Phonemic restoration in sensorineural hearing loss does not depend on baseline speech perception scores

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Abstract: The brain can restore missing speech segments using linguistic knowledge and context. The phonemic restoration effect is commonly quantified by the increase in intelligibility of interrupted speech when the silent gaps are filled with noise bursts. In normal hearing, the restoration effect is negatively correlated with the baseline scores with interrupted speech; listeners with poorer baseline show more benefit from restoration. Reanalyzing data from Başkent *et al.* [(2010). Hear. Res. **260**, 54–62], correlations with mild and moderate hearing impairment were observed to differ than with normal hearing. This analysis further shows that hearing impairment may affect top-down restoration of speech.

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1. Introduction

The brain has the ability to fill in for missing parts of speech, using linguistic rules, context, and expectations (Warren, 1970; Warren *et al.*, 1997; Davis and Johnsrude, 2007). The effect of this top-down phonemic restoration is commonly shown by the enhancement in intelligibility of interrupted speech when the silent intervals are filled with loud noise bursts (Powers and Wilcox, 1977; Verschuure and Brocaar, 1983; Bashford *et al.*, 1992). Filling the gaps with noise produces the illusionary perception of continuity and facilitates restoration, which increases intelligibility under some conditions. Using this method, Başkent *et al.* (2010) have recently shown that phonemic restoration benefit is minimal or not existent at moderate levels of sensorineural hearing loss. The implication of this finding is that degradations in speech signals due to the peripheral sensory deficit make the top-down restoration difficult.

In addition to the main finding on restoration benefit, there was also a large variation in baseline scores with interrupted speech across listeners with varying levels of hearing impairment, as was shown by the average scores in Fig. 4 of Başkent *et al.* (2010). The individual baseline scores pooled from all listeners are shown in Fig. 1, upper panel, as a function of hearing impairment [shown in pure-tone average in dB HL, the average of the thresholds at the audiometric frequencies of 500, 1000, 2000 Hz; Katz and Gabbay (1994)] and for three interruption configurations (with slow interruptions at 1.5 to 2.2 Hz). Overall, there were strong and significant negative correlations between intelligibility of interrupted speech and the degree of hearing loss. With normal hearing listeners, Verschuure and Brocaar (1983; Figs. 3 and 4) had observed that there was a negative correlation between baseline performance with interrupted speech and the benefit from restoration. By this observation, hearing-impaired listeners should have benefitted more from restoration due to their lower baseline performance, but the data by Başkent *et al.* indicated otherwise.

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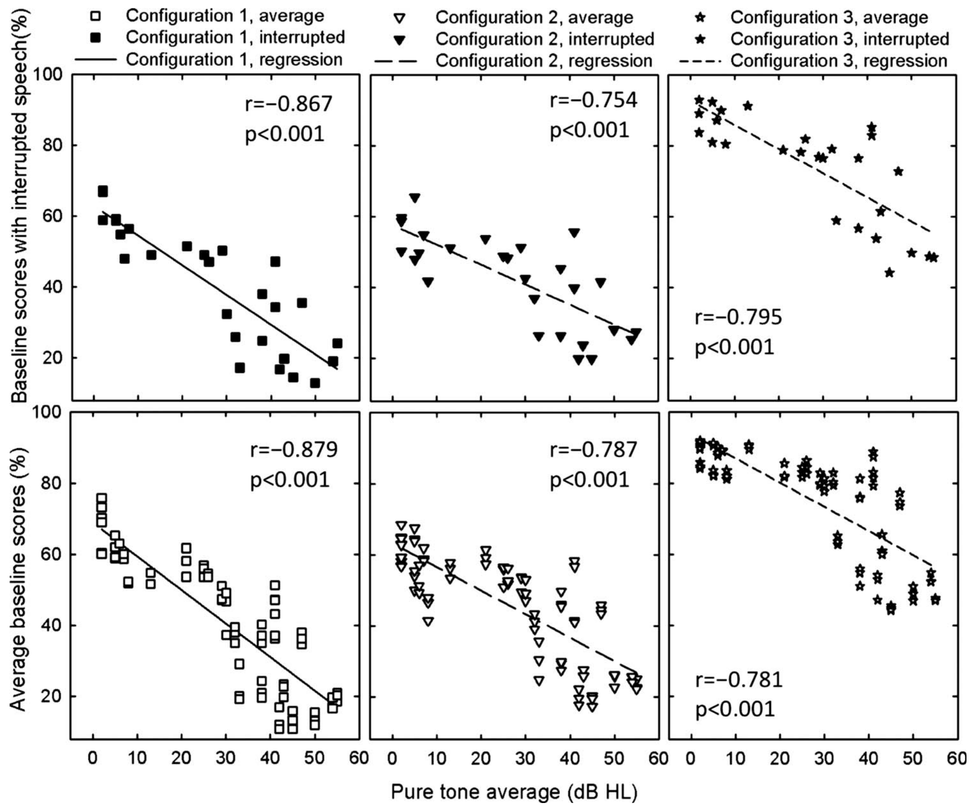

