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청력 손실자의 보청기 착용 전후의 말 지각에서의 변화

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ABSTRACT

A Relationship of Speech Perception and Amplification for Hearing-Impaired Listeners

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Individuals with sensorineural hearing loss (SNHL) are treated with hearing aids and/or a cochlear implant, based on their pure-tone thresholds and speech perception scores. Although these assistive listening devices do help those individuals communicate in quiet surroundings, many still have difficulty understanding speech in noisy environments. The purpose of current study is to compare results of consonant perception when using flat gain (or most comfortable level, MCL) and to see changes in consonant error rate occurred by hearing impairment after applying a frequency specific amplification.

Twenty American English speakers with mild-to-moderate SNHL were tested. Isolated English consonant-vowel (CV) syllables, consisting of sixteen consonants followed by the /a/ vowel, were used as stimuli. They were presented monaurally in quiet and at five different signal-to-noise ratios (SNRs) in speech-weighted noise. To compare the consonant error between ‘no NAL-R amplification’ (flat gain) and ‘NAL-R amplification’ conditions, all subjects were tested in the two conditions. When simulating the NAL-R condition, its formula was calculated in two steps for each subject, by obtaining the required gain as a function of frequency.

Overall consonant percent errors were decreased with NAL-R correction, compared to the no NAL-R conditions. When we look at the aided audibility and average consonant errors (or scores) after fitting a hearing aid, hearing-impaired (HI) speech perception seems better than before wearing the hearing aid. However, there is a significant difference among consonants: some consonants obtain great benefit from NAL-R and others do not. Also, subjects who have similar pure-tone audibility do not receive the same benefit from the amplification. We conclude that although current amplification fitting methods can offer positive benefit on average to the speech perception of HI listeners, they cannot offer equally positive benefits to every consonant and every HI listener.

KEY WORDS : Amplification Effect · Consonant Perception · Consonant-Vowel Syllable · Hearing Impairment · NAL-R amplification · Speech Perception

INTRODUCTION

Unlike normal hearing (NH) listeners who have good ability in separating speech sounds from unwanted surrounding noise and have easy conversation, hearing-impaired (HI) listeners with sensorineural hearing loss (SNHL) have trouble understanding the speech sounds in a noisy environment, even when they are wearing an assistive listening device. The HI listeners, especially with mild-to-moderate SNHL, complain that their hearing aids do not simulate/approach normal speech perception. According to Kochkin(2000) “Why are my hearing aids in the drawer?”, about 30% of hearing aid owners do not wear them. Many of the people whom Kochkin surveyed reported that their hearing aids have several serious problems: background noise, poor fit, and less benefit, and that the hearing aids amplify back-

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ground noises well, but not human speech.

Although the topic of *how speech perception for the HI population improves* has been debated for more than a half century in clinical audiology, in hearing science, and in the hearing aid industry, it remains an open and unsolved puzzle. On the side of the clinical research, various diagnostic speech perception tests have been developed using nonsense syllables (Dubno & Dirks, 1982; Dubno et al., 1982; Resnick et al., 1975), words (Plomp, 1986; Ross & Lerman, 1970), and sentence materials (Cox et al., 1987; Cox et al., 1988; Kalikow et al., 1977). In hearing science, there has been fundamental approach while modulating timing and/or frequency of speech sounds (Bacon & Gleitman, 1992; Moore & Skrodzka, 2002) and changing speech cues and features (Erber, 1975). Yet, few to none of these methods have been successful in improving HI speech perception. The hearing aid industry has also developed aids for HI speech perception by signal processing techniques, e.g., wide dynamic range compression circuit (Jenstad et al., 1999) and enhanced localization to reduce unwanted noisy sounds (Carhart, 1958; MacKeith & Coles, 1971; Welker et al., 1997). However, professionals in all three fields have not consolidated their efforts into a single approach and have no united system to data for improving speech intelligibility. Furthermore, despite a body of literature reporting a great improvement of the aided HI speech perception, based on the results of clinical measurements, it is still unclear why two people with a similar hearing loss or the same hearing configuration have significantly different abilities in speech understanding (Tremblay et al., 2006).

Here, we will address five questions that are fundamental to all three fields: (1) “Do the current clinical measurements diagnose HI speech perception accurately?” (2) “Are current fitting methods (e.g., a half-gain rule, NAL-R, and other prescription formulas) effective?” If yes, then (3) “why do these fitting procedures give unsatisfactory information to the hearing aids wearers?”, or (4) “why is it that modern hearing aids are not effective, especially in noise?” If not, (5) “do we need a more accurate and alternative measurement of SNHL listener's loss or impairment?” It seems that these questions underlie an unanswered fascinating problem, that is fundamental to both clinical practice and speech perception research. We need to scrutinize our current clinical procedures for diagnosis of hearing loss and hearing aid fitting.

<Fig. 1> illustrates the typical clinical procedure that takes place when individuals visit an audiology clinic. First of all, based on the results of the three most commonly used diagnostic tests, e.g., tympanometry, pure-tone audiometry, and *speech recognition threshold* (SRT), the clinicians typically determine a type, severity, and frequency response of hearing loss. ‘Type’ characterizes the apparent physiological origin of hearing loss as conductive or SNHL. ‘Severity’ is measured in decibels, but may be less precisely categorized as mild, moderate, severe, or profound. ‘Frequency response’ is also measured quantitatively, but may be imprecisely categorized as a flat, low-frequency, or high-frequency hearing loss. Then this typical clinical scenario, in which *# dB HL* as a function of testing frequencies, as measured using a PTA, is used for fitting hearing aids to HI patients. The patients then report their hearing aid satisfaction to the clinician, by self-report or a questionnaire in several follow-up visits (Dobie & Sakai, 2001). However, Dobie and Sakai addressed common limitations of current clinical tests. They found that the *pure-tone audiogram* (PTA) and *word recognition score* (WRS) are highly correlated, but there is a question as to whether these two predictor variables each explain the variance in self-report about HI listeners’ satisfaction with speech perception, or whether the PTA measurement alone is sufficient to predict HI speech perception. Dobie & Sakai(2001) also discovered a low correlation between current speech tests and self reports of the effect of hearing loss. They suggest that the self-report should be the gold standard. Despite the results of studies like Dobie & Sakai(2001), however clinicians typically still use PTA and WRS as a reference for fitting the hearing aid and proving benefit from it.

