The role of cue enhancement and frequency fine-tuning in hearing impaired phone recognition

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Abstract

A speech-based hearing test is designed to identify the susceptible error-prone phones for individual hearing impaired (HI) ear. Only robust tokens in the experiment noise levels had been chosen for the test. The noise-robustness of tokens is measured as SNR\textsubscript{90} of the token, which is the signal to the speech-weighted noise ratio where a normal hearing (NH) listener would recognize the token with an accuracy of 90\% on average. Two sets of tokens T\textsubscript{1} and T\textsubscript{2} having the same consonant-vowels but different talkers with distinct SNR\textsubscript{90} had been presented with flat gain at listeners’ most comfortable level. We studied the effects of frequency fine-tuning of the primary cue by presenting tokens of the same consonant but different vowels with similar SNR\textsubscript{90}. Additionally, we investigated the role of changing the intensity of primary cue in HI phone recognition, by presenting tokens from both sets T\textsubscript{1} and T\textsubscript{2}. On average, 92\% of tokens are improved when we replaced the CV with the same CV but with a more robust talker. Additionally, using CV\textsubscript{s} with similar SNR\textsubscript{90}, on average, tokens are improved by 75\%, 71\%, 63\%, and 72\%, when we replaced vowels /a, æ, i, e/ respectively. The confusion pattern in each case provides insight into how these changes affect the phone recognition in each HI ear. We propose to prescribe hearing aid amplification tailored to individual HI ears, based on the confusion pattern, the response from cue enhancement, and the response from frequency fine-tuning of the cue.

1. INTRODUCTION

World health organization statistics shows that over 5\% of world’s population has disabling Hearing Loss (HL), defined as hearing loss greater than 40 [dB] in the better ear. One out of three adults aged over 65 years also are affected by disabling hearing loss. Current solution to address hearing loss is to compensate the approximate amount of loss in different frequencies, using a frequency-dependent amplification in a hearing aid (Steinberg and Gardner, 1940; Zurek and Delhorne, 1987). Yet hearing aid users complain about their ability for speech perception specially in environments such as restaurants where the background noise is similar to speech. Previous research supports the hypothesis that HL, while a necessary factor, is not sufficient in accounting for speech perception in Hearing Impaired (HI) ears (Abavisani and Allen, 2017; Plomp, 1986; Plomp and Mimpen, 1979; Trevino and Allen, 2013b; Yoon et al., 2012).

Various insertion gain prescription methods have evolved, such as National Acoustics Lab (Revised) (NALR) (Dillon, 2001), with the assumption that the optimal insertion gain will improve audibility and as a result, speech intelligibility. Although this gain treatment can help improve speech intelligibility for some HI ears, it has been shown that it can hurt speech intelligibility in nearly 12\% of cases (Abavisani and Allen, 2017). The persistence of speech loss, once audibility has been compensated, supports the possibility that there must be other factors, such as outer hair cell loss, that are playing an important role in HI speech
recognition. A speech metric that provides diagnostic information would be easily justified, but to date, such speech metrics have not been successful.

One major problem with focusing on audibility is that there has been no fundamental understanding of the precise nature of the speech cues, namely, which speech features need to be audible? The popular view of speech cues are *distinctive features* such as voicing, manner, place and nasality (Miller and Nicely, 1955). These broad-brush features are production rather than perception based, thus they do not account for the large within-class variability, as they do not vary within a class, it is impossible for them to account for within-class variability. (Toscano and Allen, 2014). Acoustic features that are necessary for Normal Hearing (NH) listeners are also necessary for HI listeners, but they may not be sufficient (Trevino and Allen, 2013a). Consistent token-specific confusion groups between HI listeners support the hypothesis that HI ears use similar cues, despite the audiometric configuration (Abavisani and Allen, 2017; Trevino and Allen, 2013b), but no theory exists that can clearly identify what these cues may be.

It was shown in a number of earlier studies that the errors HI ears make depend on the token, not just on consonant or feature classes (Trevino and Allen, 2013a,b). These studies showed that our traditional view of class-average errors can be misleading. At any amplification condition, there are numerous zero-error tokens along with a few high error tokens, and averaging, hides the degree of error for individual errorful tokens, thus diminishes the judgment of received benefit from that amplification procedure. To identify the errorful tokens, we need to look into error changes at various conditions and keep the token index fixed, as suggested by Abavisani and Allen (2017). To do so, we may look into the accumulated error differences to evaluate improvement or degradations across various amplification gain treatments.

