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Frequency characteristics of neuromagnetic auditory steady-state responses to sinusoidally amplitude-modulated sweep tones

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HIGHLIGHTS

- Frequency characteristics of neuromagnetic auditory steady-state response (ASSR) were captured for 0.1–12.5 kHz.
- Strength of the ASSR obtained at constant SPL was maximum at 0.5 kHz.
- Corresponding loudness model was plateaued between 0.5 and 4 kHz.

ABSTRACT

Objective: This study aimed to capture the neuronal frequency characteristics, as indexed by the auditory steady-state response (ASSR), relative to physical characteristics of constant sound pressure levels (SPLs). Relationship with perceptual characteristics (loudness model) was also examined.
Methods: Neuromagnetic 40-Hz ASSR was recorded in response to sinusoidally amplitude-modulated sweep tones with carrier frequency covering the frequency range of 0.1–12.5 kHz. Sound intensity was equalized at 50-, 60-, and 70-dB SPL with an accuracy of ±0.5-dB SPL at the phasic peak of the modulation frequency. Corresponding loudness characteristics were modeled by substituting the detected individual hearing thresholds into a standard formula (ISO226:2003(E)).
Results: The strength of the ASSR component was maximum at 0.5 kHz, and it decreased linearly on logarithmic scale toward lower and higher frequencies. Loudness model was plateaued between 0.5 and 4 kHz.
Conclusions: Frequency characteristics of the ASSR were not equivalent to those of SPL and loudness model. Factors other than physical and perceptual frequency characteristics may contribute to characterizing the ASSR.
Significance: The results contribute to the discussion of the most efficient signal summation for the generation of the ASSR at 0.5 kHz and efficient neuronal processing at higher frequencies, which require less energy to retain equal perception.

1. Introduction

Auditory steady-state response (ASSR) is an electrical component of neuronal activity encoding information of periodic modulations of a sound (Langner, 1992; Picton et al., 2003; Joris et al., 2004; Stapells et al., 2004). The ASSR component is specifically characterized by its sensitivity to carrier frequencies (f_c) (Galambos et al., 1981; Pantev et al., 1996; Ross et al., 2000, 2003; Wienbruch et al., 2006), providing a useful measure with respect to evaluating the perceptual hearing characteristics per f_c, particularly at threshold levels (Aoyagi et al., 1994, 1996, 1999; Lins et al., 1996; Perez-Abalo et al., 2001; Dimitrijevic et al., 2002; Herdman and Stapells, 2003; Picton et al., 2005; Vander Werff and Brown, 2005; Scherf et al., 2006; Ahn et al., 2007). However, the relationship between the frequency characteristics of the ASSR component and hearing characteristics at the

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supra-threshold levels remains unclear (Vander Werff and Brown, 2005; Ménard et al., 2008; Zenker Castro et al., 2008), despite its possible application, for instance, to adjust the hearing aids objectively and automatically.

The key technical issues concerned with the investigation of the frequency characteristics of the neuromagnetic ASSR component at the supra-threshold level involve the frequency width and frequency resolution to be tested and the accuracy in the calibration of the sound intensity at the output. In the neuromagnetic studies so far, the neuronal sensitivity has been investigated discretely for four or five f_c covering the frequency range between 0.25 and 4 kHz (Pantev et al., 1996; Ross et al., 2000, 2002, 2003) or at most up to 6561 Hz (Wienbruch et al., 2006). In fact, the perception of the lower and higher frequencies might not be critical for daily life. However, it is important for higher cognitive functions such as music appreciation and discrimination of individuals (Hayakawa and Itakura, 1994; Besacier et al., 2000). Further, the stimulus tones are typically delivered at 60 or 70 dB sensation level (SL) above the subjects' hearing thresholds, with an accuracy of ±4 dB sound pressure level (SPL) (Pantev et al., 1996) or ±10 dB SPL (Ross et al., 2000). Considering the fact that 10-dB amplification would result in a 1.5-fold augmentation of the equivalent current dipole (ECD) moment in a 60–70-dB SL range (Ross et al., 2000), it is considered critical to improve the accuracy of the sound intensity calibration method.

In the present study, we examined the frequency characteristics of the neuromagnetic ASSR at the supra-threshold level for a wider frequency range at a finer resolution. Sinusoidally amplitude-modulated (SAM) sweep tones with modulation frequency (f_m) of 40 Hz and a carrier frequency (f_c) exponentially ascending from 0.1 to 12.5 kHz were presented as stimulus tones, taking advantage of its sweeping characteristics to test the entire frequency range en bloc at the finest resolution. The sound intensity levels of the SAM sweep tones were thoroughly equalized at the f_m phasic peaks, in the range of 50–70-dB SPL with an accuracy of ±0.5-dB SPL by applying inverse filtering and real-ear measurement techniques. The magnetoencephalographic (MEG) signal was recorded in response to several kinds of SAM sweep tones that varied in the acoustic and/or presentation parameters. Responses to SAM non-sweeping tones with fixed f_c were also examined. The instantaneous strength of the ECD moment at f_c sweeping through the frequency/time axes was captured. Corresponding loudness model was simulated by substituting the detected individual hearing threshold into a standard formula for deriving loudness level contour (ISO226:2003(E)). The frequency characteristics of the constant SPL versus the ASSR component, and the ASSR component versus the estimated loudness model, were compared. The differences were quantified and tested statistically.

