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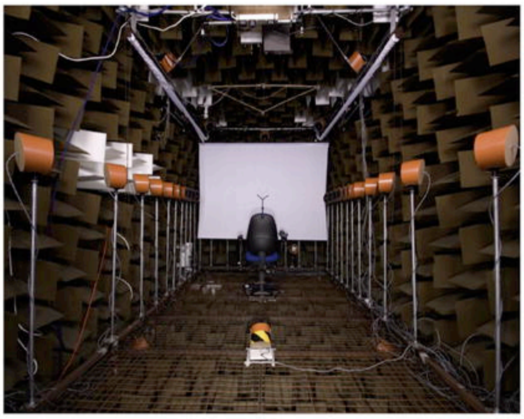

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Research paper

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

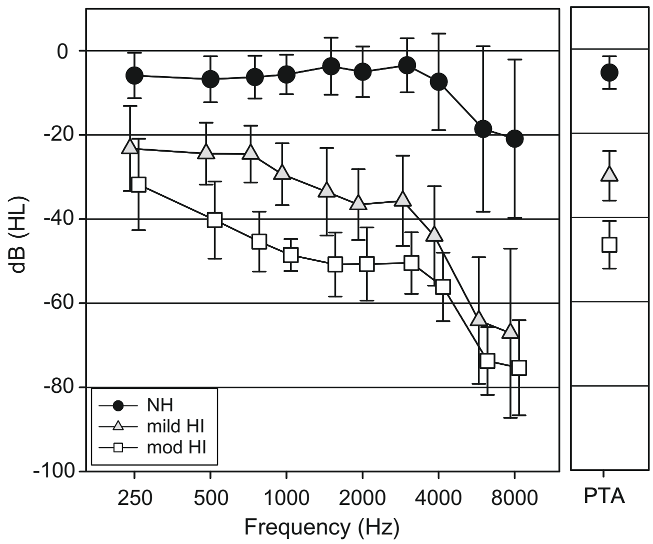


Fig. 1. Average audiometric thresholds for each subject group shown as a function of frequency. The right panel shows the average PTA. Error bars denote one standard deviation.

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.

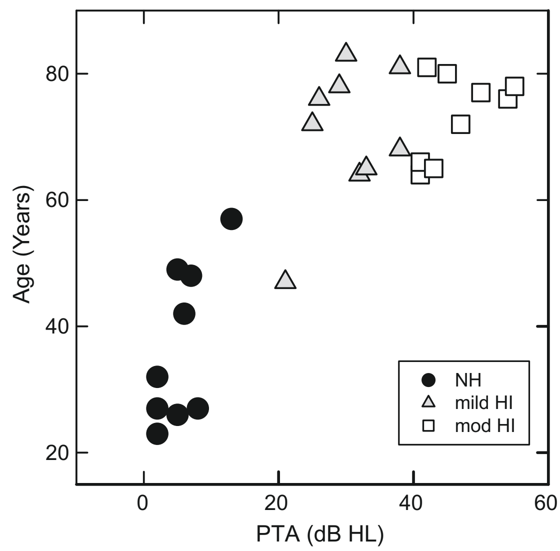
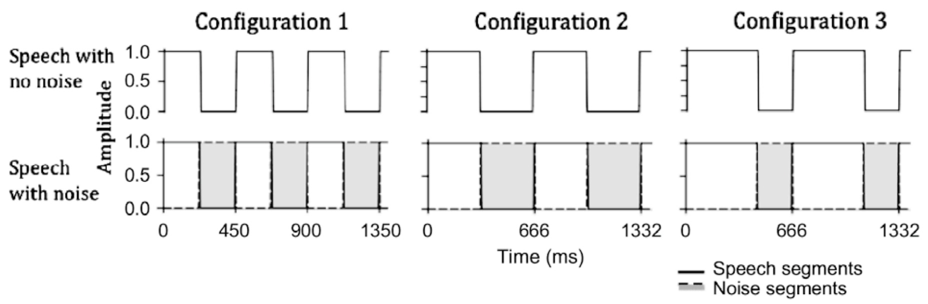


Fig. 2. Listener age shown as a function of listener PTA.



