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Research paper

Phonemic restoration by hearing-impaired listeners with mild to moderate sensorineural hearing loss

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ABSTRACT

The auditory system is capable of perceptually restoring inaudible portions of speech. This restoration may be compromised as a result of hearing impairment, particularly if it is combined with advanced age, because of degradations in the bottom-up and top-down processes. To test this hypothesis, phonemic restoration was quantitatively measured with hearing-impaired listeners of varying ages and degrees of hearing impairment, as well as with a normal hearing control group. The results showed that the restoration benefit was negatively correlated with both hearing impairment and age, supporting the original hypothesis. Group data showed that listeners with mild hearing loss were able to perceptually restore the missing speech segments as well as listeners with normal hearing. By contrast, the moderately-impaired listeners showed no evidence of perceptual restoration. Further analysis using the articulation index showed that listeners with mild hearing loss were able to increase phonemic restoration with audibility. Moderately-impaired listeners, on the other hand, were unable to do so, even when the articulation index was high. The overall findings suggest that, in addition to insufficient audibility, degradations in the bottom-up and/or top-down mechanisms as a result of hearing loss may limit or entirely prevent phonemic restoration.

1. Introduction

In daily communication, speech is commonly masked by other sounds. The auditory system has the capability to fill in parts of the inaudible portions, thereby perceptually restoring the degraded signal to a meaningful speech stream. This process is called phonemic restoration (PR; Warren, 1970; Warren and Obusek, 1971; Warren and Sherman, 1974; Bashford and Warren, 1979; Verschuure and Brocaar, 1983; Kashino, 1992). In such noisy listening environments hearing-impaired (HI) listeners (who also tend to be advanced in age) often complain about difficulties in understanding speech—even with hearing aids (HAs) that provide proper amplification (Plomp and Mimpen, 1979; Duquesnoy, 1983; Dubno et al., 1984; Working Group on Speech Understanding and Aging, 1988; Schneider et al., 2000). We hypothesized that PR may be hindered as a result of hearing impairment, which could be one of the reasons for poorer speech understanding in noise.

The explanations of the underlying processes of PR vary (Samuel, 1981a,b; Repp, 1992), however, the consensus is that PR follows the general principles of auditory scene analysis (ASA; Bregman, 1990; Bregman et al., 1999; Srinivasan and Wang, 2005). In ASA, the auditory system organizes the mixture of sounds coming from different sources into distinct objects (Bregman, 1990), using bottom-up and top-down mechanisms (Trout and Poser, 1990; Alain et al., 2001; Sussman et al., 2002; Winkler et al., 2005). Bottom-up cues, such as good continuity and common trajectory in signal intensity, pitch, temporal envelope and/or spectral content, help associating sound segments from the same source together (Darwin and Carlyon, 1995; Woods et al., 1996; Cooke and Ellis, 2001; Husain et al., 2005; Darwin, 2005, 2008). In PR, these cues are extracted from the audible segments of speech where the noise level is momentarily low. These associations are then interpreted to form meaningful auditory objects using top-down mechanisms, such as the listener's expectations and experience, selective attention, and, in the case of speech, linguistic knowledge and syntactic, semantic, lexical constraints, and context (Cusack et al., 2004; Davis and Johnsrude, 2007; Shinn-Cunningham and Wang, 2008).

Changes in bottom-up or top-down processes due to hearing impairment and/or aging could cause ASA and PR to operate differently, or even to stop working entirely (see the review by Grimault and Gaudrain, 2006). Availability of speech information, an important factor for restoration, could be compromised due to reduced audibility, a consequence of elevated thresholds (Zurek and

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Delhorne, 1987; Lee and Humes, 1993), or due to excessive forward masking from noise onto speech segments, a consequence of suprathreshold deficits, such as reduced spectral or temporal resolution (Nelson and Freyman, 1987; Festen and Plomp, 1990; Bacon et al., 1998; Dubno et al., 2003). Another negative effect of the suprathreshold deficits could be a difficulty in object formation due to degradations in bottom-up cues (Mackersie et al., 2001; Rossi-Katz and Arehart, 2005; Gaudrain et al., 2007; Shinn-Cunningham, 2007).

The interactions between bottom-up and top-down processes can also be altered due to changes in the cognitive system caused by aging. Older listeners, whether HI or not, tend to have difficulty understanding speech in the presence of background sounds (Plomp and Mimpen, 1979; Dubno et al., 1984; Frisina and Frisina, 1997; Rajan and Cainer, 2008). This difficulty is attributed to, in addition to the potential sensory deficits, age-related changes in the central auditory system, such as the general slowing down in the cognitive processes, a reduced working memory capacity, and poorer inhibition of the competing sounds (Pichora-Fuller et al., 1995; Sommers, 1996; Tun, 1998; Wingfield et al., 2005). Various scenarios are possible depending on the extent of the damage in these processes. Mild degradations in bottom-up cues may be compensated by increased effort and use of context information and/or linguistic knowledge (Wingfield et al., 2005; Wingfield and Tun, 2007; Zekveld et al., 2007; Pichora-Fuller, 2008). This compensation may not be available, however, if the degradations are too extensive (Schum and Matthews, 1992; Schneider et al., 2007; Shinn-Cunningham, 2007), imposing excessive demand and stress on the limited cognitive resources (Kahneman, 1973), or if the top-down mechanism itself is damaged (Pichora-Fuller et al., 1995; Shinn-Cunningham and Best, 2008).

