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Review

Effects of sensorineural hearing loss on temporal coding of narrowband and broadband signals in the auditory periphery

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ABSTRACT

People with sensorineural hearing loss have substantial difficulty understanding speech under degraded listening conditions. Behavioral studies suggest that this difficulty may be caused by changes in auditory processing of the rapidly-varying temporal fine structure (TFS) of acoustic signals. In this paper, we review the presently known effects of sensorineural hearing loss on processing of TFS and slower envelope modulations in the peripheral auditory system of mammals. Cochlear damage has relatively subtle effects on phase locking by auditory-nerve fibers to the temporal structure of narrowband signals under quiet conditions. In background noise, however, sensorineural loss does substantially reduce phase locking to the TFS of pure-tone stimuli. For auditory processing of broadband stimuli, sensorineural hearing loss has been shown to severely alter the neural representation of temporal information along the tonotopic axis of the cochlea. Notably, auditory-nerve fibers innervating the high-frequency part of the cochlea grow increasingly responsive to low-frequency TFS information and less responsive to temporal information near their characteristic frequency (CF). Cochlear damage also increases the correlation of the response to TFS across fibers of varying CF, decreases the traveling-wave delay between TFS responses of fibers with different CFs, and can increase the range of temporal modulation frequencies encoded in the periphery for broadband sounds. Weaker neural coding of temporal structure in background noise and degraded coding of broadband signals along the tonotopic axis of the cochlea are expected to contribute considerably to speech perception problems in people with sensorineural hearing loss.

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1. Introduction

Sensorineural hearing loss involving damage and dysfunction within the cochlea is a common, sometimes preventable disorder that can profoundly affect communication ability and hence, the social wellbeing of affected individuals. The National Institute on Deafness and Other Communication Disorders estimates that 15% of Americans between the ages of 20 and 69 have hearing loss due to overexposure to loud sounds. The incidence of reported hearing loss increases with age, rising from 18% in individuals aged 45–64 to 30% aged 65–74 and 47% aged 75 and older. While amplification from a hearing aid can improve speech perception in quiet by restoring audibility of previously imperceptible acoustic cues, listeners with sensorineural hearing loss often still struggle to understand speech under degraded conditions with background noise and reverberation (e.g., Duquesnoy, 1983; Woods et al., 2010).

The mammalian cochlea is tonotopically arranged such that high-frequency sounds evoke greatest vibration of the basilar membrane at the base of the structure near its input from the stapes while lower-frequency sounds evoke greatest vibration from progressively more apical locations (Geisler, 1998). The system is commonly modeled as a bank of overlapping band-pass "auditory filters" centered on characteristic frequencies (CFs) distributed across the frequency range of normal hearing, each representing a place on the basilar membrane. Sharply tuned filters with high CFs represent basal cochlear locations, while more broadly tuned filters (on a log frequency scale) with lower CFs represent more apical cochlear locations. The auditory filters decompose broadband

Abbreviations: AN, auditory nerve; CF, characteristic frequency; ENV, envelope; FM, frequency modulation; SPL, sound pressure level; SR, spontaneous rate; TFS, temporal fine structure.

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sound into a series of narrowband output signals (one per auditory filter), each of which contains two kinds of temporal information: slow changes in overall amplitude envelope (ENV) and faster variations in temporal fine structure (TFS; Fig. 1). Each output signal is encoded by a discrete population of auditory-nerve fibers through variation in spike rate over time. For frequencies below 4–5 kHz, both the TFS and ENV of the output signal are encoded through neural phase locking, or variation in spike rate with the temporal structure of the signal. At higher frequencies, in contrast, the TFS coding is greatly diminished and the auditory-nerve fibers encode primarily the ENV (Johnson, 1980; Joris and Yin, 1992).

Recent behavioral studies suggest that speech perception problems in people with sensorineural hearing loss may be caused by diminished sensitivity to the temporal structure of acoustic signals (reviewed by Moore, 2008). Lorenzi and colleagues (Lorenzi et al., 2006, 2009; Ardoint et al., 2010) compared the ability to use temporal information to perceive speech between subjects with varying configurations of sensorineural hearing loss and subjects with normal hearing. Consonant stimuli were decomposed into component narrowband signals (designed to fall within the bandwidth of a single auditory filter) and filtered to contain only ENV information, only TFS information, or both TFS and ENV information (i.e., left intact). The component signals were recombined and presented to subjects for identification. All study subjects, including listeners with hearing loss, could accurately identify consonants when they were intact or contained only ENV information. However, listeners with hearing loss had considerable difficulty identifying consonants containing only TFS information while normal-hearing subjects did not. A reduced ability to use TFS cues was even observed for listeners with only mild to moderate degrees of hearing loss (Ardoint et al., 2010). Furthermore, the listeners with hearing loss who were least able to identify consonants based on TFS information were also least able to perceive sentences presented in fluctuating background noise (Lorenzi et al., 2006). The results suggest that cochlear hearing loss degrades auditory processing of TFS information and that TFS information is critical for accurate perception of speech under degraded listening conditions. Processing of ENV information, in contrast, appears to be less vulnerable to hearing loss and is sufficient for perception of speech in quiet.