Figure 1 shows an example on how one can evaluate a frequency dependent hearing aid amplification comparing to a flat gain amplification, and identify the tokens in which the treatment hurt the phone recognition by HI ear. This figure also shows that for a given HI ear at a given condition, out of many test tokens, there are only a few errorful tokens that need treatment to reduce recognition error.

![Figure 1: Accumulated error differences (\(\sum \Delta P_e\)) for each subject; the line shows the difference between improved and degraded tokens error. Abscissa shows the 24 male and female talker/consonants (the vowel /a/ is omitted to save space, and consonants /S,Z/ are shown as /S,Z/). (A) in each panel shows the area under the \(\sum \Delta P_e\) curve and it is an overall measure on helpfulness of frequency dependent treatment amplification versus a flat gain amplification (Abavisani and Allen, 2017).](image-url)
This suggests the need to look deeper into individual differences, to get a better understanding of how HI ears recognize speech. For a given HI ear, it is difficult to predict which tokens can be correctly recognized, and which cannot, as they are different for each ear. To advance understanding of this idiosyncratic deficiency of HI ears, a more sensitive test is required. Such test may include pre-evaluated tokens with a perceptual measure, to control token dependent variability in speech perception for HI ear during the test.

In normal hearing ears each consonant becomes masked at a token dependent threshold, denoted SNR\textsubscript{90}. The SNR\textsubscript{90} is defined as the SNR in which on average, NH ears can recognize the token at least with 90% correctly (the score is 90% on average for NH ears). As the noise is increased from Quiet (no noise), the identification of most sounds goes from less than 0.5% error to 10% error (at SNR\textsubscript{90}), and then to chance performance, over an SNR range of just a few [dB] (i.e., less than 10 [dB]) (Toscano and Allen, 2014). Hence SNR\textsubscript{90} is an important token-specific threshold metric of noise robustness, that may be used as the perceptual measure for the token.

Previous studies showed that by examining many tokens of a particular Consonant-Vowel (CV) sound, in various noise conditions, in NH speech recognition experiments, one may construct the procedure to detect the SNR\textsubscript{90} perceptual measure. Fig. 2 illustrates the results of such experiment for various tokens of /p/ sound, where their error versus SNR curves are shifted to align them on the 50% recognition point (SNR\textsubscript{50}). According to Fig. 2, if the amount of noise is increased, the score would drop significantly (over 50%) for most of the sounds in just a few [dB] (i.e., 6 [dB]). This constitutes the theorem that for NH listeners, testing speech tokens at a few [dB] higher noise would drop the score significantly. Conversely, testing tokens at noise levels well above the SNR\textsubscript{90}, will result in correct recognition for NH listeners (Singh and Allen, 2012).

Accordingly, to test the idiosyncratic phone recognition for HI ears for a particular consonant, one should select the subset of tokens that have sharp score drop passing the SNR\textsubscript{90} threshold. Fig. 2 shows that most of tested tokens fall within this criterion. By definition of SNR\textsubscript{90} as a perceptual measure, NH listeners should have similar scores on tokens with similar SNR\textsubscript{90} if tested at noise levels above the SNR\textsubscript{90}. Additionally, comparing two tokens with well separated SNR\textsubscript{90} (i.e., |ΔSNR\textsubscript{90}| ≥ 6 [dB]) at SNR equal to the higher SNR\textsubscript{90} of two tokens (i.e., at the SNR\textsubscript{90} of less salient token), NH scores should vary significantly. By testing HI ears at noise levels much less than the threshold SNR\textsubscript{90} of the token, we propose to quantify the idiosyncratic behavior of HI ear comparing to NH ears. The background noise level may be measured by methods such as the one explained in Lee and Hasegawa-Johnson (2007).