		Configuration 1	Configuration 2	Configuration 3
Interruption rate (Hz)		2.2	1.5	1.5
Speech duty cycle (%)		50	50	67
Speech duty cycle duration (ms)	ON	225	333	444
	OFF	225	333	222

Fig. 3. The interruption configurations. In the upper half, the top row shows the window sequence applied to speech while the bottom row shows the window sequence applied to speech-noise combination. The lower half lists numeric values for the configurations.

All listeners were fully informed about the study and written informed consent was collected before their participation. The study was carried out in accordance with the National Institutes of Health regulations and ethical guidelines on experimentation with human subjects.

2.2. Stimuli

Speech stimuli were digitized sentences, sampled at 22,050 Hz and spoken by a single male talker (Harvard IEEE corpus; IEEE, 1969; recorded by Galvin and Fu at the House Ear Institute). A speech-shaped steady noise was used as the filler noise. The noise was produced by first averaging the spectra of all speech stimuli and then randomizing the phase of the average spectrum (Oppenheim et al., 1999). All stimuli were processed digitally using Matlab.

2.2.1. Interruption configurations

Periodic interruptions were introduced by multiplication of the stimuli with a sequence of square windows alternating with silence. Fig. 3 presents the interruption configurations used in the experiment, along with interruption rates and speech duty cycles. The rise/fall time of the windows was 5 ms, implemented with a cosine ramp. The first two configurations were selected based on robust PR effect observed with NH listeners previously (Powers and Wilcox, 1977; Başkent et al., 2009). A pilot study showed that the percent correct scores by moderate HI listeners were low with these configurations. To elevate their performance level, a third configuration with a similar interruption rate but a longer speech duty cycle was included in the experiment.

2.2.2. Presentation levels

For NH listeners, speech was presented at 65 dB SPL and noise was presented at three different levels of 65, 70, and 75 dB SPL. For HI listeners, these were the levels prior to amplification (explained in more detail in the next section). As a result, despite the varying absolute presentation levels, the signal to noise ratios (SNRs) were the same for all NH and HI listeners, at 0, −5, and −10 dB.

In the selection of SNRs, several considerations were taken into account. On one hand, for PR to take place, the noise level had to be high, sufficient to mask the interruptions in speech (Powers and Wilcox, 1977; Başkent et al., 2007; Başkent et al., 2009). On the other hand, if the noise level was too high excessive masking onto neighboring speech segments could occur. In addition, as a result of amplification, the noise could also be uncomfortably loud for HI listeners. The range of SNRs was then selected for both maximum PR benefit and optimal listening comfort.

2.2.3. Amplification

The best presentation level for each HI listener was determined by a linear amplification prescription, the half-gain rule (Lybarger, 1944, 1963), combined with a final volume adjustment. The half-gain rule states that the dB gain at each frequency should be half of the hearing loss (in dB HL) at that frequency. It is not known yet which speech frequencies or cues are most important for PR (Divenyi, 2005; Kewley-Port et al., 2007), and therefore we chose this simple amplification with no further spectral shaping or bandwidth limiting. As a result of this choice, however, the intensity of speech increased at a wide range of frequencies, producing stimuli with substantial energy and loudness. For comfortable listening, therefore, one final volume adjustment was necessary after the half-gain rule. An interrupted sentence from the IEEE database was played in a loop, alternating between the conditions of no noise and loudest noise and thereby providing the listener the maximum range of loudness that would be encountered during data collection. Listeners were instructed to adjust the volume to make the speech audible at a comfortable or slightly loud level while keeping the noise level tolerable.

