresholds ≤25 dB HL).

The stimulus $\boldsymbol{y}$ was digitally generated using basic frequency modulation, where $\boldsymbol{n}$ is the sample number, f_b is the base frequency, Δf is the modulation frequency, f_s is the sampling frequency of the stimulus, and $\boldsymbol{E}$ is the modulation envelope. The modulation envelope controlled the occurrence and duration of the beat. Two stimuli, $y_1(n)$ and $y_2(n)$, were generated for each ear using +1 and -1 for above and below f_b modulation, respectively (1).

$$y(n) = sin\left(\left(\frac{2\pi}{f_s}\right)\left[f_b n + \Delta f \sum_{\tau=0}^{n} E(\tau)\right]\right) \qquad (1)$$

The envelope $\mathbf{E(\tau)}$ is an array consisting of multiplier values for the modulation frequency. A rectangular envelope was used, where the non-modulating portion was filled with

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TABLE I
STIMULUS PROPERTIES AND FREQUENCY CHARACTERISTICS

Beat duration (ms)	25	50	100	200
Frequency shift Δf (Hz)	20	10	5	2.5
Base frequency shift f_b (%)	5	2.5	1.25	0.625
Beat frequency (Hz)	40	20	10	5

zeroes and the modulating portion was filled with ones. The stimulus parameters were carefully calculated and optimized to account for the starting and ending phases of the beat and the stimulus itself. Additionally, the modulation frequency was adjusted according to the duration of the beat as seen in Table I.

The stimuli $\boldsymbol{y_1}$ and $\boldsymbol{y_2}$ began with a phase difference of 180° between the two. Throughout the duration of the beat one of the stimuli oscillated faster than the other and at the midpoint of the beat the two stimuli caught up with each other and the phase difference between them became 0°. As the beat progressed, they shift out of phase until they reached 180° at the end of the beat (Figure 1).

Separate stimuli were generated for each ear and beat duration, as specified in Table I. All stimuli had a base frequency of 400Hz and an onset interval of 1 second to generate 1 beat per second. The stimulus polarity for each ear was alternated between sweeps in order to reduce any electromagnetic interference from the transducers and recording of the frequency following responses (FFRs). For this reason both of the stimuli ended on the falling edge of the zero crossings or 180° relative to the beginning of the stimulus. The right stimulus had positive polarity while the left had negative.

The AEP recordings and audiometry were performed using the Intelligent Hearing Systems (IHS) Universal Smart Box with continuous acquisition software. The stimuli were presented continuously without any gaps using the ER-3A insert earphones (Etymotic Research). The subjects were recorded in a double walled, sound attenuated booth shielded from electromagnetic (EM) noise and isolated from ambient sounds. In order to reduce noise from muscle activity the subjects laid down on a bed comfortably with their head