Previous studies reveal that hearing loss can cause confusions for consonants where the primary cue region is within the hearing loss frequencies (Abavisani and Allen, 2017; Cole, 2017). This phenomenon is confirmed also on NH ears by high/low pass filtering of the primary cue region (Li et al., 2010; Li and Allen, 2011). Furthermore, it is confirmed that amplification of primary cue region improves recognition score for both NH and HI ears (Cole, 2017; Kapoor and Allen, 2012).
One research direction yet to be explored, is the question of whether varying the frequency of primary cue region can improve the speech recognition for HI ears. The very first step toward investigating on whether it is possible to improve the speech recognition score based on frequency component manipulations, will be to explore such effects in rather small scale such as what we call the “frequency fine-tuning” of the primary cue region. For fine-tuning, we may impose a change on the time-frequency window that is necessary to identify the consonant. One way to implement such a change is to vary the vowel in the token and keep the consonant and SNR the same. From previous studies conducted by Li and Allen (2011); Régnier and Allen (2008); Singh and Allen (2012), we know that the intelligibility of a token in noise, is correlated to its SNR$_{90}$ and also that the SNR$_{90}$ is correlated with the relative intensity of the primary cue of the token. Thus, to keep the intelligibility of the primary cue in a similar level as the original token, we should select a new token that has a similar SNR$_{90}$ to the original token.

Changing the vowel has a number of effects on NH consonant recognition, including changing the center frequency of the burst spectrum (Winitz et al., 1972), changing the formant transitions (Delattre et al., 1955; Ohman, 1966; Sussman et al., 1991), changing the acoustic spectrotemporal context within which the listener tries to identify the relevant cues (Lisker, 1975), and changing the set of valid English words that are activated by the CV pair (an effect that has been shown to change the threshold for correct consonant recognition) (Ganong, 1980). By keeping the NH-based perceptual measure (SNR$_{90}$) the same across changing the vowel for HI listeners, and by testing at SNRs well above the SNR$_{90}$ threshold, we control the approximate intensity of the primary cue region, which has the dominant effect on the intelligibility of token. Thus, if vowel change increases the error, candidates for such loss would be the HI audiometric configuration in conjunction with the vowel change effects on NH listeners.

To investigate the role of SNR$_{90}$ perceptual measure in the improvement of HI consonant recognition, one may replace the errorful CV with a new but more intelligible CV with the same consonant and vowel. Being more intelligible is quantified in terms of the SNR$_{90}$ of the token. Thus, it is proposed to replace the less salient token (higher SNR$_{90}$) with a more salient token (lower SNR$_{90}$) with a new talker, to increase the score for HI phone recognition. Given that the amount of noise in the experiment is much less than the SNR$_{90}$ threshold for both tokens, such talker change should reduce error for HI ears, unless there are other factors involved. One candidate for such unexpected error path would be the conflicting cues becoming more available in the new token or noise condition.

In this article, we first explain the adaptive testing procedure to collect consonant recognition data from HI listeners. Then we provide preliminary results of experiment where the perceptual measure SNR$_{90}$ varies for same CV sound, and the experiment where the perceptual measure SNR$_{90}$ was kept in similar level, but the vowel changed for the same consonant. Finally, we discuss cases where such intervention went in the opposite direction as expected. These tests are directed at the fine-tuning of hearing aid insertion gain, with the ultimate goal of improving speech perception, and to precisely identify when and for what consonants HI ear needs treatment to enhance speech recognition.

2. METHODS

Since we are interested to investigate the speech perception for HI ears in situations similar to real world experience, we need to design experiments that test HI speech recognition in speech-weighted noise. To explore the role of noise in such experiments, this study proposes to use the speech tokens at four SNR levels well above SNR$_{90}$ (i.e., all SNRs should be above SNR$_{90}$+6 [dB] for each token). With such a scheme, a single error is highly statistically significant, since for the NH ear, one error in 40 presentations at SNR$_{90}$+6 [dB] is rare (Singh and Allen, 2012). Therefore, such schedule is highly efficient in characterizing each HI ear, to determine what are the errorful tokens, and which consonants are problematic for HI ears to recognize. Previous studies show that HI listeners will have errors in recognizing tokens for only a subset of tokens (a few tokens out of all the presented tokens), if the tokens are presented well above their SNR$_{90}$ (Abavisani
and Allen, 2017; Trevino and Allen, 2013b). Once high error sounds have been identified, one may seek the optimum treatment (insertion gain) to efficiently prevent increase of the token error relative to flat gain condition, for those errorful tokens.

