J Am Acad Audiol 22:441–459 (2011)

A Comparison of Gain for Adults from Generic Hearing Aid Prescriptive Methods: Impacts on Predicted Loudness, Frequency Bandwidth, and Speech Intelligibility

DOI: 10.3766/jaaa.22.7.5

Earl E. Johnson*†
Harvey Dillon‡

Abstract

Background: Prescriptive methods have been at the core of modern hearing aid fittings for the past several decades. Every decade or so, there have been revisions to existing methods and/or the emergence of new methods that become widely used. In 2001 Byrne et al provided a comparison of insertion gain for generic prescriptive methods available at that time.

Purpose: The purpose of this article was to compare National Acoustic Laboratories—Non-linear 1 (NAL-NL1), National Acoustic Laboratories—Non-linear 2 (NAL-NL2), Desired Sensation Level Multistage Input/Output (DSL m[i/o]), and Cambridge Method for Loudness Equalization 2—High-Frequency (CAMEQ2-HF) prescriptive methods for adults on the amplification characteristics of prescribed insertion gain and compression ratio. Following the differences observed in prescribed insertion gain among the four prescriptive methods, analyses of predicted specific loudness, overall loudness, and bandwidth of cochlear excitation and effective audibility as well as speech intelligibility of the international long-term average speech spectrum (ILTASS) at an average conversational input level were completed. These analyses allow for the discussion of similarities and differences among the present-day prescriptive methods.

Research Design: The impact of insertion gain differences among the methods is examined for seven hypothetical hearing loss configurations using models of loudness perception and speech intelligibility.

Study Sample: Hearing loss configurations for adults of various types and degrees were selected, five of which represent sensorineural impairment and were used by Byrne et al; the other two hearing losses provide an example of mixed and conductive impairment.

Data Collection and Analysis: Prescribed insertion gain data were calculated in 1/3-octave frequency bands for each of the seven hearing losses from the software application of each prescriptive method over multiple input levels. The insertion gain data along with a diffuse field-to-eardrum transfer function were used to calculate output levels at the eardrums of the hypothetical listeners. Levels of hearing loss and output were then used in the Moore and Glasberg loudness model and the ANSI S3.5-1997 Speech Intelligibility Index model.

Results: NAL-NL2 and DSL m[i/o] provided comparable overall loudness of approximately 8 sones for the five sensorineural hearing losses for a 65 dB SPL ILTASS input. This loudness was notably less than that perceived by a normal-hearing person for the same input signal, 18.6 sones. NAL-NL2 and DSL

*James H. Quillen VA Medical Center, Mountain Home, TN; †Department of Audiology and Speech-Language Pathology, East Tennessee State University, Johnson City; ‡National Acoustic Laboratories of Australia, Sydney

Earl E. Johnson, Mountain Home VA Medical Center, PO Box 4000, Audiology-126, Mountain Home, TN 37684; Phone: 423-926-1171, ext. 7149; Fax: 423-979-3403; E-mail: earl.johnson@va.gov

This article was prepared, in large part, during part of a 2.5 mo in-residence training stage at the Australian National Acoustic Laboratories under the mentorship of Harvey Dillon, Ph.D. The training stage was supported by a Career Development Award—1 granted to the authors and additional mentors, Richard Wilson, Ph.D., and Todd Ricketts, Ph.D., by the U.S. Department of Veterans Affairs Rehabilitation Research and Development Office. The in-residence training stage was also supported by an A. Charles Holland Foundation Scholarship from the Amplifon Center for Research and Studies in Milan, Italy, with approval from VA MidSouth Healthcare Network VISN 9 Regional Counsel. The opinions expressed in this article are those of the authors and do not necessarily represent the official position of the U.S. Department of Veterans Affairs or the U.S. government.

m[i/o] also provided comparable predicted speech intelligibility in quiet and noise. CAMEQ2-HF provided a greater average loudness, similar to NAL-NL1, with more high-frequency bandwidth but no significant improvement to predicted speech intelligibility.

Conclusions: Definite variation in prescribed insertion gain was present among the prescriptive methods. These differences when averaged across the hearing losses were, by and large, negligible with regard to predicted speech intelligibility at normal conversational speech levels. With regard to loudness, DSL m[i/o] and NAL-NL2 provided the least overall loudness, followed by CAMEQ2-HF and NAL-NL1 providing the most loudness. CAMEQ2-HF provided the most audibility at high frequencies; even so, the audibility became less effective for improving speech intelligibility as hearing loss severity increased.

