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Research paper

Selective attention reduces physiological noise in the external ear canals of humans. I: Auditory attention

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ABSTRACT

In this study, a nonlinear version of the stimulus-frequency OAE (SFOAE), called the nSFOAE, was used to measure cochlear responses from human subjects while they simultaneously performed behavioral tasks requiring, or not requiring, selective auditory attention. Appended to each stimulus presentation, and included in the calculation of each nSFOAE response, was a 30-ms silent period that was used to estimate the level of the inherent physiological noise in the ear canals of our subjects during each behavioral condition. Physiological-noise magnitudes were higher (noisier) for all subjects in the inattention task, and lower (quieter) in the selective auditory-attention tasks. These noise measures initially were made at the frequency of our nSFOAE probe tone (4.0 kHz), but the same attention effects also were observed across a wide range of frequencies. We attribute the observed differences in physiological-noise magnitudes between the inattention and attention conditions to different levels of efferent activation associated with the differing attentional demands of the behavioral tasks. One hypothesis is that when the attentional demand is relatively great, efferent activation is relatively high, and a decrease in the gain of the cochlear amplifier leads to lower-amplitude cochlear activity, and thus a smaller measure of noise from the ear.

1. Introduction

Although much has been learned about the anatomy, neurophysiology, and biochemistry of the olivocochlear efferent system since the early reports of Rasmussen (1946, 1953), its function during everyday listening remains uncertain. Motivated by the seminal, if controversial, report by Hernández-Peón et al. (1956), there has been continual interest in the question of whether the olivocochlear efferent system plays a role in selective attention (e.g., Picton and Hillyard, 1971; Puel et al., 1988; Meric and Collet, 1994a; Fritz et al., 2007). Hernández-Peón et al. (1956) reported that gross electrical potentials recorded from the dorsal cochlear nucleus (DCN) in the auditory brainstem of cats were reduced in magnitude when the animals attended to visual, somatic, or olfactory stimuli, relative to when the animals were in a state of inattention. Ultimately, this fascinating finding was discredited on grounds of poor experimental control (e.g., Worden, 1973). Nevertheless, it created considerable, continuing interest in the possibility that the attentional demands of a behavioral task, or those of an environment, can modulate the afferent responses of the peripheral auditory system, either at the level of the auditory brainstem (as in Hernández-Peón; e.g., Lukas, 1980), or in the responses of the cochlea (e.g., Puel et al., 1988; Giard et al., 1994; Maison et al., 2001; Harkrider and Bowers, 2009). Research confirms everyday experience that humans are able to control their attention (Hafter et al., 1998; Gallun et al., 2007). However, after more than one-half century of research, there is a paucity of clear evidence that cognitive processes—such as the selective allocation of attentional resources—can affect the responses of the afferent auditory periphery.

If attentional demands (or other cognitive or perceptual demands) were capable of modulating afferent auditory responses at the level of the cochlea—the transduction stage in the auditory system—the medial olivocochlear bundle (MOCB) would be one neural pathway through which these effects would be realized. This pathway originates in the superior olivary complex of the brainstem, which is innervated directly by efferent neurons originating in the inferior colliculus and auditory cortex (Mulders and Robertson, 2000a,b). The fibers of the MOCB terminate at the bases of the outer hair cells (OHCs) of the cochlea (Warr and Guinan, 1979), where they inhibit (hyperpolarize) the OHCs, which in turn

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increases the local stiffness of the cochlear partition and diminishes the displacement of the basilar membrane (Cooper and Guinan, 2006), thereby reducing the afferent output of the inner ear. If the efferent flow from the cortex to the brainstem varied with level of attention, then the activity in the MOCB would vary, as would the afferent flow from the cochlea.

The OHCs are part of the cochlear-amplifier system (Davis, 1983) that is thought to be involved in the production of otoacoustic emissions (OAEs)—weak sounds produced in the inner ear and measured in the external ear canal (Kemp, 1978, 1980). For this reason, OAEs have been used to examine how human cochlear responses are affected by MOCB activation, and in turn how the attentional demands of a behavioral task affect efferent feedback to the cochlea. Previous studies have demonstrated that OAE magnitudes measured during auditory- or visual-attention tasks were different from OAE magnitudes measured during tasks that did not require attention (Puel et al., 1988; Froehlich et al., 1990, 1993; Meric and Collet, 1992, 1994b; Giard et al., 1994; Ferber-Viart et al., 1995; Maison et al., 2001; Harkrider and Bowers, 2009). However, across studies, the directions of the attentional effects on OAEs have been inconsistent, the magnitudes of the observed differences always have been small (less than about 1 dB), and comparisons across studies have been made difficult by significant procedural differences (see Discussion).