2.3. Experimental procedure

Processed stimuli were presented diotically in a sound-proof booth using the Tucker-Davis Technologies System III (RP2 processor, HB7 headphone buffer, and PA5 programmable attenuator) and Sennheiser HD 580 headphones. The system was calibrated measuring the spectrum level of a white noise at the output of the headphone using an artificial ear coupler (see Başkent et al., 2009, for further details). During processing, the maximum dynamic range without distortions was used, and the final level adjustment was made with a programmable attenuator immediately before playback.

With many HI listeners a repeat audiogram and a quick reassessment of inclusion criteria were administered prior to data collection. In addition, each listener was given a short training of 10–20 min. The listening conditions used during training were similar to, but not the same as, the actual experimental conditions. During

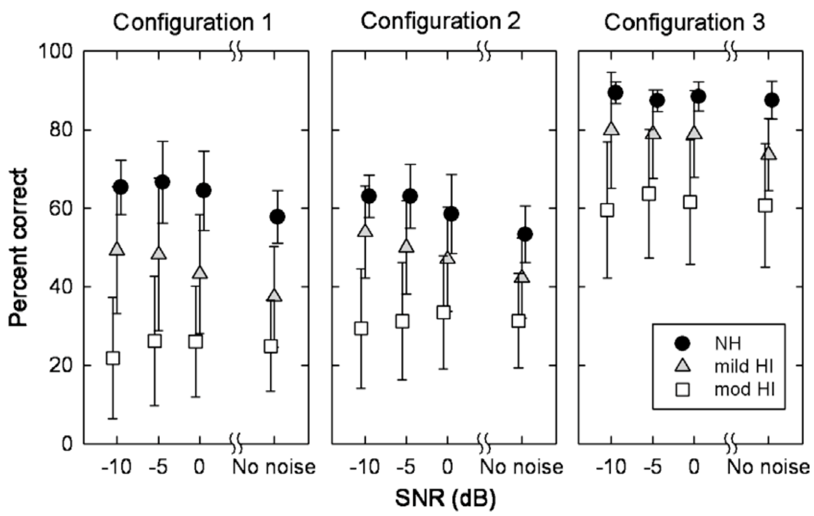


Fig. 4. Group-averaged percent correct scores, shown as a function of the noise condition. Panels show the scores with different interruption configurations (indicated above the panel). The error bars denote one standard deviation.

training after each response listeners heard the original unprocessed sentence as feedback.

The overall procedure for training and data collection was as follows: Listeners were presented with interrupted sentences, either with silent intervals or combined with gated noise. The listener's task was to repeat as many words as possible and guessing was encouraged. The experimenter marked the correctly identified words on the monitor using a Matlab Graphical User Interface.

In a single run, all 12 conditions ([speech with no noise and speech with noise at 3 different levels] × 3 interruption configurations) were tested in random order. A list of 10 sentences was used for each condition, producing 120 trials for each run. There were four runs in total. Percent correct score for each condition in each run was calculated by the ratio of the number of correctly identified words to the number of total words in the sentence list. The final percent correct score was the average from the four runs for each listener. The order of sentence lists was randomized for each listener. No sentence was played more than once to the same subject. Each run was completed in about 25–35 min.

The listeners were able to finish the entire experiment, including repeat audiograms, training, and data collection, in 1–2 sessions, with a total duration of 2.5–4 h. With many NH listeners there was no need for a repeat audiogram. These listeners also tended to complete the tests faster and they needed less or shorter breaks than HI listeners. As a result, six NH listeners were able to finish the experiment in one session, while only one moderate HI listener was able to do so. For all listeners, there was 1 week or less time between the two sessions except for one mild HI listener for whom this period was 2 weeks. In general, the testing patterns differed between NH and HI listeners, but they were similar between the subgroups of mild and moderate HI listeners. Hence, if the procedural differences contributed to the results, that could have happened only between NH and HI listeners, and not between mild and moderate HI listeners.

3. Results

3.1. Comparison of group data

Fig. 4 presents the group-averaged percent correct scores for recognition of interrupted speech, with or without filler noise, with different interruption configurations. Note that while the absolute presentation levels varied across subjects, the SNRs did not. Therefore, results are shown as a function of SNR.

