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Auditory Evoked Responses to Binaural Beat Illusion: Stimulus Generation and the Derivation of the Binaural Interaction Component (BIC)

Ozcan Ozdamar, *Member, IEEE,* Jorge Bohorquez, *Member, IEEE,* Todor Mihajloski, *Member, IEEE*
Erdem Yavuz and Magdalena Lachowska, *Member, IEEE*

Abstract— **Electrophysiological indices of auditory binaural beats illusions are studied using late latency evoked responses. Binaural beats are generated by continuous monaural FM tones with slightly different ascending and descending frequencies lasting about 25 ms presented at 1 sec intervals. Frequency changes are carefully adjusted to avoid any creation of abrupt waveform changes. Binaural Interaction Component (BIC) analysis is used to separate the neural responses due to binaural involvement. The results show that the transient auditory evoked responses can be obtained from the auditory illusion of binaural beats.**

I. INTRODUCTION

Pulsating signals are generated when two sinusoidal signals with slightly different frequencies are summated [1, 2]. The difference in frequencies determines the pulsation frequency If these signals are presented to the ears simultaneously, acoustic (peripheral) pulsating beats are heard at the pulsation frequency. This percept is heard only when the continuous tones are generated by sinusoidals with low frequencies (<1500Hz) and the difference frequency is less than about 50Hz. For higher differences two separate frequency tones are heard. When these two continuous tones are presented to the ears separately (dichotic stimulation) using insert earphones, a faint pulsation sound is heard in the head as an illusion even though there is no such physical sound. This auditory percept is called binaural (central) beats and generated by neural signals interacting in the neural centers of the brain.

Although signal and psychophysical properties of the monaural and binaural beats are well reported, their electrophysiological characteristics are less well known [1, 2]. This is especially true for binaural beats since very few studies on humans have been reported on their electrophysiological or evoked response characteristics. Due to their periodic nature, all recent studies concentrated on the steady-state response characteristics of the central beats [3, 4, 5, 6, 7]. Auditory steady-state responses are typically elicited by amplitude- or frequency-modulated periodic sounds and characterized by their magnitudes and phases. While they are very valuable for automatic processing for screening or threshold detection purposes, they do not give much physiologic insight to their neural generation. They are typically composite responses composed of overlapping transient responses elicited at high stimulus rates [8].