Fig. 1. The upper panels show the individual scores for intelligibility of interrupted speech with no filler noise, taken from the study reported by Başkent *et al.* (2010) and pooled for all listeners, shown as a function of listener's pure tone average. The lower panels show the individual intelligibility scores averaged from conditions with and without the filler noise. The panels from left to right show the scores for three different interruption configurations: (1) Interruption rate of 2.2 Hz, 50% duty cycle. (2) Interruption rate of 1.5 Hz, 50% duty cycle. (3) Interruption rate of 1.5 Hz, 67% duty cycle. These configurations produced speech on and off times of 225/225 ms, 333/333 ms, and 444/222 ms, respectively. Regression lines are superimposed with the individual scores and the correlation coefficients (by Pearson Product Moment) are indicated in each panel.

In this paper, we re-analyzed the individual scores for interrupted speech (with and without the filler noise) and restoration benefit from Başkent *et al.* (2010), to establish the correlations between the two. Based on previous studies, our hypothesis was that the negative correlation observed with normal hearing would not be observed with hearing impairment, further indicating a change in top-down restoration due to the sensory degradations in speech signals.

2. Methods

2.1 Participants

The participants in Başkent *et al.* (2010) were twenty-seven native speakers of American English; nine normal-hearing listeners, between the ages of 23 and 57 years (average 37 years), nine mildly hearing-impaired listeners, with pure tone averages between 21 and 40 dB HL and between the ages of 47 and 83 years (average 70 years), and nine moderately hearing-impaired listeners, with pure tone averages between 41 and 55 dB HL and between the ages of 64 to 81 years (average 73 years). All listeners were fully informed about the study and the written consent was collected before participation.

2.2 Stimuli

Speech stimuli were IEEE sentences (IEEE, 1968) spoken by a male speaker and recorded at the House Ear Institute by John Galvin and Qian-Je Fu. The filler noise was a steady speech-shaped noise, produced from the long-term speech spectrum of the sentence recordings.

2.3 Methods

The method employed in the previous study involved periodic interruptions that were applied to the sentences by modulating the stimuli with a square-wave envelope. A 5-ms raised cosine at the onset and offset of the speech segments prevented spectral splatter distortion. The three configurations used in the study are described in Fig. 1 caption.

The listeners were seated in a soundproof booth. Stimuli were presented diotically using Tucker Davis Technologies System III and Sennheiser HD 580 headphones. Speech was presented at 65 dB SPL, and the noise filler was presented at 65, 70, and 75 dB SPL. Stimuli were amplified for hearing-impaired listeners, based on the individual audiometric thresholds and applying the half-gain rule and a final volume control.

