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Research paper

Suprathreshold auditory processing deficits in noise: Effects of hearing loss and age

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ABSTRACT

People with sensorineural hearing loss generally suffer from a reduced ability to understand speech in complex acoustic listening situations, particularly when background noise is present. In addition to the loss of audibility, a mixture of suprathreshold processing deficits is possibly involved, like altered basilar membrane compression and related changes, as well as a reduced ability of temporal coding. A series of 6 monaural psychoacoustic experiments at 0.5, 2, and 6 kHz was conducted with 18 subjects, divided equally into groups of young normal-hearing, older normal-hearing and older hearing-impaired listeners, aiming at disentangling the effects of age and hearing loss on psychoacoustic performance in noise. Random frequency modulation detection thresholds (RFMDTs) with a low-rate modulator in wide-band noise, and discrimination of a phase-jittered Schroeder-phase from a random-phase harmonic tone complex are suggested to characterize the individual ability of temporal processing. The outcome was compared to thresholds of pure tones and narrow-band noise, loudness growth functions, auditory filter bandwidths, and tone-in-noise detection thresholds. At 500 Hz, results suggest a contribution of temporal fine structure (TFS) to pure-tone detection thresholds. Significant correlation with auditory thresholds and filter bandwidths indicated an impact of frequency selectivity on TFS usability in wide-band noise. When controlling for the effect of threshold sensitivity, the listener's age significantly correlated with tone-in-noise detection and RFMDTs in noise at 500 Hz, showing that older listeners were particularly affected by background noise at low carrier frequencies.

1. Introduction

People suffering from sensorineural hearing loss (SNHL) usually report problems in acoustically complex listening situations. The most common form of SNHL is age-related hearing loss, known as presbyacusis. It typically results in a loss of sensitivity for high frequencies progressing to the lower frequencies with increasing age. In general, the sensitivity loss, limiting audibility of soft sounds, is accompanied by an increased growth of loudness with level (recruitment phenomenon; e.g., Moore, 2012). This steep increase of loudness above (increased) threshold is significantly conditioned by a loss or dysfunction of outer hair cells (OHC; Robles and Ruggero, 2001) which act as biological motors to amplify smaller motions of the basilar membrane. Even if audibility is of less concern because sound levels are well above threshold, or because amplification and dynamic range compression are applied in a hearing aid, suprathreshold processing deficits may, however, persist. This could explain why many aided hearing-impaired (HI) listeners still have considerable problems in complex listening situations including multiple talkers, reverberation or background noise (e.g., Kates, 2010). Moreover, older persons experience more problems with suprathreshold processing (including speech-in-noise intelligibility) than young listeners, even when their hearing sensitivity is audiometrically normal (e.g., Füllgrabe, 2013; Füllgrabe et al., 2015). This suggests that age-related supra-

Abbrevations: 3-AFC, adaptive three-interval, three-alternative, forced-choice; *ACALOS*, adaptive categorical loudness scaling; *AM*, amplitude modulation; *AN*, auditory nerve; ath_{PT}, ath_{GN}, absolute threshold of hearing obtained with pure tones resp. Gaussian noise; *cu*, categorical units; *ERB*, equivalent rectangular bandwidth; *FM, FMDT*, frequency modulation (detection threshold); *HI, HIO*, hearing-impaired (old); *HL*, hearing level; *IHC*, inner hair cell; *K*, processing efficiency following auditory filtering according to notched-noise procedure; L_{25}, level that corresponds to medium loudness perception (25 cu); m_{low}, slope of the lower portion of the ACALOS fit; *NH, NHY, NHO*, normal-hearing (young / old); *OHC*, outer hair cell; *PJD*, phase jitter detection; *r*, $r_{ath/age}$, Pearson's correlation coefficient (with ath_{PT} / age partialled out); *rANOVA*, repeated-measures analyses of variance; *RFMD, RFMDT*, random low-rate frequency modulation detection (threshold); *SL*, sensation level; *SMR*, signal-to-masker ratio; *SNHL*, sensorineural hearing loss; *SNR*, signal-to-noise ratio; *TFS*, temporal fine structure

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threshold processing deficits – that cannot be quantified in the audiogram and that are not aided by restoring audibility – contribute at least partly to the impairment in everyday communication observed in older listeners (e.g., Ruggles et al., 2011; see Plack et al., 2014 for a review).

Part of the problems of HI listeners can be explained by increased filter bandwidth (at same sensation level) and the accompanying reduced basilar membrane compression. For instance, for wideband signals, the output of broadened auditory filters might form more complex patterns than the outputs of "normal" filters. In this case, "external noise" present in the sound itself (e.g. background noise in a communication situation) will lead to a specific signal-to-noise ratio (SNR) in an auditory filter and will also affect the internal representation of amplitude modulations (AM) and temporal fine structure (TFS) in a subsequent auditory nerve (AN) fiber.