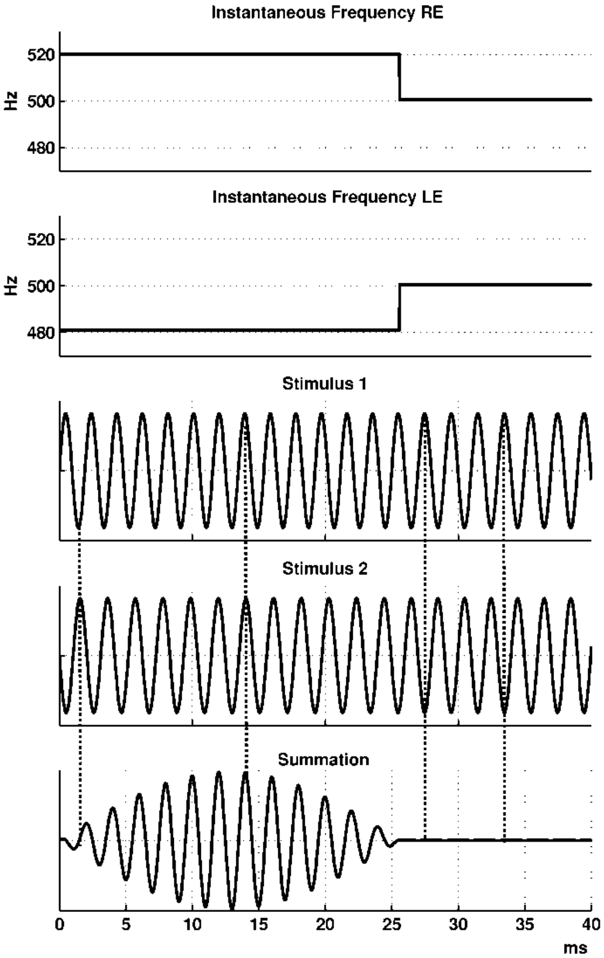

Fig. 1. Instantaneous frequencies of the continuous stimuli (Stim1 and Stim2) for a portion of the signals containing a tone pip (first and second rows). Corresponding signal waveforms are shown in the third and fourth rows. The last fifth row shows the tone pip generated by combining the two signals. The first two dotted vertical lines show the onset and the peak of the tone pip and indicate out-of-phase and in-phase waveforms. The third and fourth arbitrarily chosen dotted vertical lines indicate the out-of-phase character of the quiet period.

Ozcan Ozdamar, PhD, Professor and chairman is with the Department of Biomedical Engineering at the University of Miami in Coral Gables FL. 33214. USA He is also with Departments of Otolaryngology, Pediatrics and Neuroscience (graduate) at the Miller School of Medicine (secondary). (phone 305-284-2136; fax: 305-284-6494; e-mail: oozdamar@miami.edu).

Jorge Bohorquez is with the Department of Biomedical Engineering at the University of Miami in Coral Gables FL USA.

Todor Mihajloski is with the Department of Biomedical Engineering at the University of Miami in Coral Gables FL USA.

Erdem Yavuz is with the Intelligent Hearing Systems Miami, FL and with the Department of Biomedical Engineering at the University of Miami in Coral Gables FL USA.

Magdalena Lachowska is supported by Polish-American Fulbright Commission as Fulbright Senior Advanced Research Grantee with the Department of Biomedical Engineering, University of Miami, Coral Gables, FL, USA. Her home affiliation is the Department of Otolaryngology, Medical University of Warsaw, Warsaw, Poland.

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Auditory steady state responses (ASSR) are generally generated using periodic transient sound such as clicks or tone bursts or sinusoidally amplitude modulated (SAM) continuous tones [1, 8]. These stimulus paradigms, however, are not suitable for the generation of binaural beats since continuous tone stimulation of both ears is required for central pulsating sensation. This is accomplished by two-tone (TT) stimulation with each tone monaurally presented. TT mode generated responses provide similar ASSR characteristics as observed in SAM mode stimulation [1]. The purpose of this study is to design a stimulus paradigm capable of generating short duration tone pips heard as illusionary central beats, acquire evoked responses if generated and report on their characteristics and separate them from monaurally evoked responses. This is accomplished by modifying the two-tone stimulus paradigm so that summation of two stimuli produce short tone pips and rate can be controlled independently so that transient responses can be obtained.

II. METHODS

A. Stimuli

The stimuli (Fig.1) used in this study consisted of two continuous tones (Stim1 and Stim2) with the base frequency of 500Hz but with opposite phases, thus when combined they produced null signal. The frequency of the first stimulus (Stim1) was incremented 20 Hz with about 25 ms duration and the other stimulus (Stim2) was decremented 20 Hz at the same interval. The onset and offset of the increments/decrements were adjusted such that no extra impulse like sound is generated. The beats were presented at 1Hz. Both stimuli were generated digitally with 20 KHz sampling rate and stored in dual buffers with 20,000 samples. Stimuli were delivered using insert phones (ER-3A, Etymotic Research, Elk Grove Village, IL). Since monaural stimuli were actually rectangular frequency modulated (FM) sounds they were designated as such.

