Introduction

The human auditory system is remarkably robust in adverse listening situations. Listeners can make use of available bottom-up cues and ‘restore’ the sounds masked by noise by making use of higher-order cues, like context and linguistic knowledge [1,2]. One form of this top-down restoration is ‘phonemic restoration of speech in noise’ [1,3,4]. Phonemic restoration is typically measured as the improvement seen in intelligibility of speech interrupted by silence when the silent interruptions are filled with noise instead [5-7]. It has been demonstrated with words and non-words [3] as well as with sentences [2,6-8] using discrimination [3], continuity [9], and intelligibility paradigms [2,4]. One hypothesis used to explain this improved speech perception ability is that introduction of noise in this paradigm may help the auditory system group speech and noise into different streams, resulting in a more continuous percept of speech [10]. The noise can also mask spurious cues introduced by interrupting continuous speech with silence, leading to an increase in ambiguity and a greater activation of lexical networks facilitating restoration [10]. The magnitude of restoration, however, is characterized by large individual variability [11,12].

It has been implied by many investigators that phonemic restoration, being an aspect of top-down restoration of speech, maybe an important part of listening in adverse listening sit-
sensitivity. However, the relationship between the two is not empirically clear. While it is well-known that speech perception in noise is affected in individuals with sensorineural hearing loss and in those rehabilitated with cochlear implants, phonemic restoration has also been reported to be reduced in these two groups [6,11,14] suggesting that speech in noise performance and phonemic restoration maybe positively correlated. On the other hand, speech in noise performance is affected in older subjects [15], but phonemic restoration magnitude seems to be larger than relative to younger subjects [7,16,17]. It may well be that the two processes may not be correlated at all and may represent two independent processes. Phonemic restoration in noise is thus multidimensional and seems to be dependent on a host of factors–both bottom-up and top-down.

It is an important tool since it connects envelope distortion in adverse listening situations, dip listening, and auditory scene analysis (difficulty to group silence-interrupted speech into one stream, and easier grouping in noise-interrupted speech), all in the context of speech perception. Clearly, more studies are needed to understand how speech in noise and phonemic restoration are related and how that knowledge can be used to improve perception in adverse listening situations. In this study, we measured speech perception in noise performance in the form of signal-to-noise ratio with 50% correct speech identification (SNR-50), the signal-to-noise ratio (SNR) required to achieve 50% speech intelligibility, and investigated its correlation with the magnitude of phonemic restoration of speech in noise at various SNRs in subjects with clinically normal hearing sensitivity.

**Subjects and Methods**

**Participants**

The study consisted of 20 native speakers (11 male and 9 female) with an age range of 40–55 years (mean=45.3 years). All the subjects had their thresholds within 15 dB HL over the frequency range (in octaves) of 250 Hz to 8,000 Hz for air conduction stimuli and between 250 Hz and 4,000 Hz for bone conduction stimuli. They had normal tympanometric findings, stapedial acoustic reflex thresholds, Transient evoked oto-acoustic emissions, and Auditory Brainstem responses. They also cleared the Screening Checklist for Auditory Processing in Adults [18]. None of them had a history of otological and/or neurological complaints. “Ethical Guidelines for bio-behavioral research involving human subjects” [19] was followed and the study was approved by the Institutional Review Board.

**Speech in noise perception**

Speech in noise measurement was measured using the sentence list developed by Geetha, et al. [20]. Each list consisted of 10 sentences, each with four keywords. The sentences were concatenated, the long-term power spectrum was calculated and was used to filter broad-band noise into a speech-shaped noise. The speech level was kept constant at 65 dB SPL and mixed with speech-shaped noise to produce a range of SNRs from -10 to +8 dB in 2 dB steps (10 SNR conditions in total). Each sentence list had one sentence at each of these SNRs. The order of SNRs in the lists was randomized. The sentences were routed through a personal computer and presented to the right ear using Sennheiser HDA 200 (Sennheiser, Wedemark, Germany) headphones, and subjects were instructed to listen to the stimuli and repeat what they heard in verbatim. They were encouraged to guess the words if they were not sure of what they heard. Subjects were familiarized with the procedure using a sentence list mixed at 5 dB SNR. The responses were scored online, but were also recorded for offline verification. Each keyword repeated correctly was awarded one point, and the total for each list was calculated. The SNR-50 was estimated based on the Spearman-Karber equation [21]. Two lists were used and the SNR-50 obtained in each list was averaged to calculate the final value.