A. SPEECH MATERIALS

Throughout these studies, the term token refers to one of the specific consonant-vowel (CV) sounds. We planned to test a wide range of different consonants to cover plosive, fricative and nasal sounds. The tested consonants are /p, t, k, f, s, j, b, d, g, v, z, ñ, m, n/. These consonants combined with vowels /a, æ, i, e/ form the CV speech database for this experiment. For each CV sound there are two instances assembled in two sets: set T₁ which includes CV sounds with SNR₀ perceptual measure below -2 [dB], and set T₂ which includes same CV sounds with different talkers that are more salient and have SNR₀ much less than corresponding CV in set T₁ (i.e., |ΔSNR₀| ≥ 6 [dB] for same CV from sets T₁ and T₂).

The CV tokens were drawn from an earlier experiment that measured the confusions as a function of SNR for 30 NH listeners (Li et al., 2010). The tokens were restricted to be noise-robust, defined as having a recognition error as measured by 30 NH ears of less than 10% at SNR = -2 [dB], with an average error of <3.1% (i.e., less than 1 in 32 trials (Phatak and Allen, 2007; Singh and Allen, 2012; Toscano and Allen, 2014) at the four test SNRs (i.e., 0, 6, 12 [dB] and Quiet). During the testing, speech shaped computer generated Gaussian noise was added to the token at one of the four SNRs.

Each token was naturally spoken as an isolated (i.e., no carrier phrase) consonant-vowel (CV) token, by an American English speaking talker, from a pool of eight female talkers and twelve male talkers, available from the Linguistic Data Consortium Database (LDC-2005S22) (Fousek et al., 2004). The sampling rate was 16 [kHz].

The speech was presented at each subject’s most comfortable level (MCL), as determined during initial trials used to familiarize the subjects with the task. Initially, the software was calibrated to present speech stimuli at 75 [dB SPL]. The subjects were allowed to subsequently adjust the presentation level at any time during the experiments, and if they did such adjustment, the new presentation level is saved in the experiment log file.

B. SUBJECTS

The target subjects for these experiments are native English speakers who have mild to moderate hearing loss with the age between 18-64 years. These subjects are recruited from Urbana-Champaign, IL, community. IRB approval was obtained from the University Review Board. Subjects were paid. All subjects had hearing loss greater than 20 [dB] for at least one frequency in the range 0.25-4 [kHz].

Figure 3 illustrates the pure tone thresholds of the subjects whose test results appear in current study. All subjects have mild to moderate hearing loss in high frequencies. In addition, subjects HI₁, HI₂, HI₃ and HI₄ have mild hearing loss in low frequencies. Subjects HI₅ and HI₆ (same person) have moderate hearing loss in low frequencies as well. All the pure tone thresholds have been evaluated within the past year prior to the experiments.

C. EXPERIMENT DESIGN

To investigate the effect of cue enhancement, all the conditions were the same, other than the talker (with same gender) which is replaced by a talker who produced the target consonant more clearly in terms of SNR₀. The CV remains the same. Additionally, to investigate the effect of frequency fine-tuning of consonants via changing the vowel, all the conditions were the same, other than the talker (with same gender) and vowel of token which is replaced by a token with similar salience in terms of SNR₀. The consonant remains the same.
The experiment starts on List 1 (see Fig. 4(a)) with tokens including both male and female talkers for the 14 available consonants associated with vowel /a/ at SNR = 0 [dB]. These starting tokens are already highly intelligible as they all have SNR$_{90}$ below 0 [dB]. Thus NH listeners should recognize them correctly. If the HI ear has error for a token, that token will be presented two more times in List 2: once at 0 [dB] and once at 6 [dB] (one level higher SNR). After these three presentations, if the HI ear has two errors out of three, we consider the token to be a susceptible token that needs more scrutiny. Hence, such token will be moved to List 3, where it will be presented 10 times at each SNRs of 0, 6, 12 [dB] and Quiet, making a total of 40 more presentations.