B. Recording

Two channel EEG (Side A: C_z–A_2 and Side B: C_z–A_1) as shown in Fig. 2 were recorded (Band-pass: 1-1500 Hz (6 dB/oct), Gain: 100,000) continuously with a 5 KHz sampling rate. They were stored in 5000 point buffers with no discontinuities. To eliminate frequency following responses (FFR), stimuli were presented in alternating mode in consecutive buffers with careful phase adjustment so that no abrupt stimulus waveform changes were produced. For testing purposes monaural beats were generated by electric and acoustic mixing of two signals without any apparent problems. Final averaging was done using 512 sweeps off-line with ± 30 μV rejection level. Smart-EP Continuous Acquisition Module (SEPCAM) (Intelligent Hearing Systems, Miami FL, USA) was used for all recordings.

C. Subjects

Recordings from five subjects were obtained. All subjects had normal hearing (PTA$\leq$ 25 dB HL: ages 19-34) and no neurological problems. Subjects were volunteers and all experiments were approved by the University Institutional Review Board.

D. Procedures

Three types of recordings were conducted using 55 dB HL tones: a) monaural right ear with Stim1; b) monaural left ear with Stim2; c) dichotic right and left ears with Stim1 and Stim2, respectively. Since 20 Hz increments/decrements produce small but recordable FM onset evoked responses, their respective channel sums were subtracted from the binaural response to obtain the true central evoked response. All subjects were tested in a sound-proof chamber lying down with a head pillow and watching a close-captioned movie with subtitles of their own choice.

E. Waveform Processing and Analysis

Acquired evoked responses were stored and waveforms were analyzed for late latency response peak identification. For the neural binaural involvement of central beats the conventional Binaural Interaction Component (BIC) analysis were conducted [9] as shown in Fig.2. Binaural response were subtracted from the summed monaural responses from the right and left ears for each side.

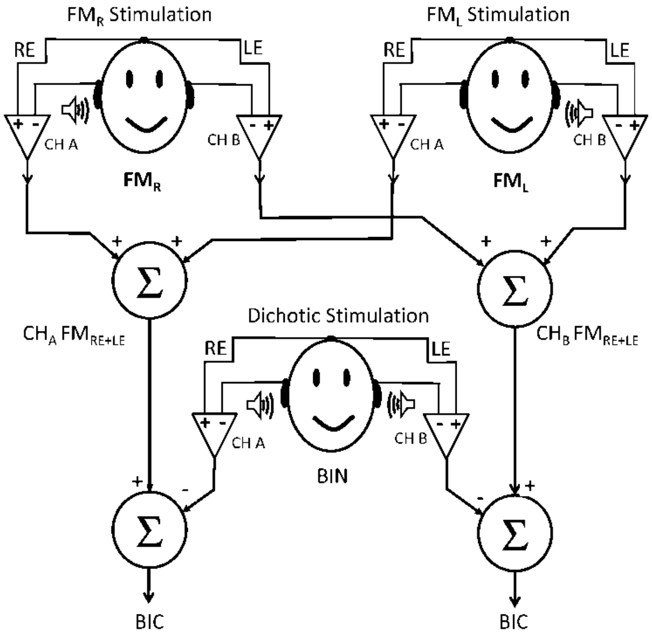

Fig. 2. Recording and signal processing paradigm used in this study. In the first row acquisition of the monaural responses from the right and left ears are shown, respectively. As indicated 2 recordings (ipsi and contra) are performed in each case. Channel A (right side) recordings are summated to obtained the computed response (Ch$_A$FM$_{RE+LE}$). The same procedure is also repeated for the left side, Channel B (Ch$_B$FM$_{RE+LE}$). Binaural responses are acquired by the simultaneous presentation of the stimuli as show in the bottom middle. BIC components from both sides are obtained by subtracting the binaural response from the computed response as shown.

III. RESULTS

In this study late latency averaged evoked response results corresponding to a window of 0-400ms are reported. Standard P_1, N_1 peaks were easily identified in most monaural FM responses (Fig. 3 and Fig. 4) [10]. P_2 and N_2 waves, however, was more variable as shown in Fig.3 and Fig.4. With binaural stimulation all subjects elicited robust responses with four peaks (P_1, N_1, P_2, N_2) as shown in Fig.3 and Fig.4. Prominent display of N_2 was clearly observed in all binaural recordings from both sides in all subjects.