A follow-up study examined perception of target speech in the presence of a competing background talker in subjects with moderate hearing loss and normal hearing (Hopkins et al., 2008). The extent of TFS information in the target speech was manipulated by decomposing the signal into component narrowband signals as above and removing TFS from a variable number of filtered signals (beginning with the highest-frequency filter). Component signals were recombined and the speech reception threshold signal-to-noise ratio was measured. Speech reception thresholds in the listeners with hearing loss improved less with the addition of TFS information than in normal-hearing control listeners. These findings further suggest that cochlear hearing loss degrades processing of TFS information and that TFS information is critical for listening in background noise.

Although these ideas are not without controversy (e.g., Oxenham and Simonson, 2009; Swaminathan and Heinz, 2012),

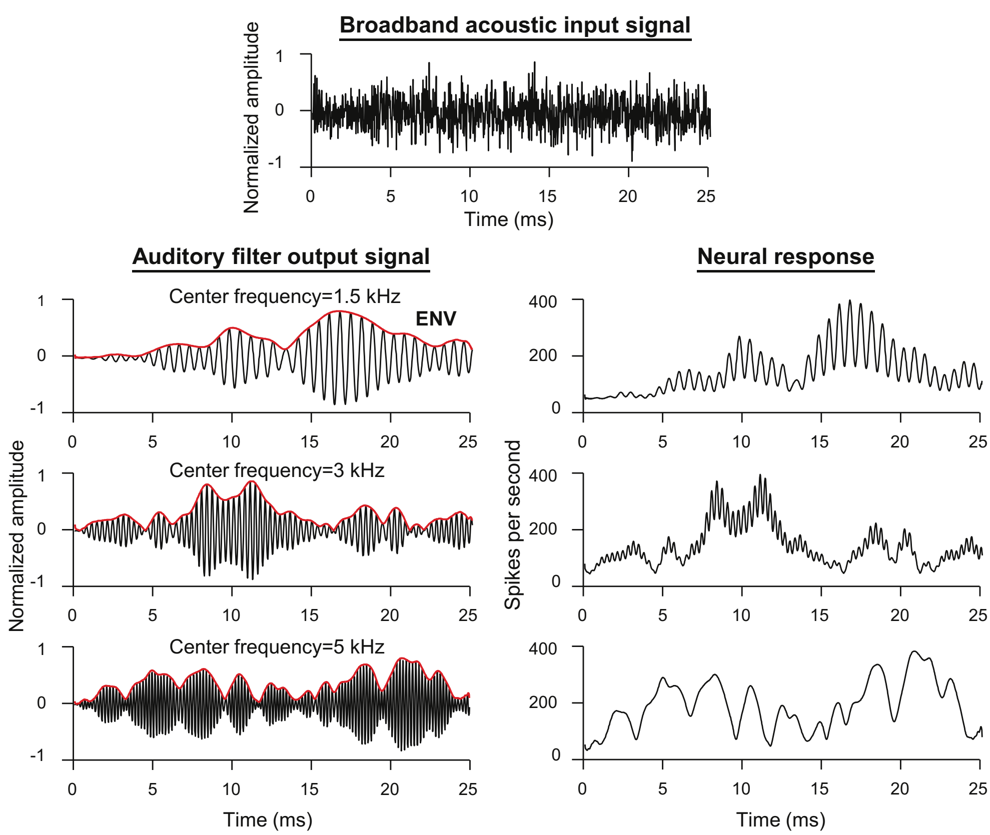

Fig. 1. Schematic of the spectral decomposition of broadband sounds and coding of TFS and ENV information in the cochlea. Broadband acoustic input signal (top) and output signals (left) of auditory filters with center frequencies between 1.5 and 5 kHz. Each output signal consists of a slowly varying amplitude envelope (ENV; red) and a quickly varying temporal fine structure (TFS, black). Auditory filter output signals are encoded in the spike rate of auditory-nerve fibers (right). In fibers with characteristic frequencies (CFs) below 4–5 kHz, spike rate varies with both the TFS and ENV of the auditory filter output signal. In fibers with higher CFs, spike rate varies primarily with the ENV of the output signal, due to the low-pass membrane filtering of the inner hair cells.