In addition, although speech perception research as related to clinical audiology has developed, the diagnostic speech tests used in a clinic are still very limited, in terms of transferring from research to clinic. Except for two popular tests (Hearing-In-Noise Test, or HINT (Nilsson et al., 1994) and Quick Speech-In-Noise test, or QSIN (Killion et al., 2004)), most measurements using speech materials are not practically accepted in the clinic, due to their being time

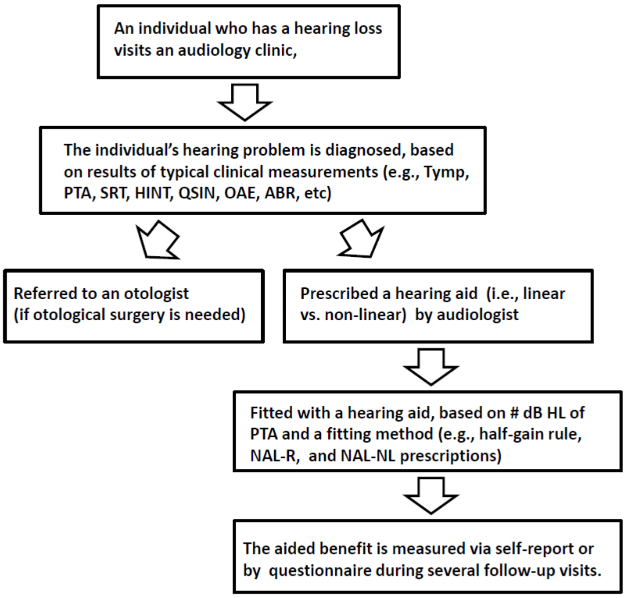


Figure 1. A flow chart of the typical clinical procedure for hearing-impaired listener as a process diagram. Abbreviations used are Tymp = Tympanometry; PTA = Pure-Tone Audiogram; SRT = Speech Recognition Threshold, HINT = Hearing-In-Noise Test; QSIN = Quick Speech-In-Noise test; OAE = Otoacustic Emission; ABR = Auditory Brain Response; NAL-R = the revised National Acoustic Laboratories prescriptive formula; NAL-NL = Nonlinear NAL formula.

consuming, complex, or poor in reliability (Killion et al., 2004).

The present study claims that the high dissatisfaction with modern hearing aids comes from the averaging scores inherent in PTA and SRT. In other words, existing clinical measurements do not give sufficiently detailed information about the characteristics of the HI listeners' feature loss in speech, to make a useful diagnosis for the hearing aid fitting. The study seeks to find an answer to the question: whether or not NAL-R amplification could positively benefit the speech perception of each SNHL listener at the consonant level. We could expect that (1) NAL-R amplification does not offer a full positive benefit to all 16 English consonants; some consonants improve and some do not, because of idiosyncratic consonant-dependence in many HI ears. We further observe that (2) the benefits of the NAL-R amplification are also idiosyncratic for each HI listener: a low correlation between NAL-R benefit and pure-tone threshold and configuration (or hearing loss pattern). Our results suggest that we will need an alternative fitting method in order to take advantage of the large individual differences across listeners, thus to enhance the speech perception of those HI listeners who do not receive a fully positive amplification benefit from the NAL-R correction.

MATERIALS AND METHODS

Subjects

Twenty HI subjects recruited from the Urbana-Champaign community participated. All subjects were native speakers of American-English and all were paid. Informed consent was obtained from all subjects, and all procedures of the study were approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign. Subjects had normal middle-ear status (type A of tympanogram) and SNHL. The etiologies of subjects' hearing loss varied. The results of the hearing screening tests varied in terms of the degree and configuration of individual hearing loss. Of the twenty subjects, nine had symmetrical and eleven had asymmetrical bilateral hearing loss. They ranged in age from 21 to 84 years (mean = 55.45 years, SD = 20.42).

Speech Stimuli

Isolated English *consonant-vowel* (CV) syllables were chosen from the Linguistic Data Consortium (LDC) 2205S22 database (Fousek et al., 2004), spoken by eighteen native speakers of American-English. The CV syllables consisted of sixteen consonants (six stops /p, b, t, d, k, g/, eight fricatives /f, v, s, ʃ, z, ʒ, ð, θ/, and two nasals /m, n/) followed by the /a/ vowel (Miller & Nicely, 1955). All stimuli used were digitally recorded at a sampling rate of 16 kHz. They were presented monaurally in quiet and at five different SNRs (+12, +6, 0, -6, -12 dB) in speech-weighted noise. The presentation level of the syllables was set to the subject's *most comfortable level* (MCL) initially, and then adjusted so that the CVs were equally loud independent of SNR. A specific overall attenuator setting (i.e., 0, +10, +20 dB) was maintained for each listener throughout the experiment, while minor variations in intensity (+3 to -3 dB) were made via numerical scaling of a sound card. Stimuli were intentionally designed to include two low, two medium, and two high error utterances (a total of six different utterances per syllable, provided, in order to create a more realistic listening situation.

NAL-R Amplification Condition

To compare the consonant error between the flat gain at MCL and NAL-R amplification (also at MCL, but gain was frequency dependent based on pure-tone threshold) conditions, all subjects were tested in the two conditions, called 'no NAL-R condition' and 'NAL-R amplification condition'. When simulating the NAL-R condition, its formula was calculated in two steps for each subject, by obtaining the required *real - ear gain* (REG) as a function of frequency (Dillon, 2001).