A possible internal source introducing coding degradations is the loss or damage of inner hair cells (IHC) including subsequent retro-cochlear neuronal processes at early stages of the auditory pathway, e.g. AN afferent terminals, referred to as auditory deafferentation. While the input level can be coded by the firing rate, the synchronization of spikes to a certain phase of the input signal, known as "phase locking", conveys information about the TFS of the signal. Animal studies suggest that AN fibers of mammals phase lock well up to 3–4 kHz (e.g., Palmer and Russell, 1986). The exact cut-off frequency for phase locking in humans is still subject of controversy. Behavioral studies show that the detection of interaural time differences is limited to frequencies lower than about 1.5 kHz (Brughera et al., 2013). Comparisons of anatomical and behavioral data in animals and humans (Joris and Verschooten, 2013) and mass potential recordings at the AN (Verschooten et al., 2015) indicate that TFS is unlikely to be accessible above about 5 kHz. Auditory deafferentation would therefore affect the suprathreshold "neural coding fidelity" of the sound waveform resulting in loss of TFS information at lower frequencies and in loss of temporal envelope information at higher frequencies. Kujawa and Liberman (2009) showed in mice that high-level noise exposure leads to a permanent degeneration of a large fraction of AN fibers in the high frequency region of the cochlea. As the shift of the hearing threshold was only temporary, it is assumed that noise overexposure primarily causes a degeneration of (high-threshold) low-spontaneous rate fibers (Furman et al., 2013). Consistently, Lobarinas et al. (2013) observed only small effects on behaviorally determined audiometric thresholds in chinchillas, even with extensive IHC losses above 80% following carboplatin treatment. Losses of synaptic elements in the IHC and degeneration of AN fibers were found to reduce the redundancy of neural coding (Henry and Heinz, 2012; Lopez-Poveda and Barrios, 2013).

Physiological studies in mammals have shown that phase locking to tones in the presence of noise decreases with increasing masker level, but generally remains strong at SNRs near behavioral masking thresholds (e.g., Rhode et al., 1978; Costalupes, 1985) suggesting that phase locking mechanisms will also play a role for tone detection in noise. Although neurophysiological studies in animals have shown little effect of SNHL on the strength of temporal neural coding in quiet (e.g., Kale and Heinz, 2010), Henry and Heinz (2012) have shown in chinchillas that peripheral temporal coding in noise-exposed fibers is substantially more degraded in background noise than in quiet.

It is likely that the described suprathreshold deficits persist even if audibility and loudness perception are restored by suitable compensation strategies. Indeed, deficits in suprathreshold signal processing (e.g., TFS sensitivity) are found in both HI and older normal-hearing listeners (Moore et al., 2012; Füllgrabe, 2013; Füllgrabe et al., 2015) and may contribute to the reduced ability to understand speech in cocktail-party situations (e.g., Lorenzi et al., 2006; Strelcyk and Dau, 2009; Neher et al., 2012; Füllgrabe et al., 2015). While the TFS1/2 test (Moore and Sek, 2009; Hopkins and Moore, 2011) that assesses monaural discrimination of harmonic and frequency-shifted tones is mainly limited to medium and high frequencies, the binaural TFS low-frequency (TFS-LF) test, described by Hopkins and Moore (2010), measures interaural phase difference thresholds for pure tones at low frequencies. Thus a purely monaural test for assessing suprathreshold sensitivity to TFS over a wider frequency range is missing. Particularly, most known TFS measures are based on tests in quiet and, so far, only a few psychoacoustic studies (e.g., Turner, 1987; Strelcyk and Dau, 2009; Sheft et al., 2012) have assessed TFS deficits of HI listeners in noise. Tests of speech perception often assess speech intelligibility in the presence of noise, however, here performance does not only reflect the listener's suprathreshold auditory processing abilities but also depends on cognitive functions (e.g., Pichora-Fuller and Souza, 2003; Humes et al., 2013; Füllgrabe et al., 2015). Speech tests therefore appear to be of limited value for specifically assessing (peripheral) suprathreshold auditory processing deficits.

In this paper, two psychoacoustic measures, specifically aiming at the characterization of monaural temporal processing deficits in noise, are introduced: i) random frequency modulation detection (RFMD) at low modulation rates (1–4 Hz) was measured in quiet and in bandlimited Gaussian white noise and ii) discrimination of a phase-jittered Schroeder-phase harmonic tone complex with a perceptible temporal sweep structure from a random phase harmonic tone complex with equal amplitude spectrum was assessed (phase-jitter detection, PJD). The two measures were embedded in a series of classical psychoacoustic experiments near and above hearing threshold. The first three experiments aimed at defining effects of OHC loss in terms of a reduced dynamic range (categorical loudness scaling), reduced sensitivity (pure-tone thresholds) and widened auditory filters (notched noise). Furthermore, masked pure tone detection thresholds in wideband noise were assessed. Most experiments were conducted at medium loudness as determined by categorical loudness scaling. The test frequencies were 0.5, 2, and 6 kHz, allowing a performance assessment in a frequency region, where TFS information is likely accessible (0.5 kHz), less accessible (2 kHz), and likely not accessible (6 kHz), leaving temporal envelope cues only. Three groups of six young normal-hearing (NHY), six older normal-hearing (NHO), and six older hearing-impaired (HIO) listeners participated in all experiments. The results were analyzed and discussed with regard to the effects of age, sensorineural hearing loss, auditory filter bandwidth, and external noise to identify a potential monaural estimate of peripheral TFS processing at low frequencies. Motivated by previous studies of monaural (Hopkins and Moore, 2011; Füllgrabe, 2013; Füllgrabe et al., 2015) or binaural (Ross et al., 2007; Grose and Mamo, 2010; Hopkins and Moore, 2011; Füllgrabe, 2013; Füllgrabe et al., 2015) TFS sensitivity, the inclusion of NHO listeners allows to assess possible age-related deficits, while controlling for effects of hearing impairment, which would otherwise confound the results. It was examined whether the proposed measures might potentially be useful to detect auditory deafferentation, independent of elevated thresholds, as suggested in the literature.

2. Material and methods

2.1. Subjects

Six young listeners with normal hearing thresholds (NHY), six older normal-hearing listeners (NHO), and six hearing-impaired older listeners (HIO) participated with each group consisting of three females and three males. The NHY ranged from 25 to 30 years