There was a strong effect of hearing loss on overall performance. The average scores were highest with the NH group and lowest with the moderately HI group. Furthermore, there was a noise effect, which depended on hearing loss. The scores by NH and mild HI listeners seemed to increase with the addition of noise, suggesting a PR benefit. No such effect was observed with the moderately HI listeners. Three analyses of variance (ANOVAs), one for each configuration, were conducted with one between subject factor (subject group) and one within subject factor (SNR). We decided to not use the configuration as a third factor because we were concerned that the ceiling performance of NH listeners in configuration 3 would result in an artificial 3-way interaction. For all three interruption configurations, as Table 1 shows, both main effects were significant. So was the interaction between the factors, supporting the observation that the change in performance due to the filler noise was not the same across subject groups.

By taking the difference between the scores with noise and those without, the average benefit from PR was calculated for each condition. Hence, when positive a PR score implies an improvement in performance with the addition of noise. With these scores, Fig. 5 provides a clearer picture of how PR benefit differed between the three subject groups. NH and mild HI listeners had similar positive PR scores for most interruption configurations and most SNRs, while moderate HI listeners had PR scores close to 0%. The statistical significance was evaluated with post hoc Tukey multiple comparisons where the scores with and without noise were compared within each subject group and for a fixed SNR. The PR advantage was significant with NH and mild HI listeners with configurations 1 and 2 at SNRs of −5 and −10 dB. The PR benefit with configuration 3 was significant with mild HI listeners only. This configuration has longer speech duty cycle and therefore, the performance by NH listeners was at ceiling, leaving no room

Table 1
F values from a two-way mixed ANOVA applied to data presented in Fig. 4.

	Configuration 1	Configuration 2	Configuration 3
Factor (between subject):			
Subject group $F(2, 24)$	21.81[b]	14.99[b]	12.66[b]
Factor (within subject):			
Noise level $F(3, 6)$	7.05[b]	12.30[b]	3.20[a]
Interaction:			
$F(6, 72)$	2.87[a]	5.60[b]	2.55[a]

[a] $p < 0.05$.
[b] $p < 0.001$.

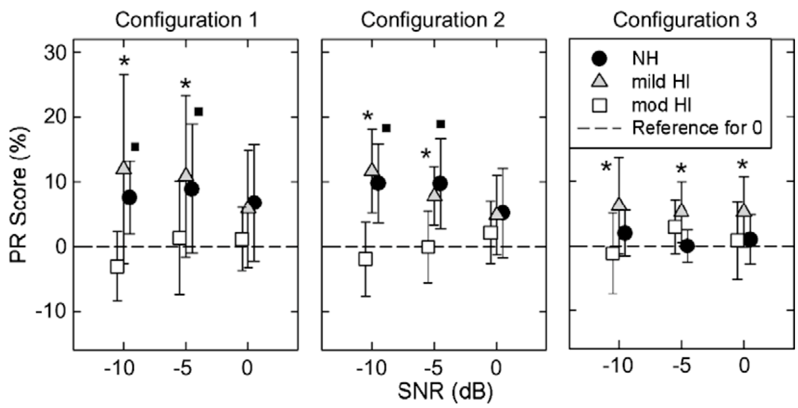


Fig. 5. Phonemic restoration scores, averaged for each subject group and shown as a function of the noise condition. These were calculated from the scores in Fig. 4. The dashed line indicates 0%, at and below which there is no benefit from PR. The asterisk and square symbols on top of the average scores indicate significant PR effect ($p < 0.05$) with NH and mild HI listener groups, respectively.

for further PR improvement. With moderately HI listeners, contrary to the NH and mild HI listeners, no significant PR effect was observed for any interruption configuration and any SNR.

3.2. Analysis of data for effects of hearing impairment and age

To further explore the effects of hearing impairment and age, scores were pooled from all HI listeners and a multiple regression analysis with forward stepwise regression was applied. The independent variables were PTA and age and the dependent variable was PR performance. We also included SNR and interruption configuration as two additional independent variables, to ensure that the trend in data was similar across these and the scores could safely be pooled.