Step 1:

Calculate $X(\mathrm{dB}) = 0.15 \times (HTL_{500} + HTL_{1000} + HTL_{2000})/3$, where HTL_f is the hearing threshold level (HTL) of the ear at frequency f.

Step 2:

Calculate the prescribed REG at each frequency:

REG_{250} (dB) $= X + 0.31 \times HTL_{250} - 17$

REG_{500} (dB) $= X + 0.31 \times HTL_{500} - 8$

REG_{1000} (dB) $= X + 0.31 \times HTL_{1000} - 3$

REG_{1500} (dB) $= X + 0.31 \times HTL_{1500} + 1$

REG_{2000} (dB) $= X + 0.31 \times HTL_{2000} + 1$

REG_{3000} (dB) $= X + 0.31 \times HTL_{3000} - 1$

REG_{4000} (dB) $= X + 0.31 \times HTL_{4000} - 2$

REG_{6000} (dB) $= X + 0.31 \times HTL_{6000} - 2$, where REG_f is the real-ear gain at frequency f.

Experimental Procedure

All subjects had one practice session consisting of ten syllables in quiet to familiarize each subject with the test. Subjects were asked to identify the consonant in the presented CV syllable by selecting one of 16 software buttons on a computer screen, each labeled with an individual consonant sound (Fig. 2). A 'noise only' button was allowed for the subjects to choose if they heard only noise without any speech. A pronunciation for each consonant was provided below its button to avoid possible confusions from any orthographic similarity between consonants (e.g., /ʃ/ of shoes). The subjects were allowed to hear each utterance a maximum of 3 times before making their decision. Once a response was entered, the next syllable was automatically presented after a short pause. Each syllable presentation was randomized with respect to consonants and speakers, but not with respect to SNR. The test proceeded from the easiest to the most difficult noise conditions - quiet first, followed by +12 to -12 dB SNR. This was done in order to gradually increase the difficulty from the onset, so that subjects were not pushed beyond their limits in terms of performance level. Each subject heard a maximum of 1,152 trials (16 consonants × 6 utterances × 2 presentations × 6 different noise conditions). When the score was less than or equal to 3/16 (18.75%, or three times chance) for each consonant, that consonant was not presented at subsequent (lower) SNRs. The experiment took a total of 1 to 1.5 hours per ear.

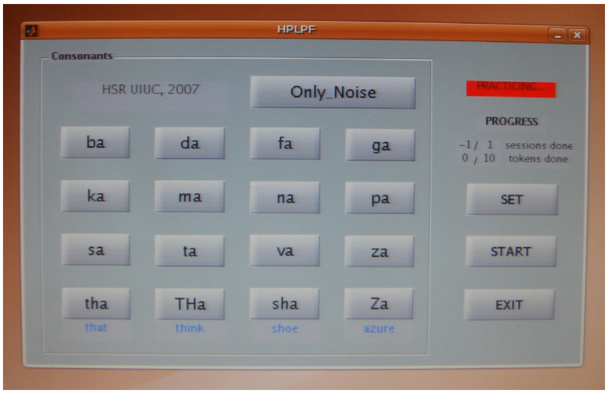
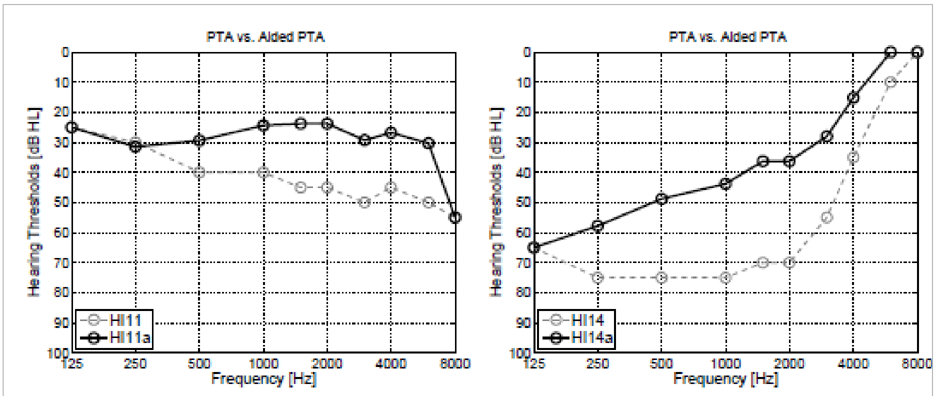


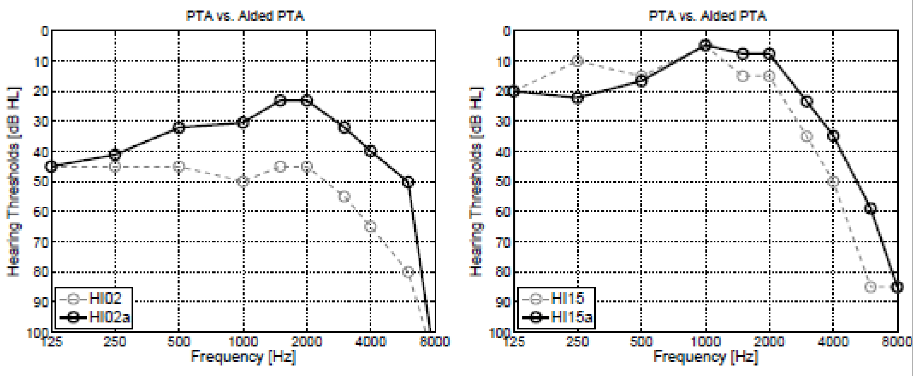
Figure 2. Example of experimental condition: Subjects make a response by selecting one of 16 software buttons on a computer screen when they hear the stimulated consonant-vowel syllable.