2. Methods

2.1. Stimulus

A stimulus tone was generated by a swept-frequency cosine (chirp) signal ascending exponentially from 0.1 to 12.5 kHz as a function of time with a constant amplitude and a continuous phase. This paradigm was intended to transiently but sequentially activate the frequency-specific auditory cortical neurons located at logarithmic spacing (Romani et al., 1982; Pantev et al., 1988, 1989, 1994, 1995, 1996; Langner et al., 1997), at an equal timing and spacing. The amplitude of the sweep tone was sinusoidally modulated at f_m of 40 Hz with 100% modulation depth and 270° of the initial phase. The duration was 5 s. A 100 ms of rise and fall time was applied to ensure a smooth onset and offset to reduce the effect of any other neuronal components such as evoked responses and transient gamma band responses (Ross et al., 2002, 2005). As listed in Table 1, we prepared 17 stimulus tones in total, which were varied in acoustic parameters to examine the effect of sweep direction ([1] ascent, [2] descent), duration/velocity ([3] 5 s, [4] 15 s, and [5] 45 s), SPL ([1] 70-dB SPL, [6] 60-dB SPL, and [7] 50-dB SPL), and f_m ([1] 40 Hz, [8] 32 Hz, and [9] 51 Hz) on the frequency characteristics of the ASSR. Reproducibility was tested by comparing [1] first with [3] second sessions. Non-sweeping SAM tones ([10]–[17]) were also prepared at eight specific f_c (0.125, 0.25, 0.5, 1, 2, 4, 8, and 10 kHz) for a duration of 200 s. All stimulus tones were synthesized digitally on a PC (Precision M2400; DELL Inc., Round Rock, TX, USA) at a sampling rate of 96 kHz with a 32-bit resolution (Matlab; The MathWorks, Inc., Natick, MA, USA).

2.2. Stimulus delivery and intensity calibration

Fig. 1 shows the sound intensity calibration procedure using a test sound, a SAM sweep tone of 45 s in duration with f_c sweeping from 0.1 to 12.5 kHz (stimulus tone [9]). The test tone was delivered from a PC (Precision M6400, DELL Inc.) through an audio interface (Quad-Capture UA-55; Roland Corporation, Hamatsu, Shizuoka, Japan), equalizer (DEQ2496; Behringer GmbH, Kirchardt, Germany), a transducer (ER2; Etymotic Research, Inc., Elk Grove Village, IL, USA), and a plastic tube of 1 m to a tip of a 2-cc cavity simulating a ear canal volume. The sound signals recorded by a probe-tube microphone (ER7c; Etymotic Research, Inc.) at the output of the transducer and at the posterior end of the cavity are shown in Fig. 1A and B, respectively. Attenuation due to the tubing effect was observed in the lower and higher f_c for approximately 30-dB SPL at maximum. Fig. 1C shows the impulse response calculated from the signal shown in Fig. 1B, with the spectrum serving as an inverse filter capable of the inverse frequency characteristics of the attenuated sound signal. The inverse filter was convoluted to the signal of Fig. 1A, resulted in generating a sound signal of a concave shape. Fig. 1D and E shows the inverse-filtered sound signal delivered and recorded at the output of the transducer and at the posterior end of the cavity, respectively. The distortion was minimized to a range of ±0.5 dB in the temporal waveform, confirming that thoroughly flat intensity characteristics were achieved for the entire frequency range. The inverse filter was then applied to all the stimulus tones of [1]–[17] listed in Table 1.

The stimulus delivery for the subjects was prepared in a magnetically shielded room for the left and right ears. First, a soft silicone rubber probe tube (0.95-mm optical density (OD) × 0.58 mm inner diameter (ID) × 76 mm long (approximately 3.0″)) (ER7-14C; Etymotic Research, Inc.) was inserted into the ear canals to a depth of approximately 30 mm from the mastoid tip to a position of 2–3 mm away from the ear drum, where the subjects reported hearing a rustling noise, and it was then fixed with a surgical tape. The outer end of the probe tube was attached to the microphone (ER7c; Etymotic Research, Inc.). Next, 13-mm foam ear pieces (ER1-14A; Etymotic Research, Inc.) attached to the tip of a 1-m plastic tube were squeezed into the ear canals to a depth of approximately 20 mm. Of note, the frequencies of peaks and dips induced by the acoustic interference inside the ear canals were shifted systematically as a function of the distance between the sound output and the recording point (lower at the exterior and higher at the interior locations inside the ear canals), and they were moved above 12.5 kHz, the upper edge of the examined frequency, when the probe tube was inserted to a depth of approximately 30 mm. The lateral ends of the ear canals, together with the probe tubes and ear pieces, were then sealed tightly with soft silicon ear plugs (Insta-putty; Insta-Mold Products, Inc., Oak, PA, USA), which resulted in flattening the global attenuation in the lower frequencies.