The analysis showed that both PTA ($p < 0.001$) and age ($p < 0.01$) were strong predictors of the PR benefit (combined $R^2 = 0.247$, $p < 0.001$). The forward stepwise regression produced the following final regression equation that accounted for most variation in data:

$$\text{Pooled HI PR scores} = 30.781 - (0.349 * \text{PTA}) - (0.187 * \text{Age}) \quad (1)$$

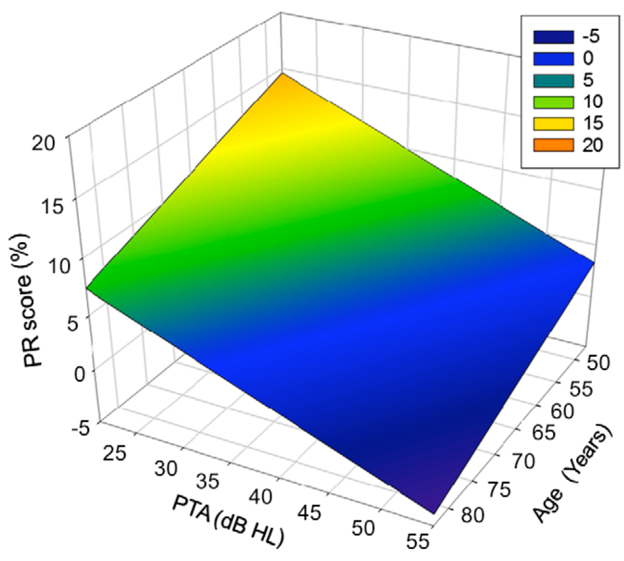


Fig. 6. The plane defined by the regression model in Eq. (1).

Fig. 6 shows the plane defined by Eq. (1). Note that this model is only meaningful within the limits of the two main independent variables, that is, 47–83 years for age, and 21–55 dB HL for PTA. The regression model implies that the most PR benefit would be expected with younger HI listeners with milder hearing loss, and the least with elderly listeners with severer hearing loss.

3.3. Analysis for audibility

The presentation levels of the present study were determined by HI listeners' preferences, to simulate real-life listening levels. This procedure, therefore, ensured comfort, but audibility was not necessarily maximized. Therefore, a separate analysis was conducted for this factor alone.

As a metric for audibility, we used the articulation index (AI) based on the formula published by American National Standards Institute (ANSI S3.5, 1997). The AI can be between 0.00 and 1.00, a value indicating the proportion of speech energy above hearing thresholds. In the calculations, listeners' audiometric thresholds at frequencies between 250 and 6000 Hz and the final presentation level of speech at the eardrum were used (Pavlovic, 1991). Root-mean-square speech spectrum was analyzed with 1/3rd octave frequency bands, and the band importance function from Table 3 (ANSI S3.5, 1997) was applied. Additional level-related adjustments were made by including level distortion factor, upward spread of masking, and self-speech masking.

Fig. 7 replicates the PR scores by HI listeners, this time plotted as a function of AI. As a reference, the average PR score by NH listeners was also included, at the average and almost perfect AI of 0.98 (without configuration 3 due to the ceiling effect). When scores from all HI listeners were combined and analyzed together, the importance of audibility became apparent from two observations: (1) PR scores were closer to 0% when AI was low (lower than about 0.60), implying that a certain amount of audibility seems to be necessary for PR. (2) There was a significant correlation between AI and PR ($r = 0.428$, $p < 0.001$, by Pearson Product Moment Correlation), as indicated by the solid regression line in Fig. 7. Next, data were analyzed for subject groups separately. For mild HI listeners, PR and AI were significantly correlated ($r = 0.426$, $p < 0.001$, regression indicated by the long-dashed line). These listeners seemed to take full advantage of increasing audibility and therefore would be expected to benefit from PR as long as adequate audibility was provided. For moderate HI listeners, on the other hand, there was no correlation between PR and AI ($r = -0.0232$, $p = 0.837$, regression indicated by the short-dashed line). These listeners did not seem