Statistical Analysis

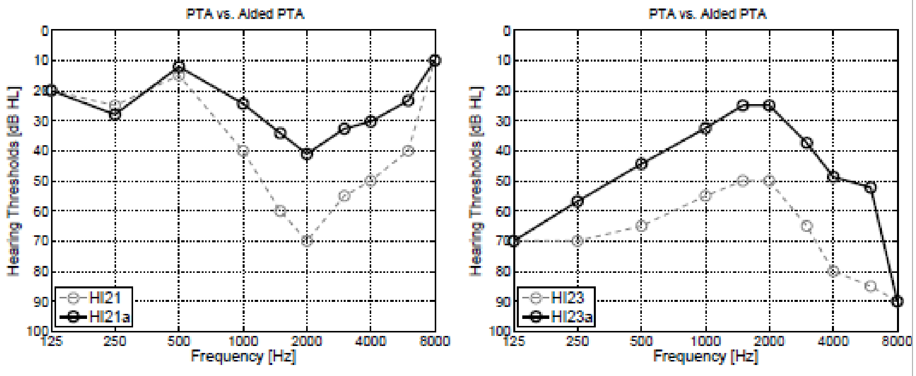
In this section, we would like to not suggest a typical statistical analysis which has used in audiology and speech perception research, i.e., *t*-test, ANOVA, regression, and so



(a) Flat Hearing Loss (b) Low-frequency Hearing Loss



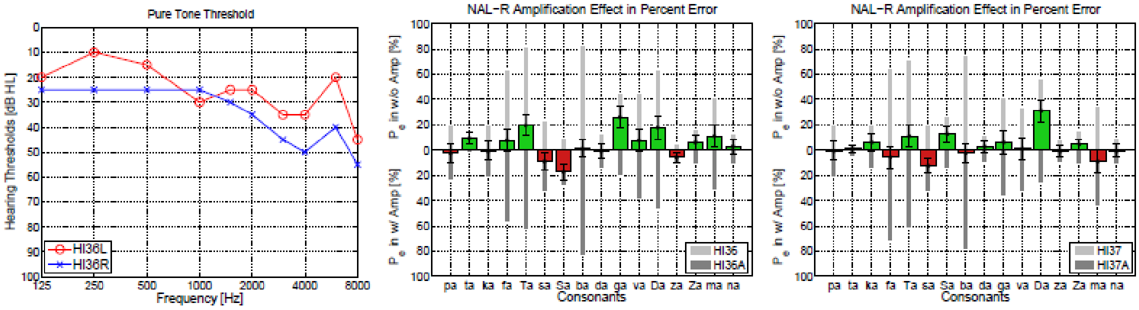
(c) High-frequency Hearing Loss (d) Ski-slope HF Hearing Loss



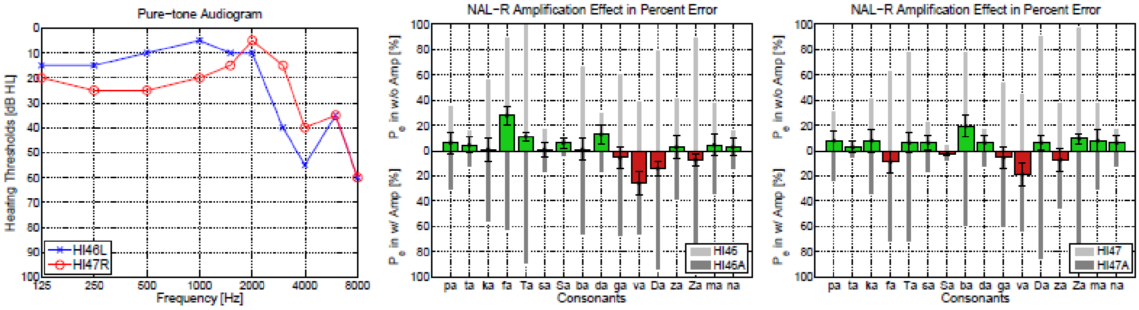
(e) Notched Hearing Loss (f) Reverse-Notched Hearing Loss

Figure 3. Examples of the comparison between pure-tone audiogram (light dashed grey curve) and aided pure-tone threshold (black solid curve) by applying the NAL-R insertion gain to the hearing aids of 6 HI listeners. Each panel represents a different configuration of hearing loss: Flat hearing loss, low-frequency hearing loss, high-frequency hearing loss, ski-slope high-frequency hearing loss, notched hearing loss (or middle-frequency hearing loss), and reverse-notched hearing loss.

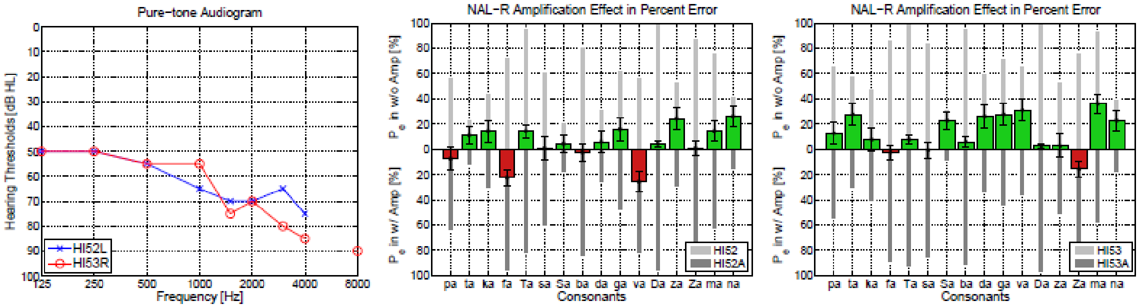
on. Since such analysis methods fail to show individual characteristics of HI speech perception, we consisted of a large number of CV trials in order to statistically show the characteristic difference in the beginning of the experimental design. We dealt with the difficult problem of determining the number of trials required to quantify speech perception, when building CV confusion matrices (or a count matrix). We proposed *Bernoulli trails*; N_t of a particular CV sound is required in order to determine the 35 probability = $P_{h|s}$ with a specific confidence that consonant was heard ($_h$) when consonant is spoken ($_s$), resulting in a maximum of 1,152 trial per ear.