Key Words: bandwidth, CAMEQ2-HF, compression, DSL m[i/o], hearing aid, loudness, NAL-NL2, prescription, speech intelligibility

Abbreviations: ABG = air–bone gap; AC = air conduction; BC = bone conduction; CAMEQ2-HF = Cambridge Method for Loudness Equalization 2—High-Frequency; DSL i/o = Desired Sensation Level Input/Output; DSL m[i/o] = Desired Sensation Level Multistage Input/Output; ERB = equivalent rectangular bandwidth; FIG6 = Figure 6; IHAFF = Independent Hearing Aid Fitting Forum; ILTASS = international long-term average speech spectrum; NAL-NL1 = National Acoustic Laboratories—Non-linear 1; NAL-NL2 = National Acoustic Laboratories—Non-linear 2; NAL-R = National Acoustic Laboratories—Revised; NAL-RP = National Acoustic Laboratories—Revised Profound; rms = root mean square; SII = Speech Intelligibility Index; ULC = upper limits of comfort

INTRODUCTION

Prescriptive methods of frequency-dependent insertion gain as a function of input level are a vital part of hearing aid fittings particularly during the initial part of the process. During and/or following the initial visit, prescriptive recommendations may be modified based on patient feedback obtained via face-to-face interaction with the audiologist, also known as the typical follow-up appointment, or via the training of parameters through patient interaction with the hearing aid. In support of using prescriptive methods at the initial fitting visit, recent research has indicated that when listeners are allowed to train the frequency-dependent gain of the hearing aids, the end result is affected by the starting response baseline (Dreschler et al, 2008; Keidser et al, 2008; Mueller et al, 2008).

Specifically, Dreschler et al (2008) reported that if the baseline response had 4 dB less overall gain and a 6 dB/octave steeper slope, then listeners would, on average, select 2 dB less gain and a 3 dB/octave steeper slope than the response preferred when starting at a National Acoustic Laboratories—Revised Profound (NAL-RP) baseline. Keidser et al (2008) further indicated that the "preferred" responses following training that began at differing baselines were in actuality not overwhelmingly preferred after all. Only 25% of participants in the study demonstrated a reliable preference between two alternative trained frequency responses. These authors concluded that adjustments to frequency-dependent gain should begin from an appropriately prescribed starting response.

Surveys of clinical practice have shown that prescriptive methods and real-ear probe-microphone equipment are currently a part of many practices. Almost 60% of audiologists report owning real-ear probe-microphone equipment, and 45% of audiologists report using real-ear probe-microphone equipment routinely in their practice (Mueller and Picou, 2010). Thirty percent of audiologists reported use of the equipment for the primary purpose of matching either NAL or Desired Sensation Level (DSL) targets; other primary purposes included ensuring that speech was within the residual dynamic range (35%), ensuring that gain was appropriate (28%), and matching manufacturer software targets (7%) (Mueller and Picou, 2010).

Accordingly, and due to the utility of prescriptive methods in common clinical practice, hearing health-care providers need ongoing information and comparisons of currently available prescriptive methods. Additionally, because providing maximal speech intelligibility through audibility restoration without exceeding normal loudness, causing loudness discomfort, or the like is typically sought by current prescriptive methods (Dillon, 1999; Byrne et al, 2001; Scollie et al, 2005; Keidser et al, 2011; Moore et al, 2010), models of predicted speech intelligibility and loudness provide a basis for comparing the methods. In this article, only prescriptive methods for an adult-aged population are considered.

This study is an extension of a Byrne et al (2001) publication comparing prescriptive methods available at that time: National Acoustic Laboratories—Non-linear 1 (NAL-NL1), Independent Hearing Aid Fitting Forum (IHAFF; threshold version), Desired Sensation Level Input/Output (DSL i/o), and Figure 6 (FIG6), each of which used either a loudness normalization or a loudness equalization approach to assigning gain and output targets. In brief, loudness normalization intends to restore, at each frequency, the loudness perception of the listener with hearing impairment to the same

loudness perceived by a listener with normal hearing, whereas loudness equalization aims to equalize the perception of loudness over a range of frequencies instead of having lower frequencies dominate loudness, as is the case for listeners with normal hearing.

Both FIG6 and IHAFF were based on a loudness normalization approach. Byrne et al (2001) classified the DSL i/o as ambiguous with regard to loudness equalization or normalization. The originally reported DSL formula of Cornelisse et al (1995) normalized loudness, whereas Seewald et al (1996) described DSL as a loudness equalization procedure that can be modified to provide normalization.

NAL-NL1, which was a revision of NAL (Byrne and Tonisson, 1976), NAL-R (Byrne and Dillon, 1986), and NAL-RP (Byrne et al, 1991), aimed to maximize predicted speech intelligibility while limiting loudness for the hearing-impaired listener to no greater than that perceived by a normal-hearing person for the same input signal. The NAL-NL1 prescription usually led to 1/3-octave bands of speech being equally loud (according to the loudness model) except for very low and very high frequencies, which had lower predicted loudness. A flattening of loudness was the explicit aim of the first NAL prescription method (Byrne and Tonisson, 1976) and was confirmed as an appropriate goal in later evaluations of prescription efficacy (Byrne, 1986a, 1986b; Byrne et al, 2001).