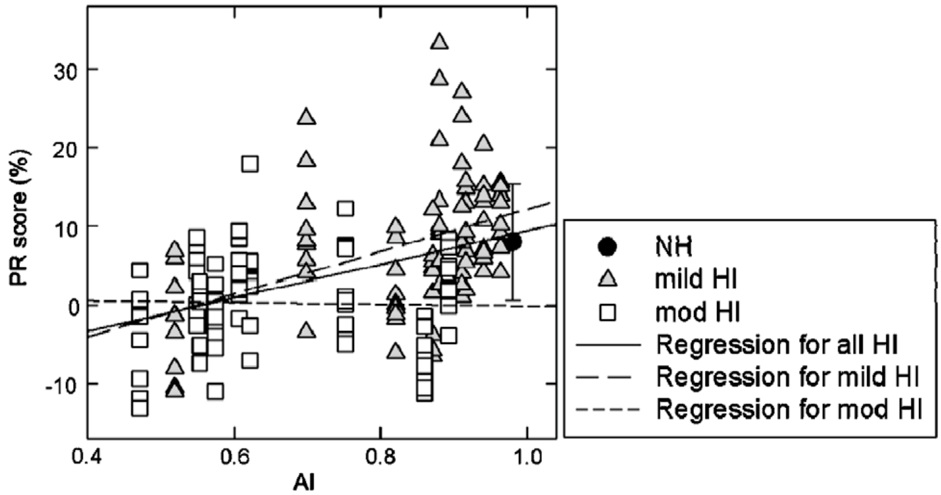


Fig. 7. Phonemic restoration scores by HI listeners, pooled from all interruption configurations and SNR levels and shown as a function of AI. The average score from NH listeners is included as a reference.

to take advantage of increasing audibility; even when AI was high (0.70–0.90), PR with these listeners was minimal.

4. Discussion

In the present study, we hypothesized that hearing impairment, usually accompanied by advanced age, may reduce PR benefit. Quantitative measurements of PR with listeners who varied in age and hearing loss supported the hypothesis. Listeners with mild hearing impairment had similar benefit from PR to the NH control group while listeners with moderate hearing impairment had significantly lower benefit than either group. We assume that PR is related to the intelligibility of speech in complex listening environments, where the listener has to continually and actively fill in for inaudible parts of speech (Warren, 1983, 1984; Kashino, 2006). It follows, then, the findings of the present study are crucial for further identifying the underlying deficiencies that contribute to difficulties encountered by HI listeners understanding speech in such environments.

4.1. Potential factors reducing PR with moderate hearing loss

As both bottom-up and top-down processes of the auditory system are important for PR (Samuel, 1981a,b; Elman and McClelland, 1988; Trout and Poser, 1990; Repp, 1992), degradations in the bottom-up cues—due to hearing impairment, inadequate audibility, and/or age—and the top-down mechanisms—mostly due to age—could reduce the PR benefit. The factors relevant to the present study, namely hearing impairment and age, are discussed as follows.

4.1.1. Hearing impairment

The group-averaged PR scores by mild and moderate HI listeners differed significantly, indicating the effect of hearing impairment. While mild HI listeners seemed to benefit from PR in general, no PR benefit was observed with moderate HI listeners. In the present study, only the PTA was used in categorizing mild and moderate hearing impairment (Table 5.4, Katz et al., 2002). A PTA between 21 and 40 dB HL was deemed a mild hearing loss while a PTA higher than 40 dB HL was deemed a moderate hearing loss. This simple separation was sufficient to observe a significant difference in the average PR benefit; hence, the degree of hearing loss, with or without other factors, seems to have a strong effect.

