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Cortical signal-in-noise coding varies by noise type, signal-to-noise ratio, age, and hearing status

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HIGHLIGHTS

- SNR, noise type, and group variables significantly contribute to CAEPs.
- Spectrotemporal properties of background noise determine the effect of SNR on CAEPs.
- Hearing status and age interact with noise type to affect the timing of N1 and P2.

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ABSTRACT

The purpose of this study was to determine the effects of noise type, signal-to-noise ratio (SNR), age, and hearing status on cortical auditory evoked potentials (CAEPs) to speech sounds. This helps to explain the hearing-in-noise difficulties often seen in the aging and hearing impaired population. Continuous, modulated, and babble noise types were presented at varying SNRs to 30 individuals divided into three groups according to age and hearing status. Significant main effects of noise type, SNR, and group were found. Interaction effects revealed that the SNR effect varies as a function of noise type and is most systematic for continuous noise. Effects of age and hearing loss were limited to CAEP latency and were differentially modulated by energetic and informational-like masking. It is clear that the spectrotemporal characteristics of signals and noises play an important role in determining the morphology of neural responses. Participant factors such as age and hearing status, also play an important role in determining the brain's response to complex auditory stimuli and contribute to the ability to listen in noise.

1. Introduction

Understanding speech in background noise is a complex process which is dependent upon the integrity of both the auditory system and cognitive functioning. It is generally accepted that acoustically adverse environments affect speech understanding more in older hearing-impaired individuals than in young normal-hearing individuals. However, it is unclear whether perception-in-noise difficulties are predominantly caused by reduced central processing ability (including, but not limited to, cognitive functioning) or by the lack of acoustical information necessary to differentiate the signal from the noise at the level of the peripheral auditory system. In certain cases it may be that cognition compensates for peripheral coding failures or the lack of available acoustic cues. Given the many contributions to accurate speech understanding in background noise, it is not surprising that some types of background noise are more detrimental to speech understanding than others [1]. Understanding how speech in noise is neurally coded in normal and impaired individuals may improve our understanding of the underlying mechanisms that contribute to successful perception in noise, allowing for better management and treatment of individuals with speech-perception-in-noise difficulties.

Cortical auditory speech-in-noise coding is determined by several factors. For example, the level of the signal and its relationship

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Abbreviations: CAEP, cortical auditory evoked potentials; SNR, signal to-noise ratio; SSC, continuous noise; 1TM, one-talker-modulated noise; 4TB, four-talker babble noise; YNH, younger-normal hearing individuals; ONH, older-normal hearing individuals; OHI, older-hearing impaired individuals.

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to the noise (i.e, signal-to-noise ratio) affect both the timing and magnitude of cortical neural responses [2]. In addition, the spectrotemporal properties of both signal and noise can interact and affect neural coding. Signals presented in modulated or interrupted noise produce stronger cortical responses than those presented in unmodulated noise [3,4], which is consistent with behavioral data that demonstrate better speech reception thresholds in fluctuating noise [5]. These improvements are thought to be due to the listener's ability to take advantage of gaps in the noise as a means of identifying the signal [6].

Masking release as a function of age and hearing loss has been studied extensively in the behavioral domain [5,7,8]; however, in the physiological domain, masking release and the effect of different noise types in individuals with hearing loss has not been determined. Age-related changes are reported to be independent of peripheral hearing sensitivity in both animal and human studies [9]. However, physiological studies on the effect of background noise as a function of age are not as conclusive. While some studies have found differences in the evoked responses between younger and older individuals [10–12], others found that the effect persisted when co-varying for age; suggesting that the change in CAEPs to signal in noise were not attributable to normal aging [13].

We aim to clarify the effects of noise type and SNR on cortical neural coding to improve our understanding of the underlying process of signal extraction in a dynamic environment with specific focus on how older individuals differ from younger individuals and how individuals with and without hearing loss differ from each other. A better understanding of the neural coding of signals in noise may help to improve assessment and treatment of perception-in-noise difficulties. We hypothesize that there will be important effects of noise type, SNR, and group, but that these effects will interact such that the effects of noise type differ by both SNR and group.