**Perceptual restoration of sentences in noise**

Sentence lists developed by Geetha, et al. [20] were also used in this part of the experiment. The sentence lists used were different from that used for speech in noise measurement to avoid practice effect (The sentence bank cited consists of 20 different lists of similar difficulty). The sentences were interrupted in two ways: with periodic silent intervals, or with the silent intervals filled with speech-shaped noise bursts. Interruptions were applied by modulating the sentences with a periodic, 1.5-Hz square wave with duty cycles of 50% on-duration (corresponding to 333 ms), ramped with 5 ms of raised cosine. The rate of interruption and duty cycle were chosen based on what has been shown to consistently yield phonemic restoration [6]. For interruption with speech noise, sentence level was kept constant at 65 dB SPL, and noise level was varied to create lists with SNRs of 5, 0, -5, and -10 dB. The stimulus presentation and the response recording were similar to that of speech in noise measurement. The order of lists was randomized to prevent any order effect. Familiarization trials were carried out before the actual assessment using sentences interrupted at 1 Hz with silence and -2 dB SNR speech-shaped noise. Phonemic Restoration benefit was calculated as the difference in the intelligibility of sentences interrupted by silence and speech-shaped noise.
Statistical analysis

Statistical package for the Social Sciences software (version 18, SPSS Inc., Chicago, IL, USA) was used for analysis for both descriptive and inferential statistics. In the interrupted speech intelligibility task, the speech identification scores did not deviate significantly from normality in any of the conditions based on Shapiro Wilk test ($p>0.05$) and met the sphericity assumption (Mauchly’s test of sphericity, $p>0.05$). Repeated measures Analysis of Variance was done with the interruption condition as the main effect and was followed up by Bonferroni post-hoc pairwise comparisons. Pearson product moment correlation was used to analyze the relationship between speech in noise perception and phonemic restoration.

Results

Speech in noise performance

The estimated SNR-50 was used to quantify speech in noise performance. The mean SNR-50 in the sample was -4.38 dB with a standard deviation (SD) of 0.75 dB. The 95% confidence interval spread was -4.8 dB to -3.99 dB (Fig. 1).

Phonemic restoration of speech in noise

Speech identification was measured for sentences interrupted with silence or speech-shaped noise (Fig. 2). The mean score with silent interruption was 22.5 (SD=0.99) and improved when silent interruptions were filled with speech shaped noise. The mean (SD in parenthesis) for the noise interruptions at various SNRs were 25.8 (2.27), 28.9 (1.68), 28.7 (1.67), and 32.5 (1.68) at +5, 0, -5, and -10 dB SNR, respectively.

Repeated measures ANOVA indicated a main effect of interruption condition ($F_{(3,12)}=46.1$, $p=0.00$, $n^2=0.92$). Bonferroni post-hoc pairwise comparisons revealed that all interruption conditions were significantly different from each other ($p<0.05$) with the exception of 0 dB vs. -5 dB SNR conditions ($p>0.05$). Phonemic restoration of speech in noise was calculated as the difference between the performance for sentences interrupted with silence and those interrupted by

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speech-shaped noise (Fig. 3). Phonemic restoration tended to increase with the noise level and was the highest at -10 dB SNR. The improvement function was non-monotonic with a modest improvement at +5 dB SNR (with respect to quiet), larger increments at 0 and -5 dB SNR interruption conditions, followed by the largest increment at -10 dB SNR.