As soon as a token reaches List 3, other versions of that CV will be added to List 2, in order to investigate the enhanced cue effects (more salient talker). Also, other versions of the same consonant with various vowels will be added to List 2, such that for each CV, there will be at least two different talkers one with similar SNR$_{90}$ as the original CV, and one with better SNR$_{90}$ (more salient). Furthermore, to prevent subjects from guessing the correct response, seed tokens that are confusable with the original consonant will be added to List 2. The confusable consonants are determined from previous CV recognition experiments in noise with NH listeners (Miller and Nicely, 1955). Fig. 4(b) illustrates the confusable consonants and their transition probabilities.

Token orders are randomized in all experiment lists initially and whenever a new token is added to a list. Since List 2 and 3 usually include more tokens, seed tokens are provided in a Seed List to mix the token presentation order with seed tokens and increase the randomness. Additionally, presentation from different lists are randomized to prevent subjects from guessing. The transition probabilities between lists are shown in Fig. 4(a).

A Matlab® graphical user interface was provided to run the experiment. All of the data collection sessions were conducted with the subject seated in a single-walled, soundproof booth with the door of the outer room closed. The speech was presented through an Etymotic ER-3 insert ear phone, one ear at a time. The contra-lateral ear was not masked or occluded. To familiarize the subjects with the testing paradigm, a practice session was run using non-test tokens. The MCL was determined during the practice session.

After hearing each token, the subject was instructed to choose the response from 14 possible consonant labeled buttons that were provided on the screen via a graphical interface. To get more precise results, subjects were allowed to play uncertain tokens up to two additional times before making their decision. To reduce fatigue, subjects were encouraged to take short breaks approximately every 20 min.

**D. DATA ANALYSIS**

Collected data were saved into log plain text files on disk. For each presented token, the saved data include talker, played consonant, vowel, heard consonant, SNR, Sound Pressure Level (SPL), number of
Figure 4: Scheduled procedure for adaptive testing. Numbers on each edge show the probability of transition: (i) Transition probabilities between the lists at different stages of the experiments: (a) Initial probability distribution indicating that only List 1 contains tokens, (b) distribution when only List 1 and 2 contain tokens to present, (c) distribution when only List 2 contains tokens, (d) distribution when all lists contain tokens, (e) distribution when only List 2 and 3 contain tokens, (f) distribution when only List 3 contains tokens, (g) distribution when only List 2 and 3 contain tokens and List 3 includes more than than 10 distinctive consonants, and (h) distribution when only List 3 contains tokens and it has more than 10 distinctive consonants. (ii) Transition probabilities between various consonants, which are used to add induced confusing consonants as seed tokens during the experiments.
repeats, List number, name of wave sound file, and the time the subject took from hearing the CV till hitting the response button.

From the collected data, we use the responses from List 3, which are the results of full investigation of susceptible tokens, that are presented evenly at four SNRs (0, 6, 12 [dB], and Quiet). From these data, we can form the confusion matrix as a function of SNR. Since we conduct the study on 14 consonants, the confusion matrix will be of size 14 × 14. Each of the tokens presented in List 3, has an empirical probability distribution defined by a row of the count (unnormalized confusion) matrix. We refer to the \( i \)th token as \( CV_i \), \( i = 1, \ldots , 14 \). The probability of error of this token is:

\[
P_e(CV_i, SNR) = \sum_{j \neq i} P\{\text{heard} CV_j | \text{spoken} CV_i\},
\]

where \( P_{ii} = 1 - P_e \) is the corresponding probability of correct response (diagonal element). For simplicity in notation, we may refer to \( P_e(CV_i, SNR) \) as \( P_e \). Given the above probability of error for each of the tokens, the average error of erroneous consonants for each ear is then

\[
\overline{P_e}(Ear, SNR) = \frac{1}{N_3} \sum_{i=1}^{N_3} P_e(CV_i, SNR), \tag{2}
\]

where \( N_3 \) is the number of CV tokens that are reached to List 3, i.e., the number of consonants that were hard to hear.

Another measures that is considered is the confusion pattern (CP); for a given token, the confusion pattern is a plot of one row of the confusion matrix (i.e., \( P_{\text{heard} | \text{spoken}}(SNR) \)), as a function of SNR (Allen, 2005). This measure shows how the token score and confusions depend on SNR.

3. RESULTS

In this section we discuss the results of both experiments on cue enhancement and frequency fine-tuning of the speech cue for HI listeners. While on average, HI ears responded positively to cue enhancement, the result of vowel change is mixed and varies regarding various vowel.