2. Methods

2.1. Participants

Participants included 30 right-handed individuals recruited into three groups: 10 younger normal-hearing individuals (YNH, mean age = 27.1, SD = 7.0), 10 older normal-hearing individuals (ONH, mean age = 67.2, SD = 5.1), and 10 older hearing-impaired individuals (OHI, mean age = 68.8 years, SD = 5.9). The two older groups did not differ significantly in age ($T_{(18)} = -0.645$; $p = 0.527$). All three groups consisted of four male and six female participants. Normal-hearing participants had thresholds below 25 dB HL bilaterally up to 4000 Hz, and hearing-impaired individuals had mild-to-moderate sloping sensorineural hearing loss. Each group's pure-tone average (average of hearing thresholds at 500, 1000, and 2000 Hz) was calculated (young normal hearing: 6.0 ± 4.4 dB); older normal-hearing: 7.9 ± 4.9 dB; older hearing impaired: 32.3 ± 7.7 dB) and revealed no significant difference between normal-hearing groups ($T_{(18)} = -0.95$; $p = 0.355$). The mean thresholds for all participant groups are shown in Table 1. All participants gave their informed consent and the research was completed with the approval of the local institutional review board.

2.2. Signals and maskers

Naturally produced syllables/ba/and/da/, shortened to 150 ms by windowing the syllable offset, were used in an oddball test paradigm (see electrophysiological measurement section below). These syllables have been used previously [14]. The signals were monaurally presented to the right ear in quiet and in three types of background noise at three different signal-to-noise ratios (SNRs): −3, 3, and 9 dB SNR. These SNRs were chosen because previous work suggested that such a range would show a main effect of SNR in each group of participants [12,15]. Overall, there were 10 conditions: nine were signal-in-noise conditions and one was a signal-in-quiet condition. For every condition, the level of the signal was kept constant at 65 dB SPL.

The three noise types were (1) a continuous speech-spectrum noise or SSC, (2) a one-talker modulated noise or 1TM, and (3) a four-talker babble or 4TB. All noises were low-pass filtered at 4000 Hz. The continuous noise and four-talker babble were used in our previous work [14,16]. The continuous noise was then modulated with the envelope of 10 concatenated Institute of Electrical and Electronic Engineers (IEEE) sentences to create the one-talker modulated noise, which would make for a better representation of modulated noise in the real world instead of a simple interrupted speech noise as used in the study by Billings and colleagues [14]. The one-talker modulated noise also had greater envelope fluctuations than the four-talker babble, which in theory should result in better CAEP responses, allowing a point for comparison.

2.3. Electrophysiological measurements

Evoked potentials were recorded using Neuroscan Synamps RT/Scan 4.5 and a 64-channel electrode cap (Electro-Cap International, Inc). A passive oddball paradigm was used for stimulus presentation, with the probability of presentation of the standard/ba/at 0.8 and the deviant/da/at 0.2. Two blocks of trials for each condition were completed, totaling 375 trials (75 deviants and 300 standards). Only the responses to standards following identical standards are presented in this article (i.e., only when/ba/followed another/ba/, or 225 trials per condition). To ensure that responses obtained were free from the interacting effect of age and interstimulus interval [17], a relatively long interval of 1600 ms (offset to onset) was used. The ordering of test conditions was randomized across participants.

Recordings were completed while participants reclined comfortably in an electro-acoustically shielded booth, watching a silent close-captioned movie of their choice. Each block took eight minutes to complete, during which the participants were instructed to ignore the stimuli and minimize head and body movement. Overall, the CAEP visit lasted 3.5 h including breaks given throughout testing.

The online reference electrode was located at vertex and the ground electrode was placed on the forehead. Waveforms were digitized at 1000 Hz and recorded from 0 to 100 Hz. Recorded responses were further analyzed offline. The waveforms were epoched using a range of 100-ms pre-stimulus period to 1000-ms post-stimulus period. Trials with blink artifacts were corrected using a procedure that calculates the amount of covariation between each evoked potential channel and a vertical eye channel using a spatial filter, in which singular value decomposition is used to remove the blink activity from each electrode on a point-by-point basis to the degree that the evoked potential and blink activity covaried [18]. Sweeps containing voltages exceeding 70 μV were then rejected, and the remaining sweeps were averaged, filtered from 1 Hz to 30 Hz, and re-referenced using an average reference.

For the purpose of this study, only responses recorded at electrode Cz was analyzed. Based on the CAEP grand average of the 30 participants, we defined P1 and P2 to be the positive peaks that occur prominently within the latency ranges of 40–110 ms and 180–280 ms respectively, while N1 was defined as the negative peak occurring prominently between 90 ms and 180 ms. At −3 dB SNR and for all waveforms recorded in babble noise, 30 ms were added to the allowances used to determine the latency of all of the evoked potentials given the established effect of SNR on CAEPs [2]. The initial peaks were picked automatically by the Neuroscan