P_1, N_1, P_2, N_2 latencies and P_1-N_1, P_2-N_1 and P_2-N_2 amplitudes were measured for each binaural recording. Grand averages of the acquired and computed responses from both sides and all subjects were displayed in Fig. 5. Triphasic responses (P_1, N_1, P_2) were easily identified in all acquired and computed monaural responses. The binaural response, however, showed all four positive and negative peaks (P_1, N_1, P_2, N_2). N_2 component was very large and prominent in the binaural response. Table I lists all the BIN latencies and amplitudes of all subjects and their averages.

BIC waveform was characterized by the tri-phasic (P-N-P) waveform. The first positivity (P_{80}) occurred at around 80ms latency with a small amplitude (about 0.5 μV). This was followed by a large negativity (N_{120}) with a latency around 120ms (about 2.0 μV amplitude). The second positivity (P_{220}) occurred at around 220 ms (about 2.0 μV amplitude). All latencies / amplitudes are listed in Table II.

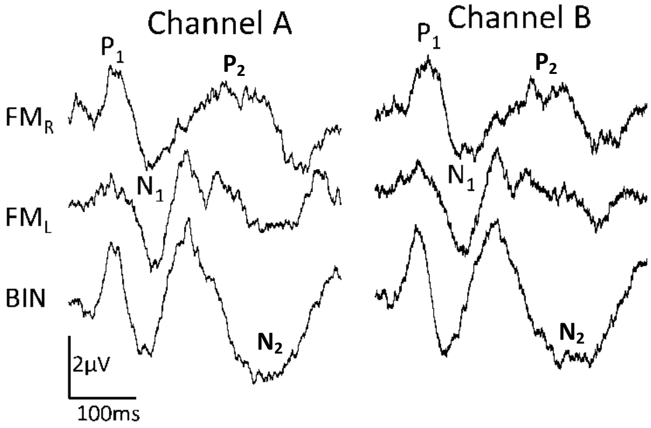

Fig. 3. Right, left and binaural responses from a subject with large amplitude components. As seen the binaural response displays a large N_2 component not seen in the monaural FM responses.

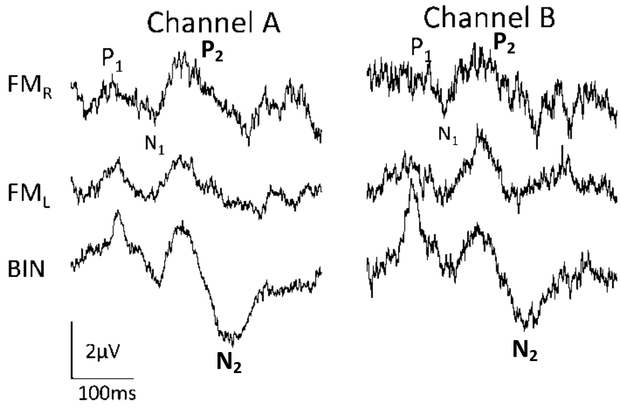

Fig. 4. Right, left and binaural responses from a subject with small amplitude components. In this subject a large binaural response is elicited.

IV. DISCUSSION AND CONCLUSION

In this study we designed two continuous auditory FM tones such that when combined they create tone pips. When these two stimuli were presented to separate ears dichotically, they generated the illusion of beats. These binaural beats were experienced by all subjects as pulsating sounds in the center of their heads. This study showed that electrophysiological indices in the form of late evoked potentials were generated by the use of specially designed two-tone dichotic sounds. These evoked responses clearly showed that the interaction of neural signals coming from separate ears can combine and create the central beat illusion in the absence of physical stimuli. Both N_{120} and P_{220} components can be associated with the generation of binaural beats. These late potentials can help elucidate the source and generation mechanism of this phenomenon. This new approach can also help us to identify and analyze the cognitive involvement of this illusion.