In the present study, we explored the hypothesis that typical HI listeners—who may also be elderly—might not benefit from PR as much as NH listeners, due to the reasons listed above. We used a method that made quantitative measurement of PR possible (Cherry and Wiley, 1967; Powers and Wilcox, 1977; Verschuure and Brocaar, 1983). In this method, speech is periodically interrupted and its recognition is measured in two conditions: once with the interruptions left silent and once with the interruptions filled with loud noise bursts. In the former condition, the interruptions are clearly perceptible. The latter condition tends to create an illusory percept of continuous speech (Miller and Licklider, 1950; Warren, 1970), and an increase in intelligibility may also be seen even though the noise bursts do not add speech information (Bashford et al., 1992; Carlyon et al., 2002). The increase in intelligibility with the addition of noise is the measure used for PR benefit in the present study. By measuring this effect with listeners of varying degrees of hearing loss and ages, we have the opportunity to analyze the results for a number of predictive factors, such as hearing loss, age, and audibility. The ultimate goal of the research is, with this baseline information, to give insight into the type of technologies that can be developed to help HI listeners understand speech better in background noise.

2. Materials and methods

2.1. Listeners

A total of 27 listeners, all native speakers of American English, participated in the study. The listeners were divided equally into groups of normal hearing, mild hearing loss, and moderate hearing loss, based on the classification of hearing impairment severity presented in Table 5.4 by Katz et al., 2002. For normal hearing (NH), the pure-tone average (PTA), defined as the average of hearing thresholds at the audiometric frequencies of 500, 1000, and 2000 Hz, was 15 dB or less. We additionally limited the thresholds to 20 dB HL at each audiometric frequency between 250 and 3000 Hz. To allow a more extended age range than usually possible for NH, thresholds at higher frequencies were not used as inclusion criteria. HI listeners had symmetrical sensorineural hearing loss with gently sloping audiometric thresholds and displayed no apparent cognitive deficiencies. A PTA between 26 and 40 dB HL indicated mild hearing loss, except for one listener with a PTA of 21 dB HL, who was also included in this group. A PTA between 41 and 55 dB HL indicated moderate hearing loss. The average audiometric thresholds and PTAs are shown in Fig. 1 for each subject group.

Age was not an inclusion criterion as we sought a wide range of ages across listeners to represent typical HA-user population. As a result, HI listeners were older than NH listeners, while the ages of mild and moderate HI groups overlapped (Fig. 2). The age range for NH listeners was from 23 to 57 years, with an average of 37, for mild HI listeners from 47 to 83 years, with an average of 70, and for moderate HI listeners from 64 to 81 years, with an average of 73.

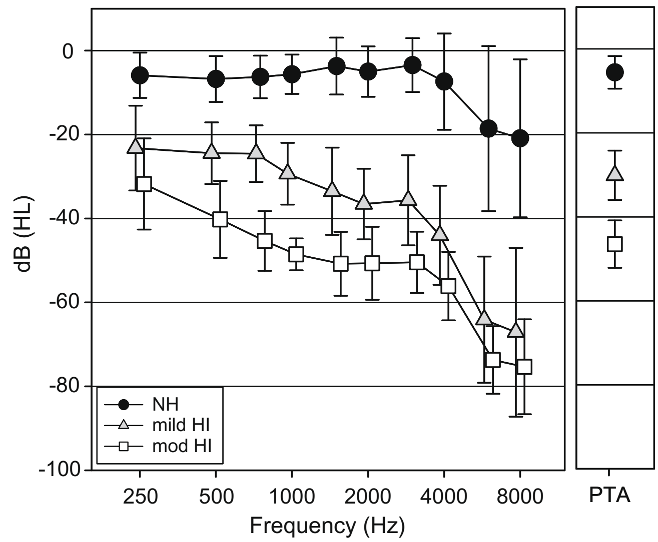

Fig. 1. Average audiometric thresholds for each subject group shown as a function of frequency. The right panel shows the average PTA. Error bars denote one standard deviation.

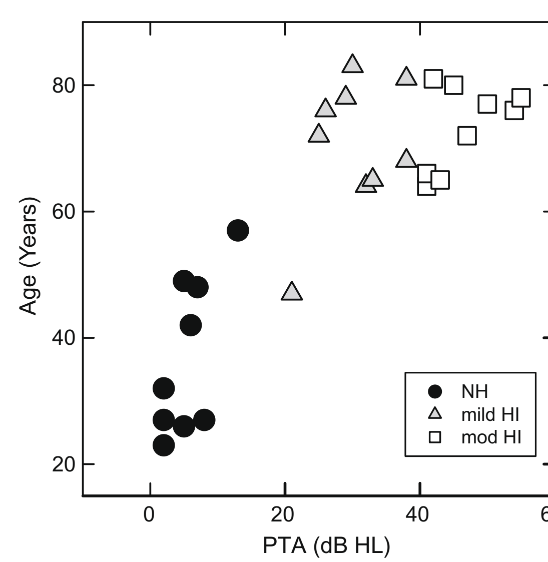

Fig. 2. Listener age shown as a function of listener PTA.