A. CUE ENHANCEMENT

i. Error summary

Figure 5 illustrates the average log-probability of error \( \overline{P_e}(Ear, SNR) \) for all HI ears in current study. From Fig.5 we observe that \( \overline{P_e} \) have linear relationship with SNR for HI ears. Generally, when the noise decreases, the error also decreases. However, there are cases such as subject HI4 (top right panel in Fig. 5), where eliminating noise from SNR = 12 [dB] to Quiet, caused the error to increase. This happened for tokens from both set T1 talkers and the more salient talker set T2, for this subject. Such phenomenon indicates that conflicting cues became available when the noise reduced, causing the subject to confuse the consonant with the corresponding consonant from the newly available cues.

As depicted, on average, when tokens are replaced by same CV but with better perceptual measure (lower SNR), all HI ears responded with better consonant recognition. This confirms that HI ears use same perceptual features as NH listeners and if one enhances the speech cue, the speech perception will improve for HI listeners.

Given that in both experiments no frequency-dependent amplification was provided for HI ears, one may expect the two \( \overline{P_e}(Ear, SNR) \) curves before and after replacing token with the same CV but with more salient talker, should be parallel. Fig. 5 confirms such expectation for most HI ears, however, passing
from SNR = 12 [dB] to Quiet, there are cases where these two curve converge (subject HI7) or diverge (subject HI6). Accordingly, at the presence of noise $\overline{Pe}(Ear, SNR)$ curves converged for subjects HI2, HI5, HI7 and HI8, when the talker is replaced to enhance primary cue. This convergence is an indication of the limit on cue enhancement (on average) for consonant recognition improvement for HI ears. Apparently, some HI ears will have errors for some tokens even though the cue is enhanced and the noise is reduced. We should look into individual consonant error changes to identify corresponding consonants that are not responding to cue enhancement for each HI ear. Such consonants are idiosyncratic for each HI ear.

**ii. Improvement and degradation due to talker change**

To have more precise understanding on the effects of cue enhancement through changing the talker to a more salient talker, we may look into the individual token error changes. Fig. 6 illustrates the token error changes for subjects (left panel) and for consonants (right panel). The ordinate is the number of tokens that are improved or degraded due to replacing talker with another talker that had better SNR90. These improvement and degradations are from the consonants which had error both when provided token from set $T_1$ (less salient talker) and set $T_2$ (more salient talker), at various SNR. Overall, considering the tokens where improving SNR90 vanished the error, 85% of tokens are improved and 10% of tokens are degraded.

According to the degradations by subjects, we observe that subjects HI6, HI5, HI3 and HI4 had the most degradations, respectively. By comparing the audiometric thresholds (Fig. 3), we find out that these subjects had hearing loss in low frequencies (below 1 [kHz]) in addition to high frequency sloping loss.

Moreover, right panel in Fig. 6 shows that consonants /f, p, n/ had the most degradations, respectively. Analysis such as the one in Fig. 1 will describe consonant degradations according to HI ears, thus one may associate the specific consonant degradation with audiometric configuration.
B. FREQUENCY FINE-TUNING

i. Error summary

Figure 7 illustrates the $P_e(\text{Ear}, \text{SNR})$ for each subject when the consonant is kept the same and the vowel is changed while the perceptual measure SNR$_{90}$ of both tokens are kept in the similar level. As expected, the $P_e$ has a linear relationship with SNR in all cases with various vowels. Following, we describe several events that are observable from these average error vs SNR plots.

First, it appears that some subjects had less average error for vowel /i/ comparing to other tested vowels. By checking the average SNR$_{90}$ of the initial test tokens in table 1, we observe that on average, tokens with vowel /i/ had lower SNR$_{90}$. Second, subject HI$_4$ (top right panel) had higher error in Quiet than at SNR = 12 [dB] for various vowels with the exception of vowel /i/. Third, in the presence of noise, the $P_e$ curve remains parallel for various vowels for most of the subjects, meaning that reducing the noise improved CV recognition scores with similar degrees. There are exceptions to this observation such as subjects HI$_7$ and HI$_8$ (same person) for vowel /e/ (marker ▼ in lower right two panels in Fig. 7).