Hearing impairment poses an audibility problem due to elevated thresholds, which could be corrected to a degree by proper amplification. It can additionally result in suprathreshold deficits, such as reduced frequency and/or temporal resolution, which could cause distortions in the bottom-up cues (Plomp, 1978, 1986). Moore (1996) suggested that for hearing impairment up to 45 dB HL, a value close to the PTA that we used for separating mild and moderate hearing loss, audibility is the most important factor for speech perception. For more severe losses the importance of suprathreshold deficits increases (Florentine, 1980; Nelson and Freyman, 1987; Nelson, 1991). These statements are consistent with our data. Mild auditory impairment did not prevent PR benefit—in fact, Fig. 5 shows that in some conditions mild HI listeners had slightly better scores than NH listeners. There were likely no suprathreshold deficits with these listeners and restoring audibility with simple linear amplification was sufficient to achieve PR. Alternatively, even if there were some bottom-up degradations due to cochlear pathology, they could be subtle enough to be compensated by the top-down processes, such as with increased use of cognitive resources and effort (Rabbitt, 1966; Schneider and Pichora-Fuller, 2000; Zekveld et al., 2007). Moderate auditory impairment, on the other hand, seemed to strongly and negatively affect PR benefit. Degradations in bottom-up cues, such as reduced speech information due to excessive masking from noise segments or distortions in speech representation extracted from speech segments, may have been too severe to be compensated by simple linear amplification and/or use of top-down mechanisms (Schneider et al., 2007; Akeroyd, 2008).

4.1.2. Combined effects of hearing impairment and age

A multiregression analysis of pooled data with the independent variables of hearing impairment (PTA in dB HL) and age (in years) showed that both factors together were strong predictors for PR. Multiregression analysis assumes a linear relationship while the interaction between these factors could have been complex and nonlinear. However, this trend at least implies a (negative) monotonic relationship. A higher degree of hearing loss and older age are highly correlated with lower PR scores.

Age alone could have both negative and positive effects on PR. Bottom-up and top-down processing could be negatively affected due to reduced temporal acuity and/or cognitive skills (Bergman et al., 1976; Gordon-Salant and Fitzgibbons, 1993; Tun, 1998; Wingfield et al., 2005). On the other hand, elderly listeners could partially compensate for these deficiencies by an increased effort and more reliance on their advanced linguistic knowledge stored in long-term memory (Wingfield et al., 2005; Wingfield and Tun, 2007; Pichora-Fuller, 2008). Data in literature on how PR changes as a function of age are at best limited. Madix et al. (2005) and Başkent et al. (2009) observed no effect of age when PR was measured with NH listeners, however, the majority of these listeners was younger than 60 years old. It is possible that an age effect would appear if a wider range of ages was included.

Hearing impairment and age together may have an interactive effect on PR. On one hand, when listeners have deficits from both advanced age and hearing impairment, the negative effects from each factor could be magnified. Compensation of bottom-up degradations with the help of cognitive skills could be more difficult (Pichora-Fuller et al., 1995; Tun and Wingfield, 1999; Schneider et al., 2007). On the other hand, additional compensation may come from increased effort and higher reliance on linguistic knowledge by the elderly (Wingfield and Tun, 2007; Pichora-Fuller, 2008). To our knowledge, there is no study that systematically explored the effects of hearing impairment and age specifically on PR. The most relevant studies are on other ASA-related tasks, such as stream segregation with tone patterns (Bregman et al., 1999), and the results have been mixed. Mackersie et al. (2001) observed that the stream segregation ability of elderly HI listeners (10 out of 11 were older than 65 years old) was different from that of young NH listeners (all younger than 41 years). In contrast, Valentine and Lentz (2008) observed no difference between NH and HI listeners who matched in age and were all younger than 65 years old. Grimault et al. (2001) mentioned the possibility of aging and hearing impairment jointly leading to a decreased ability of stream segregation. Even though there is a considerable step from stream segregation with simple stimuli to speech understanding in complex environments, it is possible that advanced age and moderate levels of hearing impairment have similar effects on most mechanisms related to ASA, including PR (Schneider et al., 2007).