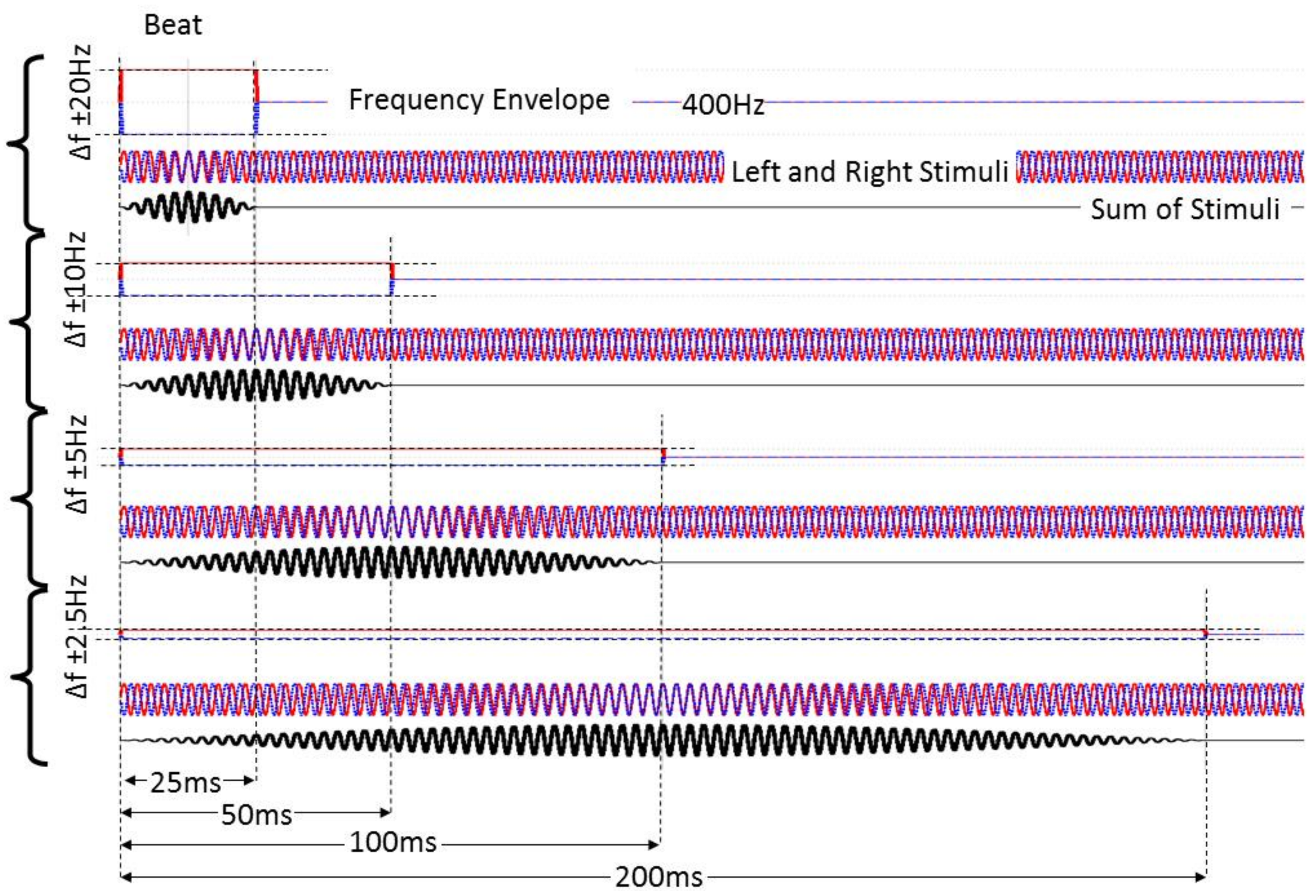

Figure 1.– Visualization of the stimuli, $\boldsymbol{y_1}$ (red, right ear) and $\boldsymbol{y_2}$ (blue, left ear), used in the study and their parameters, with the beat portion enlarged. The four beat durations 25, 50, 100, and 200ms used in the study are presented in four rows (top to bottom). Each of the four rows shows the stimulus frequency envelope with the frequency. The left and right sinusoidal stimuli superimposed showing the phase differences and interference. The sum of the left and right stimuli showing the mathematical sum and interaction of the two is shown in black.