A Matlab program was used for signal processing and playback of the stimuli. A short tone was played before each sentence for alert. The listeners heard one sentence at a time and repeated what they heard, even if they had to guess or if they could understand only one word. The experimenter, seated outside the booth, marked the correctly identified words. For each interruption configuration ($\times$3 levels) and each noise level ($\times$4 levels, including no noise with baseline interrupted sentences), 10 sentences were used. Each run, thus, had 12 conditions, producing 120 trials. The order of the conditions was randomized within each run. Each run was repeated 4 times, producing 480 trials in total for each listener. No sentence was repeated and no feedback was provided.

3. Results

Verschuure and Brocaar (1983) observed a strong negative correlation between the baseline intelligibility scores with interrupted speech and the restoration benefit ($r=-0.93$, $p<0.001$) with normal-hearing listeners. This correlation, however, could have been overly estimated, because the restoration benefit is the difference between the scores with and without the filler noise, and the restoration scores would therefore be mathematically coupled with the baseline scores with interrupted speech. To reduce this effect, Oldham (1962) proposes establishment of the correlations between the difference scores (restoration benefit scores) and the averaged scores from the two measurements (baseline scores with and without the filler noise). Therefore, in the correlation analyses, we have used both baseline scores. The baseline scores with interrupted speech denote the scores with interrupted speech with no noise, and the average baseline scores denote the scores averaged from the conditions with and without the filler noise.

First, the negative correlation observed by Verschuure and Brocaar (1983) for the baseline scores with interrupted speech had to be confirmed for the average baseline scores. For this purpose, the individual scores were digitized from a scanned version of Fig. 3 using GetData graph digitizer software. Similar to the correlations with the interrupted speech, the correlation of the restoration scores with the average baseline scores was also negative and significant ($r=-0.76$, $p<0.001$).

Second, we also confirmed that the average baseline scores were negatively correlated with increasing hearing impairment, similar to the baseline scores with interrupted speech (Fig. 1).

Next, the correlations between the restoration scores and both versions of the baseline scores were analyzed for the data from Başkent *et al.* (2010). Figure 2 shows the phonemic restoration scores as a function of baseline scores for individual listeners. The upper and lower panels show the results for the baseline scores with interrupted speech and for the average baseline, respectively. The panels from left to right show the scores for normal-hearing, mildly hearing-impaired, and moderately hearing-impaired listeners. In each panel, all scores were first averaged from four runs and then pooled for all configurations and noise levels. The regression