(a) PTA: HI36 (b) HI36L (c) HI36R



(d) PTA: HI46 (e) HI46L (f) HI46R



(g) PTA: HI52 (h) HI52L (i) HI52R

Figure 4. Consonant-dependence in applying no NAL-R condition at MCL vs. NAL-R amplification condition across the 16 consonants. The three left panels show PTA results in the HI subjects and the middle and right panels show their consonant loss profiles in left and right ears, respectively. On the middle and right panels, bar graphs present percent error of each consonant in light grey for no-amplification condition and dark grey for with-amplification. Green bars (above zero) mean NAL-R positive benefit and red bars (below zero) show negative benefit. Error bars indicate one standard error (SE). Note some consonants improve when applying NAL-R amplification and some do not, showing a consonant-dependence.

RESULTS

1. Comparison between the PTA vs. Aided Threshold

<Fig. 3> demonstrates how much pure-tone audibility is shifted after applying the NAL-R prescriptive method. Each panel has two audibility curves: a light dashed grey curve for PTA and a black solid curve for *aided* PTA. Because of no REG for .125 and 8 kHz in the NAL-R formula, there was a greater audibility change in the middle frequencies including .5, 1, and 2 kHz, generally. However, there was also an individual difference between *PTA* and *aided* PTA depending on the subject's PTA and calculated REG. Compared to the other subjects, the subject in panel (d) <Fig. 3> of did not get a change of the aided PTA except

for 25 dB at 6 kHz.

2. Consonant-Dependence

<Fig. 4> shows three PTAs (left panels) along with their consonant loss profile (middle and right panels). Each of the middle and right panels shows percentage error for each consonant in left and right ears, respectively, as light grey bars from the baseline for no NAL-R condition (using flat gain with MCL) and dark grey bars for NAL-R amplification condition. The difference in the percentage error of consonant identification between the no NAL-R and NAL-R amplification conditions across 16 consonants is presented as block wide green and red bar graphs. The green bar located above the horizontal axis indicates a NAL-R positive benefit; the red bar below the horizontal axis indicates a NAL-R negative benefit for that consonant. Since the number of presentations at each SNR was not statistically sufficient in the low SNRs, we averaged the error rates over five SNRs (tested at quiet, 12, 6, 0, and -6 dB) for each consonant, raising the number of presentation trials from 12 to 60. We did not include -12 dB SNR in this average, since at this level most HI subjects had 100% error in all 16 consonants.

Most importantly, three listeners showed different NAL-R amplification positive/negative benefits at different consonants: some consonants improved up to 38% (positive), yet some were worse 20% or more (negative). In the top panels (a,b,c) of <Fig. 4>, subject HI36 showed positive benefits of 10% or more in/ta/ and /ma/ and 20% or more in /θa/, /ga/, and /ða/ at the left ear (HI36L), and for 10-15% in /θa/ and /ʃa/ and 30% in /ða/ at the right ear (HI36R), whereas there was negative benefit (about 20%) for /ʃa/ and /sa/ sounds for left and right ears, respectively. The /ʃa/ sound resulted in 16% positive benefit for the right ear; in contrast it showed 18% negative benefit for the left ear. In the middle panels (d,e,f), subject HI46 showed the positive benefit for /fa/ (28%), /θa/ (12%), and /da/(14%) in the left ear (HI46L) and for /ba/ (20%), and /ʒa/ (11%) in the right ear (HI46R), whereas /va/ (25%) and /ða/ (18%) sounds in left ear and /va/ (20%) sound in the right ear were worse in the NAL-R condition than in the no-amplification condition. In the bottom panels (g,h,i), subject HI52 had highly positive benefit in most consonants, with a maximum benefit of 38% for /ma/ (52R). That is, his results showed positive benefit for /ta/, /ka/, /θa/, /ga/, /za/, /ma/, and /na/ in the left ear and /pa/, /ta/, /ʃa/, /da/, /ga/, /va/, /ma/, and /na/ in the right ear, although he also had negative benefit for /fa/ and /va/ in the left ear and /ʒa/ in the right ear. Note that all 20 subjects (40 ears) had different positive/negative benefits of NAL-R amplification for different consonants, even though the amplification condition was fitted to each ear under the same procedure.