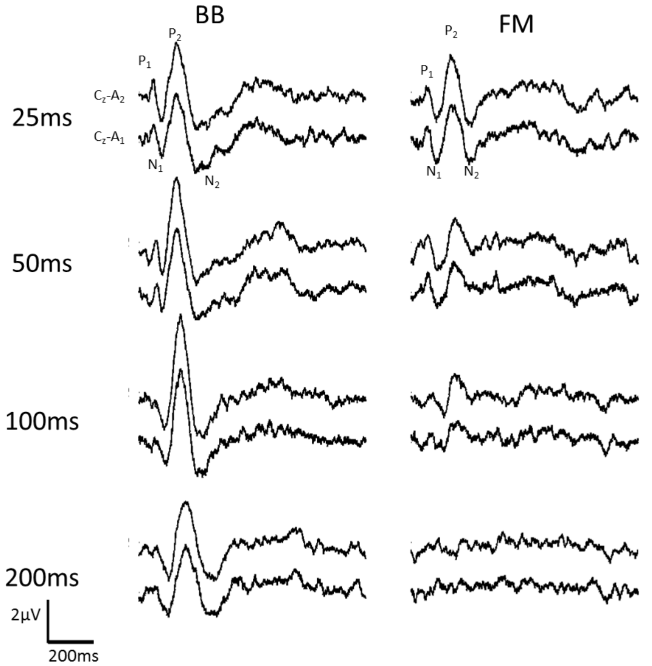

Figure 2. Population average (n=5) of BB (left) and FM (right) AEPs for each beat duration. Upper trace is C_z-A_2 and lower is C_z-A_1. The AEP show relatively constant BB waveform morphology, with a slight latency shift to the right for P_2 and variations in amplitude. The FM shows a significant decrease in amplitude with increasing beat duration and the absence of responses at 200ms.

relaxed on a pillow. The subjects stayed awake and quietly watched a subtitled movie during the duration of the experiment.

The electroencephalography (EEG) was acquired at 5000 samples per second, with a bandwidth filter between 1 and 1500Hz and a gain of 100,000. A two channel electrode configuration was used with channel one and two having montages C_z-A_2 and C_z-A_1, respectively. The AEPs were recorded as a continuous EEG recording in epochs determined by the interval between stimulus onsets. Minimum of 512 epochs of EEG were recorded for each condition. In order to extract the AEPs from the ongoing EEG caused by regular brain activity, even and odd numbered epochs were averaged into separate buffers. Epochs with amplitudes above or below 45µV were rejected and excluded from the average. The two buffers were averaged together to obtain a cleaner overall signal with 512 averages and subtracted from each other to obtain the overall noise. When superimposed, the overlapping waveforms of the two buffers were used as an indicator of the quality of the recording and the identified components.

III. Results

The amplitudes and latencies of the peaks (P_1, N_1, P_2, N_2) were identified, measured and tabulated by two judges. In the dichotic BB recordings all subjects generated large amplitude responses with clearly observable peaks and all of the above mentioned peaks were identified in all subjects. In the diotic FM configuration, however, responses were generally of smaller amplitude and more variable. Some subjects did not

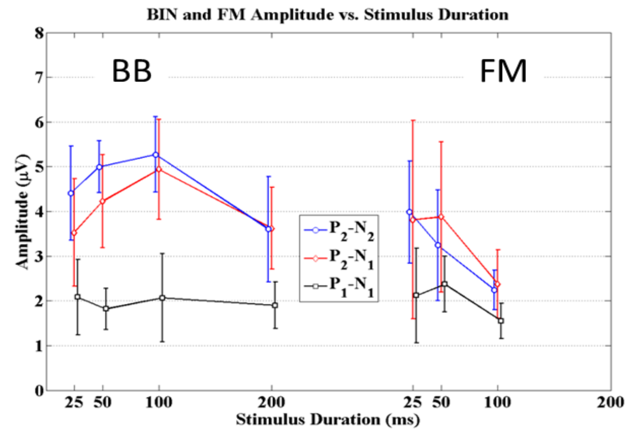

Figure 3. Amplitude measurements and standard deviations, binaural (left stack) and FM (right stack) without measurements for 200ms due to the absence of AEPs.

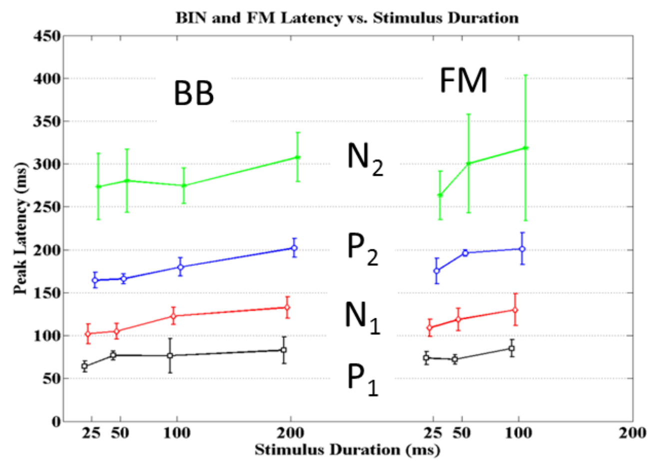

Figure 4. Peak latency measurements with standard deviations, binaural (left stack) and FM (right stack) without measurements for 200ms due to the absence of AEPs.