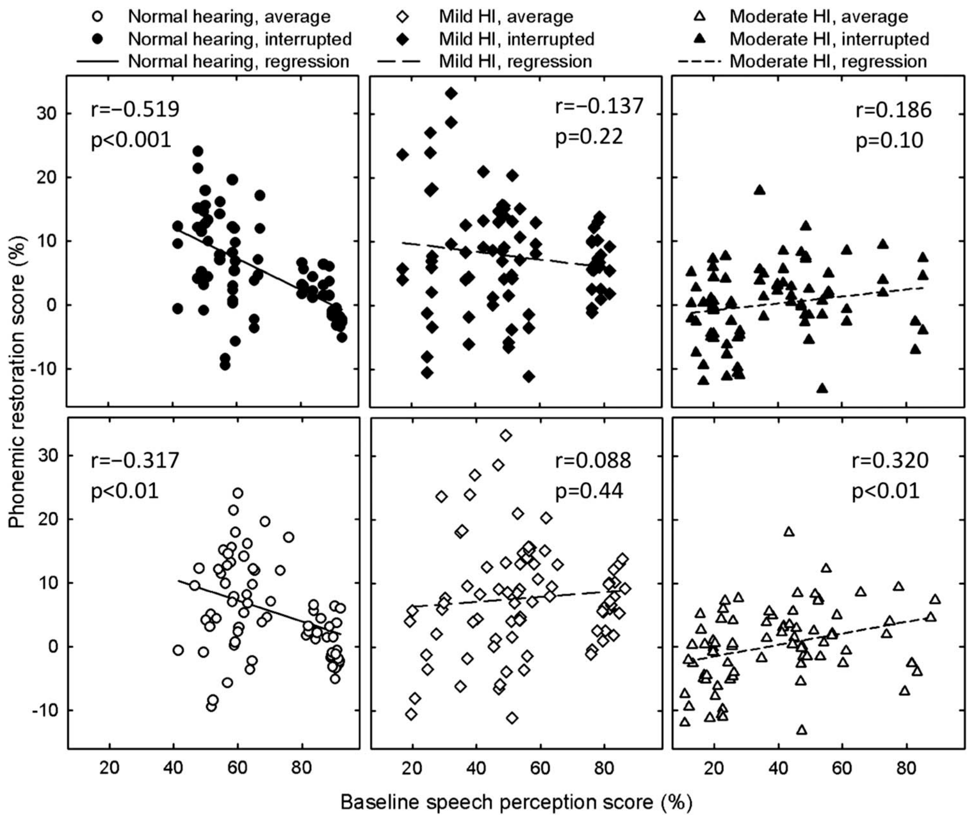

Fig. 2. Individual phonemic restoration scores, shown as a function of the baseline intelligibility scores with interrupted speech (upper panels) and the average baseline scores (lower panels). The panels from left to right show the scores for normal-hearing, mildly hearing-impaired, and moderately hearing-impaired listeners. Regression lines are superimposed with the individual scores and the correlation coefficients (by Pearson Product Moment) are indicated in each panel.

lines are shown and the Pearson Product Moment correlation coefficients and the significance levels are listed. Contrary to the moderate and significant negative correlation between baseline and restoration scores observed with normal hearing (left panels), no significant correlation was observed with mild hearing impairment (middle panels), and a positive correlation was observed with moderate hearing impairment, which was significant for the average baseline scores (right panels). A linear regression analysis with the additional covariate of hearing impairment confirmed a significant difference in correlations across the listener groups ($F=13.69$, $p<0.001$ and $F=10.49$, $p<0.001$, for upper and lower panels, respectively).

Figure 2 also shows that the range of the baseline scores varied substantially between the participant groups, and different groups were operating on different points of psychometric functions. For a comparison of normalized baseline scores, the correlation analysis was repeated for a selected subset of scores. For this purpose, the largest range of baseline scores, where scores from all three groups co-existed, was selected for both versions of the baseline scores. The selection reduced the number of data points from 81 in each group to 60, 57, 28, and 63, 60, 36, for normal-hearing and mildly and moderately hearing-impaired groups, respectively, and for upper and lower panels of Fig. 2, respectively. Figure 3 shows the restoration scores as a function of the selected baseline scores in a format similar to Fig. 2.

Figure 3 shows that when baseline performance levels were equated across listener groups the trends in correlations stayed the same for the baseline scores with interrupted speech (upper panels), but they differed for the average baseline scores (lower panels). With the base-