Note that our results showed that hearing impairment and age could together affect PR negatively, but they did not identify exactly what degradations (sensory or cognitive?) and what reduced functions (extracting sufficient speech information from speech glimpses during noise gaps, object formation, synthesis of phonemes with linguistic skills?) caused this effect. To identify these factors in such detail would require extensive testing of individual listeners and running correlation analyses similar to ones reported by Jerger et al. (1991) and Divenyi and Haupt (1997).

Overall, the present results combined with previous work suggest that PR ability seems to be preserved up to mild levels of hearing loss and/or 7th decade of life. As the degree of hearing impairment and/or age increase, so do the likelihood of degradations in bottom-up and/or top-down processes. Top-down processes could potentially compensate for degraded bottom-up cues, if the degradations are small. But if either mechanism is severely damaged or if both mechanisms are degraded, PR ability may diminish.

4.2. Audibility and amplification

Audibility is an important factor affecting speech recognition by HI listeners in general. As extracting speech information during the noise gaps may be compromised with reduced audibility (Nelson et al., 2009), it could also potentially affect PR benefit. In the present study, realistic and comfortable presentation levels were used and as a result audibility varied across the listeners (Fig. 7). Therefore, the scores were analyzed separately for this factor alone.

A metric, AI, was used for characterizing the audibility effect on PR performance. When the scores from all HI listeners were included in the analysis, there was a positive correlation between AI and PR scores—an expected finding as a natural consequence of varying amounts of speech information available to the listener (Bashford and Warren, 1979; Verschuure and Brocaar, 1983). When the analysis was repeated with data from the subgroup of mild HI listeners only, a positive correlation was observed. Hence, as long as audibility was provided, mild HI listeners were able to benefit from PR. In contrast, with the subgroup of moderate HI listeners, no correlation between AI and PR scores was observed. Even listeners with high AI measures—indicating proper amplification—did not seem to benefit from PR. For these listeners, factors other than audibility seem to have contributed to the results, limiting the benefit from PR. As mentioned in Section 1, PR ability could be related to speech understanding in noisy and complex listening environments. In previous studies, HI listeners, especially with moderate levels of hearing loss and/or advanced age, were observed to have lower speech intelligibility scores in such listening environments than what would be predicted from audibility only (Plomp, 1978; Bacon et al., 1998; Killion, 2002; Başkent, 2006; Dubno et al., 2008). In the present study, we similarly observed lower PR benefit than what would be predicted from audibility only, but only for moderately HI listeners.

4.3. Implications for hearing aids

The AI analysis showed the importance of audibility for PR benefit. With the potential relationship between PR ability and understanding speech in noisy environments, then, a proper HA fitting that maximizes PR could be crucial.

In the present study we used linear amplification while many modern HAs provide compressive amplification. The reason for this choice was that this study was the first to provide baseline PR data with HI listeners, and compressive prescriptions could have had unexpected effects due to their nonlinear nature (Edwards, 2004). Başkent et al. (2009), for example, showed that alterations in speech envelope due to release time constants of amplitude compression could potentially affect PR with NH listeners, an observation that could very well apply to HI listeners. On the other hand, compression could be useful in maximizing speech audibility by fitting the entire speech dynamic range into the listener's limited dynamic range. A small advantage with fast multichannel compression over linear amplification was seen for release from masking (Moore et al., 1999). If this finding is due to better audibility of speech during low levels of noise, a similar enhancement could be observed for PR.

In general, the results of the present study, combined with previous ASA studies with HI listeners, provide guidelines for potential improvement of HAs. Even though the main purpose of HAs has been to amplify sounds and increase the audibility, the technology in today's HAs has the capability to do much more than that. A number of approaches based on ASA have been proposed for front-end processing to help segregation (Kates, 1995; Nordqvist and Leijon, 2004; Büchler et al., 2005; Roch et al., 2007; Wang, 2008), however, these are rarely used in commercial HAs and success has been limited in real-life listening conditions. New information from studies similar to the present one is needed to develop new sophisticated algorithms.

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