present observable peaks. For 25 and 100ms beat durations, the peaks are observable in 4 subjects (80%). For 50ms duration, peaks were observable in 3 subjects. For 200ms duration none of the subjects presented any observable peaks showing lack of FM responses.

The population averages of five subjects for all beat durations and recording configurations are plotted to visualize the AEPs from the study (Figure 2). From the figure it can be seen that the responses from the dichotic BB configuration have a relatively similar morphology (P_1, N_1, P_2, N_2) across all different beat durations. Waveform morphology and the identifiable peaks especially P_1 and N_2, however, change with duration and type of recording. Variations in amplitude and latency of the identified peaks can be observed across the different durations as well as BB and FM recording types. In the dichotic BB response, however, the quad-phasic morphology is preserved without much change while in diotic FM configuration, the whole response diminishes and disappears as duration increases. Overall in the population averaged responses, the four peak response morphology is observable only in the 25ms duration. N_2 peak disappears in the 50ms beat duration. For the 100ms beat duration N_1 and P_2 are very small and all peaks disappear at 200ms duration. The FM configuration shows a consistent decrease in all amplitudes for all peaks with increasing beat duration until no longer visible at 200ms.

The differential amplitudes P_1-N_1, P_2-N_1, and P_2-N_2 were calculated between consecutive peaks instead of absolute measurements to reduce the slow wave variation effects. Since there is little difference between C_z-A_2 and C_z-A_1 recordings, these two measurements were averaged together (Figure **3**). The amplitude of P_1-N_1 of the dichotic BB response is not affected by the beat duration and remain relatively consistent around 2μV. However, the amplitudes of P_2-N_1 and P_2-N_2 show changes with beat duration. Both increase steadily between 25 and 100ms beat duration, then peak at 100ms, and then decrease from 100 to 200ms. Unlike the dichotic BB, the diotic FM peaks exhibit maxima at 50ms beat duration for P_1-N_1 and P_2-N_1. While the amplitude of P_2-N_2 shows a steady decrease with increasing beat duration.

The latencies of the four peaks were measured and plotted in Figure 4. For both dichotic BB and diotic FM they show a slight increase in peak latency as the beat duration increases. In the BB configuration P_1 increases from 25 to 50ms and remains relatively constant for the rest of the durations.

IV. Discussion

The goal of the study was to investigate the behavior of the responses to changes in the beat duration or frequency modulation and to see if it is possible to evoke binaural beat (BB) responses without evoking FM responses. The results showed that the beat duration has a significant effect on the evoked responses both in the BB and the FM configuration. The study showed that it is possible to evoke transient binaural beat responses with a frequency modulating stimulus which are not contaminated by the frequency modulation itself. This was accomplished by increasing the duration, or lowering the modulation from the carrier frequency. In this case the modulation was not large enough to evoke large enough responses [4], but the dichotic configuration was still able to evoke transient binaural beat responses.

Most of the binaural beats research has been done using two pure tone stimuli which result in steady state responses which are typically small from low beating frequencies ~3Hz [5]. The result of this study showed that the FM stimulation method is capable of evoking transient BB responses at low frequencies ~2.5Hz with significantly large amplitudes, which can be captured using AEP methods.

Generation of BB transient AEP responses without FM response contamination demonstrated in this study can be very useful in basic electrophysiological research as well as clinical applications. The relationship between these transient responses and the steady state BB responses demonstrated in previous studies [1, 2, 5] can now be investigated. Deconvolution and synthesis methods developed in our laboratory can be used for such purposes [6].

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