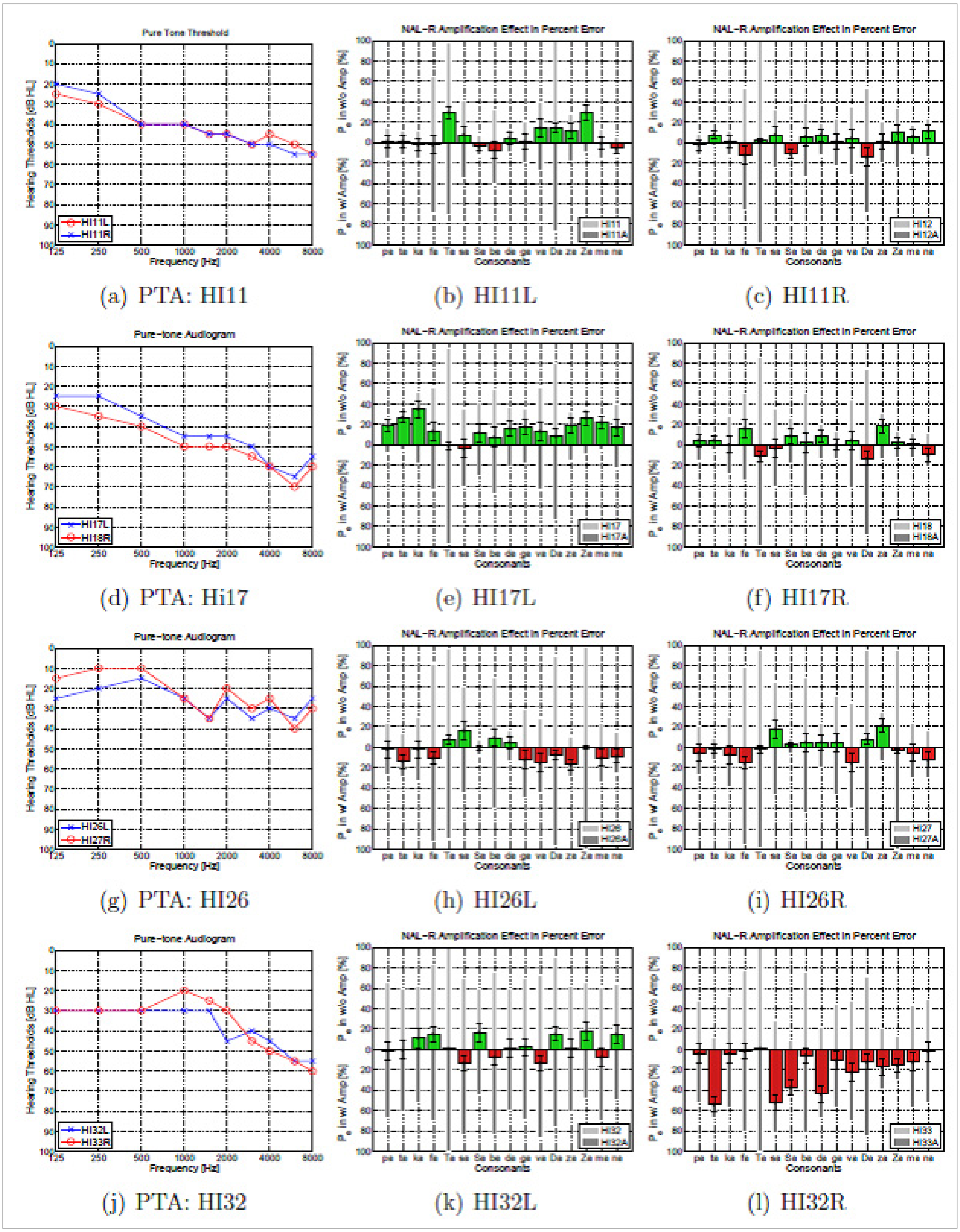
3. Listener-Dependence

1) Symmetric Hearing Loss

<Fig. 5> explains that the subjects who have symmetric bilateral hearing loss (criterion is less than a 10-dB difference of pure-tone threshold between left and right ears at all testing frequencies) do not receive the same benefit of NAL-R amplification for consonants in left vs. right ear. In the first row of panels (a,b,c), the subject HI11 has symmetric mild-to-moderate gradual high frequency hearing loss. She reported an 18-30% positive benefit with NAL-R amplification for /θa/, /va/, /ða/, /za/, and /ʒa/ in her left ear (HI11L) and 10% or more positive benefit for /ta/, /sa/, /da/, /ʒa/, and /na/ in the right ear (HI11R). Although having no negative NAL-R amplification benefit of any consonant on her left ear, three sounds, /fa/, /ʃa/, and /ða/, were worse up to 17% in her right ear after applying the NAL-R amplification. Interestingly, /ða/ sound gave 18% positive benefit to her left ear, but an 18% negative benefit to her right ear.

In the second row of panels (d,e,f) of <Fig. 5>, subject HI17 showed positive benefit in most consonants in her left ear (HI17L), whereas her right ear (HI17R) results in about 15% negative amplification benefit for /θa/, /ða/, and /na/; all three of these improved in the left ear, especially /na/ (18%-positive). Her left ear seems to be an ideal candidate for a hearing aid. Although her left and right ears showed a very similar degree (41-46 dB HL) and configuration (gradual high frequency sloping hearing loss) in the PTA result, the application of NAL-R amplification to her right ear did not result in uniformly enhanced speech perception having the amplified sounds.

Subject HI26 in the third row panels (g,h,i) showed a 10-17% positive amplification benefit for /sa/ and /ba/