Fourth, for several vowels $P_e$ curve does not decay as the noise decreases. These include vowel /æ/ for subjects HI$_1$ and HI$_3$ (marker ●) and vowel /e/ for subjects HI$_1$, HI$_2$, HI$_5$, HI$_7$ and HI$_8$ (marker ▼). Fifth, all subjects are not sensitive to eliminating the noise for at least one vowel, meaning that the $P_e$ curve did not change across SNR = 12 [dB] and Quiet. For some subjects, there are vowels in which the $P_e$ did not change significantly from SNR = 0 [dB] (highest noise) to Quiet. These cases include vowel /æ/ for subjects HI$_1$ and HI$_3$, and vowel /e/ for subjects HI$_2$ and HI$_8$.

![Figure 7: Average probability of error for tokens in vowel change experiment; in each panel vowels /a, x, 1, e/ are shown by symbols ▲, ●, ■, ▼, respectively. In the legend, vowels /a, x, 1, e/ are shown with characters /A, ae, I, E/, respectively.](image)

All of these observations need to be investigated by more detail combining subjects’ audiometric configuration and individual consonants contributing to such events, so we can have better judgement on whether the coarticulatory cues that affect NH phone recognition, also affect HI phone recognition by similar weights.

ii. Improvement and degradation due to vowel change

Table 1 shows the percent improvement and degradations when the vowel is changed from the original vowel, and the token is replaced by a new token with same consonant and different vowel, but with similar SNR$_{90}$ that reflects similar perception for an NH listener. The average SNR$_{90}$ of the tokens for each vowel is also provided in table 1.

The percentage in table 1 indicate the absolute number of improved/degraded tokens and not the degree of improvement/degradation. To find out about the degree, methods such as the one used in Fig. 1 is needed.
Figure 8: Number of improved versus degraded tokens when the vowel was replaced, and a new token with similar SNR is presented to HI listeners: (a) Vowel /a/ replaced by /æ, i, e/, (b) Vowel /æ/ replaced by /a, i, e/, (c) Vowel /i/ replaced by /a, æ, e/, and (d) Vowel /e/ replaced by /a, æ, i/. On the title in each panel, vowels /æ, i, e/ are shown with characters /A, æ, I, E/, respectively. Consonants /s, z/ are shown by S, Z in the abscissa labels. The cases where changing the vowel vanished the error are not shown in these plots.
Overall, vowels /a, æ, e/ improved and degraded similarly. Their average SNR$_{90}$ perceptual measure is also very close.

Figure 8 illustrates the overall improvement vs degradations when the consonant is kept the same and the vowel changed to a new vowel, excluding the cases where the error vanished by vowel change. Each panel include two summary bar plots: the left axes indicates the improvement vs degradation for subjects, and the right axes indicates same information collapsed on various consonants.

At a glance, Fig. 8 shows that subject HI$_6$ had the most number of improvement specifically when vowels /a, e/ are involved. This can be related to this subject’s low frequency hearing loss that affects low frequency energy vowels such as /a, e/. On the other hand, looking to the degradations, we see that subject HI$_6$ had the highest degradations when the vowel changed from /ɪ/ to other vowels. Generally, vowel /ɪ/ has low frequency first formant along with a high frequency second formant (Hillenbrand et al., 1995; Patterson et al., 1982). Thus, the low frequency hearing loss of subject HI$_5$ can play a role in degradation of perceiving consonants+/ɪ/, comparing to other CVs. Such conclusions may be deemed for each individual subject by accompanying their hearing loss with the frequency components of the degraded vowels.

### Table 1: Percent improvement and degradations in errors on HI consonant recognition when the vowel changed.

| Changed Vowel | Improvement [%] | Degradation [%] | Average SNR$_{90}$ |
|---------------|-----------------|-----------------|--------------------|
| /a/           | 75              | 14              | -9.6               |
| /æ/           | 71              | 16              | -9.9               |
| /ɪ/           | 63              | 24              | -12                |
| /e/           | 72              | 18              | -10.5              |

### 4. DISCUSSION

It is clear from Fig. 5 that on average enhancing the token in terms of perceptual measure (SNR$_{90}$) will improve the speech perception for HI subjects. However, when looking into individual tokens, this may not be the case always. Fig. 9 illustrates the confusion patterns for several cases where the intervention (change in vowel or talker), showed some unexpected results for the HI listener. For the vowel change experiments, the changes in error pattern depends to each subject’s audiometric configuration so we cannot extend a rule from average error.