Correlation between speech perception in noise and perceptual restoration of speech in noise

A trend for a negative correlation with increasing noise levels was observed (Fig. 4). While correlations were not statistically significant at +5, 0, and -5 dB SNRs (lower noise levels), a moderate negative correlation \( r = -0.60, p = 0.017 \) was found between restoration magnitude at -10 dB SNR and SNR-50 indicating that those with more negative SNR-50 (better performance in noise) also tended to have a greater phonemic restoration of speech in noise.

Discussion

The hypothesis of the study was that there would be a correlation between speech perception in noise (SPIN) scores and phonemic restoration of speech, since those with better speech intelligibility in noise may have better top-down repair strategies to overcome the deleterious effects of noise.

Speech in noise performance

The SNR-50 score can vary widely with the material used as well as the competing signal employed [22]. Quick Speech-in-Noise test (Quick-SIN) [23] places it at +2 dB while Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN) and Hearing in Noise Test (HINT) have their 50% performances at -2.5 dB and -2.92 dB SNRs, respectively [22]. The former two tests use speech babble maskers, while HINT uses speech shaped noise instead. The SNR-50 scores obtained in this study (mean SNR-50 was -4.38 dB) are in agreement with those reported by Jain [24] who used similar speech material and noise conditions used in the present study. They reported a mean SNR-50 of -4.3 dB in their sample of 50–60 year-old subjects. The relatively large variation observed in SNR-50, even though hearing sensitivity itself was within normal limits, is in line with observations about individual variability in suprathreshold processing in normal hearing subjects [22,23].

Perceptual restoration of speech in noise

Interrupt with speech-shaped noise led to improved speech intelligibility [1,2,4,6,11]. The growth of restoration
magnitude was non-monotonic. A similar pattern was also reported by Bhargava and colleagues [6] as well. Direct comparison of the magnitude of phonemic restoration obtained in the present study vis-a-vis other studies is difficult since we preferred to use the raw scores instead of the typical rationalized arcsine unit (RAU) transformation [6,8] or percentages [11,25]. Since the datapoints were already normally distributed without large skews, we preferred this over other transformations to preserve the actual/natural distribution of speech scores. Transforming the data scores for the sake of comparison with other studies, the average restoration in RAU was around 4.96, 9.82, 9.60, and 16.57 for +5, 0, -5, and -10 dB SNRs, respectively, which are similar to those reported by other studies [6-8], after taking into consideration the relatively easy/predictable sentence lists used as well as the age of the subjects who participated in the study. In general, the easier the list, the better the phonemic restoration [7]. Age is an important consideration since studies [7,16] suggest that phonemic restoration is in fact increased in magnitude in older individuals (without much hearing loss). They suggest that older individuals tend to have poorer access to bottom-up cues and may be more dependent on top-down processing, resulting in a larger phonemic restoration. Variations in working memory abilities and linguistic proficiency [7,12,25] among the subjects could also contribute to the variance in the magnitude of restoration.

The reason for this intelligibility increase with noise interruption over silent interruption is likely multi-faceted. Silent interruptions may introduce spurious cues, like word-ending, stop-burst etc., thus, feeding wrong input to the top-down mechanisms. It is also possible that silent interruptions make it difficult to group the segments of speech into one stream [4]. Introduction of noise in these interruptions can alleviate this by masking off the spurious cues and may also help in integration of speech segments into one stream (noise being the other stream), resulting in activation of larger lexical networks [10]. Top-down mechanisms are thus able to make better lexical choices leading to better speech intelligibility. Increased noise levels may make speech feel more continuous [6] and may also contribute to better speech intelligibility at higher noise levels. Increased noise level can also help in better discrimination of speech and noise, which is helpful in grouping of speech and noise into different streams [7,10,13] and in turn, facilitate a better top-down repair.

Degraded perception of bottom-up cues can affect phonemic restoration by ineffective activation of top-down networks [6,7]. Reduced phonemic restoration has been reported in individuals with normal hearing when speech is distorted [6,7,11,13]. Reduction in phonemic restoration has also been reported in those with sensory neural hearing loss [11] and in subjects who have undergone cochlear implantation [6]. Degraded bottom-up cues due to hidden hearing loss [26] resulting from cochlear synaptopathy (due to causes like ageing, noise exposure etc.) may also be a factor since cochlear synaptopathy can result in affected temporal processing [27] and poorer speech perception in noise performance [28,29]. This may explain some individual variation across supra-threshold processing tests in subjects with normal peripheral hearing sensitivity.