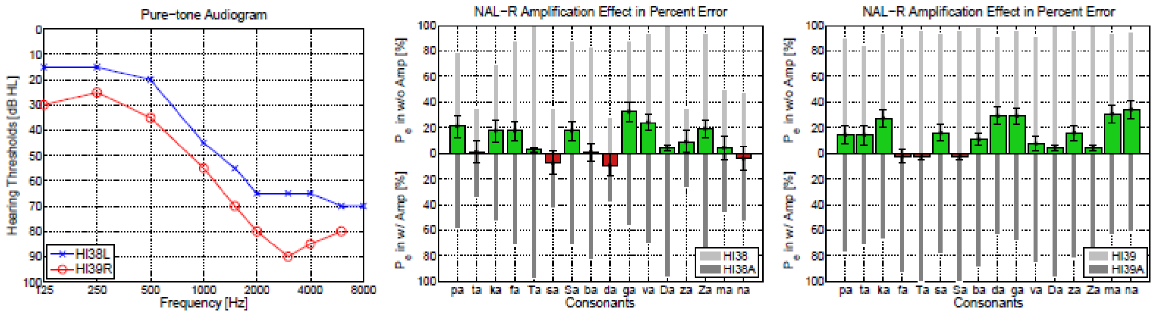
(a) PTA: HI11 (b) HI11L (c) HI11R

(d) PTA: Hi17 (e) HI17L (f) HI17R

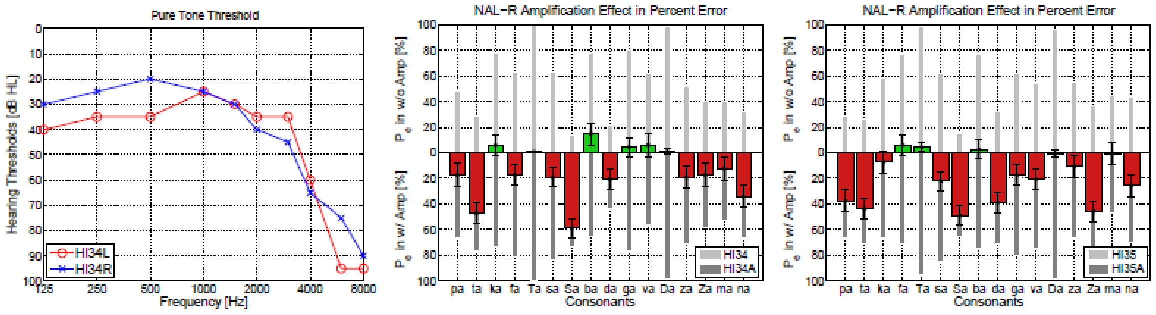
(g) PTA: HI26 (h) HI26L (i) HI26R

(j) PTA: HI32 (k) HI32L (l) HI32R

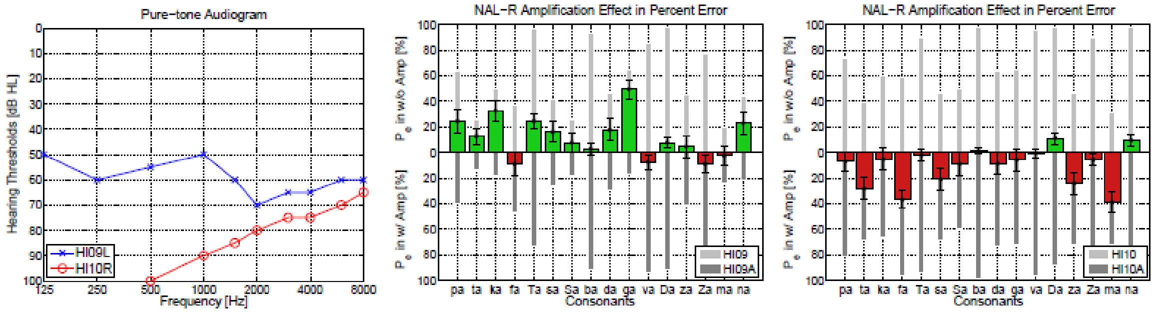
Figure 5. Symmetric bilateral hearing loss and asymmetric benefit of NAL-R amplification. The four left panels show PTA results in the HI subjects and the middle and right panels show their consonant loss profiles in left and right ears, respectively. On the middle and right panels, bar graphs present percent error (%) of each consonant in light grey for no-amplification condition and dark grey for with-amplification. Green bars (above zero) mean NAL-R positive benefit and red bars (below zero) show negative benefit. Error bars indicate one standard error (SE). There is a different positive-benefit in NAL-R amplification in left and right ears in four HI subjects despite a symmetric pure-tone hearing loss, showing that their consonant perception is not homogeneous across consonants.



(a) PTA: HI38 (b) HI38L (c) HI38R



(d) PTA: HI34 (e) HI34L (f) HI34R



(g) PTA: HI09 (h) HI09L (i) HI09R

Figure 6. Consonant perception and NAL-R benefit for the subjects who have asymmetric bilateral hearing loss. The three left panels show PTA results in the HI subjects and the middle and right panels show their consonant loss profiles in left and right ears, respectively. On the middle and right panels, bar graphs present percent error (%) of each consonant in light grey for no-amplification condition and dark grey for with-amplification. Green bars (above zero) mean NAL-R positive benefit and red bars (below zero) show negative benefit. Error bars indicate one standard error (SE). First top panels (a,b,c) show positive benefit in most consonants after applying NAL-R amplification for both left and right ears. Middle panels (d,e,f) show negative benefit in most consonants after applying NAL-R amplification for both ears. The third row panels (g,h,i) show positive benefit in most consonants on her left ear, yet negative in most consonants on her right ear.

sounds and 20% positive benefit for /sa/ and /za/ sounds in left (HI26L) and right (HI26R) ears, respectively. Although /za/ showed a 20% positive benefit in the right ear, her left ear responded to it with an 18% negative benefit. Including /za/ sounds, the subject also has negative benefit for /ta/, /fa/, /ga/, /va/, and /ma/ in her left ear, whereas the right ear had negative benefit for /fa/, /va/, and /na/. Compared to the positive benefit in only two consonants per ear after using the amplification condition, her consonant perception was worse overall.

In the last row of panels (j,k,l) of <Fig. 5>, subject HI32 had a positive benefit for /ka/, /fa/, /ʃa/, /ða/, /ʒa/, and /na/, and a negative benefit for /sa/ and /va/ in her left ear (HI32L). Remarkably, her right ear (HI32R) did not have positive benefit for any consonant. Further, the /ʃa/ and /ʒa/ sounds, which showed a positive amplification benefit in her left ear, showed 38% and 26% negative benefit in her right ear, respectively. In addition, she had more than 40% negative benefit for /ta/, /sa/, and /da/ sounds. Despite these findings, her right ear, which she felt had much more difficulty in consonant perception and made high errors in the CV measurement, was not much different from the left ear in terms of PTA results.

2) Asymmetric Hearing Loss

<Fig. 6> shows that subjects who have asymmetric bilateral hearing loss (criteria are at least a 15-dB or greater difference at two or more frequencies) also exhibit consonant perception results that are not predicted by the PTA. The three subjects display obviously different results of consonant loss profiles and positive/negative amplification benefits in left vs. right ears.

Subject HI38, in the first row of panels (a,b,c) of <Fig. 6>, received an NAL-R benefit of about 20% in most consonants for the left (except for /sa/ and /da/ sounds) and right ears. Even though the right ear (HI38R) is 10-25 dB HL higher than the left ear (HI38L) in the PTA result, her right ear had more benefit, especially in /ma/ and /na/ sounds. In contrast, subject HI34, who has a similar configuration of ski-slope high frequency hearing loss, had different results from the subject HI38. In the second row panels (d,e,f), HI34 had negative benefit in all consonants after applying the NAL-R amplification. Except for a positive benefit of the /ba/ sound in the left ear, she heard distorted consonants, resulting in up to 60% worse perceptual accuracy. This result could not be predicted with only the PTA result and NAL-R fitting based on the PTA result, indeed, this result predicts her dissatisfaction with the hearing aid.