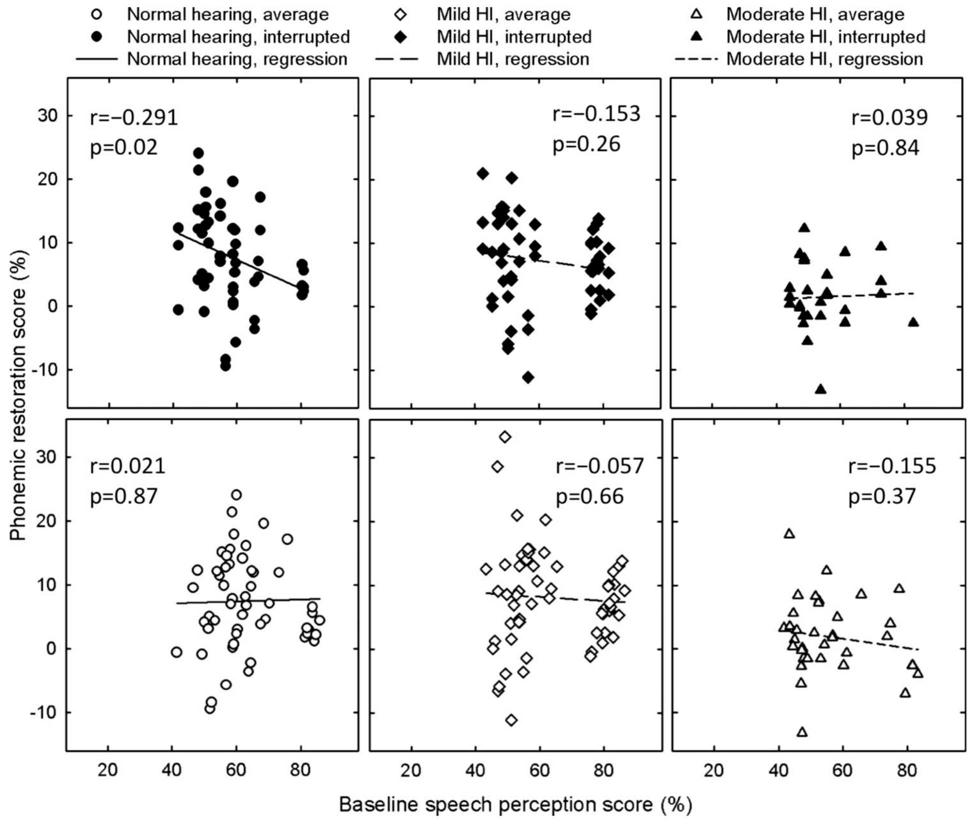

Fig. 3. Similar to Fig. 2, except shown for a subset of the scores. This selection ensured that the range of baseline scores were the same across all three listener groups for each version of the baseline scores.

line scores with interrupted speech (upper panels), there was again a significant negative correlation for the normal-hearing listeners, while there was no correlation for the mild and moderate hearing-impairment groups, and the correlations differed significantly ($F=7.66$, $p=0.001$). With the average baseline scores (lower panels), the strong correlations observed in Fig. 2 have disappeared and the trends in correlations changed. However, the correlations were still significantly different across listener groups ($F=4.96$, $p<0.01$).

4. Discussion

In the present study, two versions of baseline scores were used; the baseline scores with interrupted speech without the filler noise, and the average baseline scores calculated from scores with and without the filler noise.

For normal-hearing listeners, both versions of the baseline scores and the phonemic restoration scores were negatively and significantly correlated. In agreement with findings by Verschuure and Brocaar (1983), listeners who had poorer intelligibility with interrupted speech showed a larger benefit from restoration. The restoration benefit and the correlations of the present analysis were weaker than those reported by Verschuure and Brocaar (1983), which could have resulted from methodological differences (such as in speech context and interruption rates).

In the report by Başkent *et al.* (2010) the baseline scores, shown in average values for each group, varied substantially between the three groups of participants. As the reanalysis of individual scores in Fig. 1 showed both versions of baseline scores in fact decreased as the hearing impairment increased. This figure implies that if the finding of Vershcuure and Brocaar with normal hearing held for hearing impairment, listeners with more hearing impairment would be expected to benefit more from restoration. However, the results in Başkent *et al.* (2010) showed otherwise; contrary to the expectation, the average restoration benefit in mild hearing impairment was similar to that of in normal hearing, and the restoration benefit in moderate hearing impairment was different than either group and negligible. The present correlation analysis with individual scores showed that the trends differed between all three groups. Overall, the new analysis of data from Başkent *et al.* (2010) further supports the idea that the degradations in speech signals caused by the damage in the peripheral system due to hearing loss may affect the top-down restoration of speech.

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