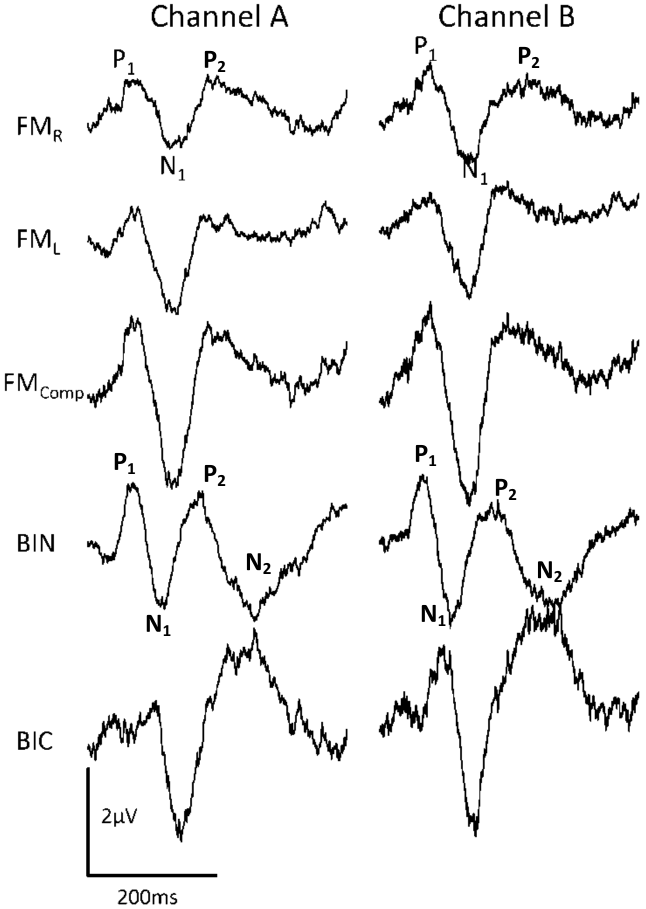

Fig. 5. Grand averages of responses from 5 subjects. Monaural averaged responses from the right and left ear stimulation are shown in the first two rows. Computed sum (FM_{comp}) of these averaged responses are shown in the third row. Averaged binaural responses (BIN) obtained by dichotic stimulation are shown in the fourth column. The last row displays the averaged binaural interaction component (BIC) as computed according to Fig.2. Channel A and B recordings are separately shown on the left and right columns, respectively.

TABLE I
BINAURAL RECORDINGS (BIN) LATENCY (ms) AND AMPLITUDE (μV)

Subject	P_1	N_1	P_2	N_2	P_1-N_1	P_2-N_1	P_2-N_2
S01	65	109	168	289	3.49	3.65	4.78
S02	64	92	121	249	0.60	1.22	5.06
S03	63	109	179	263	3.30	4.46	3.21
S04	74	110	174	248	1.17	0.87	4.16
S05	91	120	150	217	2.36	1.34	1.64
Avg	**72**	**108**	**158**	**253**	**2.18**	**2.31**	**3.77**
Std	**12**	**10**	**24**	**26**	**1.28**	**1.63**	**1.39**

TABLE II
BINAURAL INTERACTION (BIC) LATENCY (ms) AND AMPLITUDE (μV)

Subject	P_{80}	N_{120}	P_{220}	P_{80}-N_{120}	P_{220}-N_{120}
S01	88	138	240	3.85	6.46
S02	88	121	205	1.90	3.87
S03	96	147	225	5.23	4.88
S04	60	108	241	1.29	3.38
S05	77	96	184	1.56	2.78
Avg	**82**	**122**	**219**	**2.77**	**4.27**
Std	**14**	**21**	**24**	**1.70**	**1.44**

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