The confusion patterns in Fig. 9 informs about the role of cue enhancement (enhance SNR$_{90}$) and the frequency fine-tuning in complex cases, where the speech perception for a consonant, did not follow the average rule. Figure 9 indicates the confusion pattern of perception of consonant /b/ for subject HI$_6$. As it is shown, various /b/+vowel tokens had better score when the token is replaced with a better token in terms of SNR$_{90}$. Comparing the score for less salient tokens with different vowels (left panels in Fig. 9), for instance, we observe that at Quiet /bæ/ was recognized correctly, but /bɑ/ and /bɛ/ were perceived by 60% and 50% error, respectively. For explanation, we look into the spectrograms of these tokens provided in Fig. 10, along with the audiometric thresholds of subject HI$_6$.

Since the characteristics of the labial stop consonant /b/ is to have a diffuse spread of energy over a wide range of frequencies (Blumstein and Stevens, 1979), the strength of the burst release into the following vowel seems to have an important role in correct perception of this stop consonant for subject HI$_6$. Fig.10(a)-(c) show that the burst release of /b/ at frequencies above 1 [kHz] is stronger in token /bæ/ comparing to /bɑ/ and /bɛ/. This is evident by comparing higher frequency formants of these vowels in Fig.10(a)-(c). On the other hand, as depicted in Fig.10(d), subject HI$_6$ had better hearing abilities in mid-frequencies of
1.5-4 [kHz]. Hence, if the burst release of /b/ associated with formants of the next vowel appears to be present in this frequency range, one would predict the correct perception. Fig.10(a) indicates that the second formant of vowel /æ/ falls in this range and is strong enough to be heard by HI6. As appears in Fig.10(a)-(c), although the first and second formants of /a/ and /e/ are strong, but they fall into the sever HL range of subject HI6. The first formant of /æ/ also falls in this range. Hence, we may conclude that the vowel formants in association with the audiometric configuration of the HI listener, have eminent role in consonant perception for HI listeners.

On the other hand, comparing the Voice Onset Time (VOT) of the vowel in the three panels in Fig. 10, we observe that the VOT for /bæ/ starts approximately 100 [msec] sooner than /ba/ and /bɛ/. Thus, the VOT may also played a role in better perception of /bæ/ for subject HI6. This indicates that the role of the VOT in the case of HI consonant recognition, is similar to the VOT role in NH consonant recognition as explained by Lisker (1975).

The confusion patterns of Fig.9 provides summary of some unexpected events as a result of frequency fine-tuning and cue enhancement for token. Each condition in these plots can be analyzed by illustrations such as Fig. 10 for various tokens and subjects. This analysis indicated that for instance, given the audiometric thresholds of subject HI6, for perception of /b/, a frequency fine-tuning toward vowel /æ/ would increase the score. Similar explanation may be given for other cases to recommend an individual frequency fine-tuning prescription for HI subjects.

5. CONCLUSION

Throughout this study, we analyzed the speech recognition data from HI listeners with mild to moderate hearing loss, to investigate the role of cue enhancement and frequency fine-tuning. The control factor in these experiments was the perceptual measure SNR90 which assures that in the SNR levels of the test study,
NH listeners would recognize the tokens correctly. The results show that the cue enhancement with no frequency-dependent amplification improves consonant recognition for all HI subjects on average.

The results of the frequency fine-tuning experiment, did not indicate any favorable vowel for consonant recognition on average. The CV tokens with vowel /i/ that had slightly better SNR$_{90}$, showed less improvement and more degradation when the vowel replaced, indicating the importance of the SNR$_{90}$.

Using the confusion pattern plots such as the ones in Fig. 9, we can observe whether the enhancement in conditions such as noise, cue, frequency fine-tuning, does not provide the expected outcome. To further analyze the reason behind such event, we may look into the illustrations such as Fig. 10. The studied case showed that the strength of burst release of stop consonant /b/ into the formants of the following vowel, plays an important role in identification of the consonant.

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