This is the first in a series of reports describing differences in cochlear responses when human subjects are, or are not, engaged in selective attention to either auditory or visual stimuli. In all cases, physiological and behavioral auditory measures were obtained simultaneously during the same test trials. In this first report, a nonlinear version of the stimulus-frequency OAE (SFOAE), called the nSFOAE or the residual from linear prediction (Walsh et al., 2010a,b), was used to measure cochlear responses during tasks that required either selective *auditory* attention to strings of digits spoken by one of two simultaneous talkers (dichotic or diotic listening), or relative inattention. In a companion paper, we report similar results involving visual rather than auditory attention (Walsh et al., 2014). These first two reports emphasize cochlear measures made during brief silent periods following the nSFOAE-evoking stimuli. Later we also will report parallel measurements obtained *during* the nSFOAE-evoking stimuli, which we call "perstimulatory" measures. Both the silent-period and perstimulatory measures exhibited marked differences during attention and inattention conditions.

Our measure of physiological noise was recorded in the external ear canals of our subjects during every behavioral condition, using the same cancellation procedure used to estimate the perstimulatory nSFOAE response. In contrast to the majority of previous studies on the effects of attention on OAEs that also measured noise levels in the test ears (Froehlich et al., 1990, 1993; Ferber-Viart et al., 1995; de Boer and Thornton, 2007; Harkrider and Bowers, 2009), every subject exhibited consistent differences in our physiological-noise measure between the inattention and selective-attention conditions. Specifically, the magnitudes of the physiological noise always were higher during the inattention condition than during the auditory selective-attention conditions, the differences being about 3.0 dB averaged across subjects, attention condition, and test frequency.

2. Methods

2.1. General

This first report focuses on an auditory measure of the physiological noise present in the external ear canals of humans during each of several auditory-attention conditions. A nonlinear procedure was used to estimate the level of the nSFOAE during a brief silent period following each nSFOAE-evoking stimulus presentation. The Institutional Review Board at The University of Texas at Austin approved the procedures described here. All subjects provided their informed consent prior to any testing, and they were paid for their participation. The behavioral measures will be described first, followed by the physiological measures. Then, a description will be provided of the integration of the behavioral and physiological measures.

2.1.1. Subjects

Two males (both aged 22) and six females (aged 20–25) were paid an hourly rate to participate in this study. All eight subjects completed two 2-hr auditory-attention sessions. Across those sessions, each subject completed each of the experimental conditions to be described a minimum of four times. All subjects had normal hearing [≤15 dB Hearing Level (HL)] at octave frequencies between 250 and 8000 Hz, and normal middle-ear and tympanic reflexes, as determined using an audiometric screening device (Auto Tymp 38, GSI/VIASYS, Inc., Madison, WI). Across the eight subjects, two ears, and four frequencies (0.5, 1.0, 2.0, and 4.0 kHz), the average middle-ear reflex (MER) threshold in our subjects was about 91 dB HL, and no individual subject had unusually low or high thresholds. No subject had a spontaneous otoacoustic emission (SOAE) stronger than −15.0 dB SPL within 600 Hz of the frequency of the 4.0-kHz probe tone used to elicit the nSFOAE.

2.2. Behavioral measures

Each subject was tested individually while seated in a reclining chair inside a double-walled, sound-attenuated room. Two insert earphone systems delivered sounds directly to the two external ear canals. (The earphone systems are described in detail in Section 2.3 below.) Some of the sounds presented were relevant for the behavioral task, and interleaved with these sounds were the stimuli for evoking the nSFOAE response. A computer screen attached to an articulating mounting arm was positioned by the subject to a comfortable viewing distance, and was used to provide task instructions and trial-by-trial feedback. A numerical keypad was provided to the subject to indicate his or her responses on the behavioral task.

2.2.1. Selective auditory-attention conditions

2.2.1.1. Dichotic condition. There were two auditory selective-attention conditions: one involved dichotic presentation of the stimuli for the behavioral task, and one involved diotic presentation. For the dichotic-listening condition, two competing speech streams were presented separately to the ears, and the task of the subject was to attend to one of the speech streams. In one ear the talker was female, in the other ear the talker was male, and which ear received the female talker was selected trial-by-trial from a closed set of random permutations. The number of trials having the female voice presented to the right ear was approximately equal to the number of trials having the female voice presented to the left ear. On each trial, the two talkers simultaneously spoke two different sequences of seven single-digit numbers. Each digit (0–9) was selected randomly with replacement, and the digit sequence spoken by the single female talker was selected independently from that spoken by the single male talker. Each digit was presented during a 500-ms interval, and consecutive digits were separated by 330-ms interstimulus intervals (ISIs). As described below, the stimulus waveforms used to elicit the nSFOAE response were presented in the ISIs between spoken digits. Fig. 1 shows an example of the speech waveforms presented on a single trial of the dichotic-listening condition.