**Correlation between phonemic restoration and speech in noise**

We found a significant moderate negative correlation (Fig. 4) between SNR-50 scores and phonemic restoration magnitude at -10 dB SNR. Those with larger magnitude of phonemic restoration effect tended to be more resistant to the effects of noise (had a more negative SNR-50). This correlation could indicate that there maybe an overlap of mechanisms involved in speech perception in noise and phonemic restoration. It is also possible, however, that both of them are related to something else altogether, and the two are not actually directly correlated.

Speech in noise perception is multidimensional and involves: integration of available bottom-up cues (dip listening for example, in the context of interrupted speech), using cues, like fundamental frequency, to perceive target speech as one stream and others as background, resorting to educated guesses to compensate for missed parts based on the context as well as making predictions on the go as to what maybe spoken next [30]. As such, there can be no doubt that it involves a complex interaction of bottom-up and top-down mechanisms in an effort to make sense of what is being heard. Phonemic restoration is a top-down effect based on the perception of illusory continuity of speech and grouping of speech and noise into separate streams, leading to a better access of lexical candidates [2,4,6,10,11,25]. So, it is possible that mechanisms serving phonemic restoration may well be at least partially involved in speech in noise perception as well and hence, the observed correlation. Those with better restoration abilities than their counterparts may perform better when bottom-up cues become disrupted as frequently happens in real world communication scenarios.

It is interesting that no statistically significant correlation with SNR-50 was found at better SNRs (lower noise) where the magnitude of restoration was less. This raises the possibility that a good amount of phonemic restoration is required for the mechanisms to sufficiently overlap with that of speech in noise perception, which as discussed before, also has components of top-down processing. However, the explanation
maybe simpler. Verbal working memory (like speech in noise) has been reported to be associated with phonemic restoration only when the interruptions were with speech noise, but not with other types of noise [25]. It is thus possible that top-down mechanisms are better activated when evidences of gaps are masked more efficiently (for example, with a more intense noise). Further studies are needed to verify if this is indeed the general case or if this is just a one-off finding.

The type of noise used for interruption affects phonemic restoration in a complex manner. Noise similar to speech makes it a more plausible masker [2,4] and leads to a perception of continuity of interrupted speech. However, it is also the case that noise needs to be sufficiently different from speech as well [10] in order to split into a different stream (and not become part of the same stream as speech) and thus help in better restoration. For the same reason, it is possible that a speech babble masker might lead to a lower phonemic restoration than speech-shaped noise. Studying correlation with different kinds of maskers may give us more insights on the complex interaction between opposing cues operating to serve the same phenomenon and help us better understand the relationship between phonemic restoration and speech in noise perception.

In summary, the study found a negative correlation between speech perception in noise and phonemic restoration magnitude at -10 dB SNR, suggesting that this type of top-down repair maybe operational in adverse listening situations. However, the findings have to be interpreted within the constraints of the limitations of the study. This is a correlational study and no causal relationship can be established. The findings also need to be considered provisional until they are replicated on a larger sample using different types of maskers over a wide range of SNRs. Future studies can focus on investigating phonemic restoration in the SNRs between -5 and -10 dB SNRs with smaller step sizes (e.g.: 1 dB SNR steps) since this range seems promising to gain further insight on the nature of phonemic restoration and its relationship with perception under adverse listening situations.

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Conflicts of interest

The authors have no financial conflicts of interest.

Author Contributions

Conceptualization: all authors. Data curation: Srikar Vijayasarathy. Formal analysis: all authors. Methodology: all authors. Project administration: all authors. Resources: all authors. Validation: all authors. Writing—original draft: Srikar Vijayasarathy. Writing—review & editing: all authors. Approval of final manuscript: all authors.

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