As an interesting case, HI09 in the third row of panels (g,h,i) had a positive benefit for /pa/, /ta/, /ka/, /θa/, /sa/, /da/, /ga/ (50%), and /na/ in her left ear (HI09L), but negative benefit for /ta/, /fa/ (38%), /sa/, /za/, and /ma/ (40%) in her right ear (HI09R). Her worse ear (according to the PTA result) did not perceive the consonants clearly with-amplification, contrary to the experience of subject HI38.

DISCUSSION AND CONCLUSION

Amplification Effect of Speech Perception

When we applied the additional audibility calculated by the NAL-R amplification correction to HI ears, pure-tone audibility was enhanced (Fig. 3). In addition, there was a statistically significant difference of HI consonant perception scores between no NAL-R and NAL-R amplification conditions. Overall consonant percent errors were decreased with NAL-R correction, compared to no NAL-R (flat gain) conditions. However, most HI subjects did report that to understand the consonants was not much different between the two conditions, and they sometimes complained that it was more difficult to understand the consonants with NAL-R correction. In other words, when we look at the aided audibility and average consonant errors (or scores) after fitting a hearing aid, the HI speech perception seems better than before wearing the hearing aid. However, we claim that the average score is an insufficient description of the effect of NAL-R.

As we already confirmed in the results, there is a significant difference among consonants: some consonants obtain great benefit from NAL-R and others do not. Also, subjects who have similar pure-tone audibility do not receive the same benefit from the amplification. Therefore, we conclude that although current amplification fitting methods can offer positive benefit on average to the speech perception of HI listeners, they cannot offer equally positive benefits to every consonant and every HI listener. We propose that a more consistent benefit could be obtained by using the CV measurement for detecting problems of HI speech perception and for a better strategy in fitting hearing aids.

Limitation of the Study

We have successfully developed full-rank consonant-confusion matrices as a function of SNR to provide a new clinical diagnostic test for quantifying speech perception in HI listeners. Our results indicate that SNHL listeners have a distinct impact on consonant identification. It is generally true that a HI listener cannot hear a sound because the dominant cue that defines the sound is distorted or inaudible due to the hearing loss or masking noise. Under certain circumstances, the HI listener may learn to use a set of minor cues that are ignored by the average normal hearing listeners because of the existence of the dominant cue. This is one of the reasons for which we need to measure HI speech perception using a slight different set of speech stimuli, called 'zero-error (ZE) utterances' which means utterances perceived with zero-error by NH listeners. If we use it, we will be able to avoid confounding NH and HI problems (or mistakes) and to find unique HI problems.

We tried to NAL-R amplification formula for the current study because of much simpler than other non-linear amplification formulas in terms of experimental design. However, the NAL-R formula is appropriate to hearing impaired listeners who have flat loss configuration. Therefore, although we could not generalize that current hearing aid fitting formula has the limitation to improve speech/consonant perception for SNHL, we extend to various current hearing aid fitting formula in the near future.

For the current study, we could not consider auditory and/or neural plasticity. Since our experiment is a sort of simulation that SNHL listeners wear the hearing aid fitted by using PTA results and amplification correction. However, we might agree that some listeners would be improved in their speech perception after wearing the hearing aid for several months.

Future Directions

Our findings should be applicable to the clinical settings to improve hearing aid fittings and design in the future. This CV test is too time-consuming for clinical use in its current format, but by reducing the number of syllables presented and carefully selecting exceptional tokens, it should be possible to develop a convenient, fast, and statistically viable speech prescription test for clinical HA fitting. It should also be a motivation for further studies in speech perception research related to the clinical practice. Methodology on how to best classify the inhomogeneous HI listeners' error patterns on a consonant-by-consonant basis is difficult. Another concern remains regarding how to effectively amplify consonants having high error rate, without distorting the perceptual cues for an HI listener's intact sound sensitivity (e.g., utterances for which NH subjects have no error in environments where the noise is as low as -2 dB SNR). We will continue to develop a categorical model of HI speech intelligibility, establishing a new 'no distortion' amplification formula that is based on individual prescriptive speech scores. The research will help HI listeners hear day-to-day conversations more clearly in both quiet and in noise, and aid in audiological diagnosis and successful rehabilitation to increase speech perception for the HI population.

Future research and several ongoing studies related to the consonant confusion measures will seek to address several possible future goals. The first is to find the relationship between consonant error and cochlear dead regions, analyzing the confusions for clues on specific feature loss. It may be possible to use a test based on the consonant confusion matrices to detect cochlear dead regions as an alternative to existing psychoacoustic measurements (e.g., psychophysical tuning curve and TEN, by Moore et al.(2004)), which are not functional for clinical use. We will also study the reverse mapping from confusions to distorted features, given consonant-loss in the CLP.

A second goal is to examine the benefit of amplified speech through our individual consonant-loss measure, our gold standard. Linear and non-linear multi-band amplification, corresponding to a dead region, may not be beneficial and may even impair speech intelligibility (Moore & Skrodzka, 2002; Moore & Alcantara, 2001). Our ongoing studies will explore the problem of speech perception in noisy situations.

Finally, we continue to work on establishing a delicate amplification formula that is based on individual speech scores, applying differential amplification (i.e., manipulating both frequency loudness and feature detection). The goal is to use features in the HI ears to provide no-distortion amplification. Our approach differs considerably from the current clinical amplification formulae because it is very efficient in manipulating relevant speech features; hence, it might benefit both experienced hearing-aid patients and new wearers in terms of auditory plasticity. The study could thus contribute significantly to helping HI listeners hear conversations more clearly and could further aid in audiological diagnosis and successful rehabilitation in the future.

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