Since the Byrne et al (2001) publication, both the NAL and DSL methods for fitting hearing aids have been revised. The newest NAL method is the National Acoustic Laboratories—Non-linear 2 (NAL-NL2) (Dillon, 2006; Keidser and Dillon, 2006). NAL-NL2 retains the same design rationale as NAL-NL1 (i.e., maximizing predicted speech intelligibility while constraining loudness) but can prescribe targets up to 10 kHz using a new desensitization factor for predicting speech intelligibility, a more recent loudness model (Moore and Glasberg, 2004), and behavioral preferences for gain and compression ratio based on human subject experience with the NAL-NL1 procedure. The desensitization factor reduces the effectiveness of audibility with increasing hearing loss and as a result, may not prescribe insertion gain to achieve audibility at higher frequencies on purpose.

The newest DSL method is Desired Sensation Level Multistage Input/Output (DSL m[i/o]), also known as DSL v5.0 (Bagatto et al, 2005; Scollie et al, 2005). The DSL method has the stated goals of avoiding loudness discomfort, providing audibility of speech across a wide range of input levels, and accommodating the prescriptive targets for both quiet and noisy environments, as well as for infants versus children versus adults (Scollie et al, 2005).

In that same period, the series of prescriptive methods emerging from the University of Cambridge leading to the development of the Cambridge Method for Loudness Equalization 2—High-Frequency (CAMEQ2-HF) have also gained recognition. Like its predecessor, the Cambridge Method for Loudness Equalization (Moore et al, 1999; Moore, 2005), CAMEQ2-HF aims to place as much of the speech spectrum as possible above absolute threshold for a given overall loudness (Moore et al, 2010). A defining feature of CAMEQ2-HF is its prescription of gain at 10 kHz to place the root mean square (rms) level of speech at this frequency at hearing threshold irrespective of hearing loss severity.

While there are many prescriptive methods other than the ones listed already, most of these are not generic but have been developed by hearing aid manufacturers specifically for their products. Some of these manufacturer-specific methods do, however, have a body of supporting research (e.g., Lunner et al, 1997a, 1997b, 1997c; Arlinger et al, 1998), as noted by Byrne et al (2001). At the time of writing, generic, non-brand-specific prescriptive methods available for fitting hearing aids are CAMEQ2-HF, DSL m[i/o], and NAL-NL2. As this article follows on the work of Byrne et al (2001) and as NAL-NL1 has been widely used for adults over the past decade, NAL-NL1 was included as a comparative reference in this study.

In some respects, current methods reflect past prescriptive methods. For example, the half-gain rule of Lybarger (1963) influenced the NAL prescriptive methods (Byrne et al, 2001). Likewise, the POGO formula of McCandless and Lyregaard (1983) is reportedly almost identical to the original University of Cambridge formula (Byrne et al, 2001). The IHAFF and FIG6 methods were not included in this article because there have been no changes to these methods since the Byrne et al (2001) publication. Additionally, IHAFF and FIG6 methods are no longer typically used clinically, as evidenced by a general lack of inclusion in commonly available real-ear probe-microphone equipment and clinical surveys of practice. The lack of their use reflects a trend to move away from normalizing loudness to equalizing loudness when prescribing amplification.

Comparisons of Relevant Evaluation Criteria

This article compares the prescriptive methods in terms of their recommended real-ear insertion gains. From the insertion gains, real-ear aided response levels were calculated and then used to predict, as described in the Methods section, frequency-specific loudness, overall loudness, and bandwidth of cochlear excitation and effective audibility, as well as speech intelligibility. These evaluation criteria were selected because each has been shown to be salient to hearing-impaired listeners with regard to hearing aid outcomes. That is, two out of three principal component outcome categories pertinent to hearing aids identified by Humes (2003),

that is, subject benefit/satisfaction and actual speech recognition performance, are best accounted for by variables that pertain to loudness and speech intelligibility measures. Aided judgments of sound quality pertaining to softness and not exceeding loudness discomfort levels were significant predictors of subjective benefit/satisfaction. Audibility, which is quantified as part of a speech intelligibility prediction, was the best predictor of obtained speech recognition performance. The salience of bandwidth to improving speech recognition performance with hearing aids and sound quality preference has been demonstrated by a number of studies (Stelmachowicz, 2001; Turner and Henry, 2002; Hornsby and Ricketts, 2003; Moore and Tan, 2003; Ricketts et al, 2008); however, results can be dependent on the magnitude and/or slope of high-frequency hearing loss (Ching et al, 1998; Hogan and Turner, 1998; Ricketts et al, 2008). For this reason, it is of interest to compare prescriptive methods like NAL-NL2 and CAMEQ2-HF, which have differing approaches to amplifying high frequencies when hearing loss severity increases, as described already.

METHODS

Audiograms

For consistency, this article used the same five audiograms of sensorineural hearing losses as given in Figure 2 of Byrne et al (2001). These audiograms were chosen by Byrne et al after a careful review of prescribed insertion gains from 13 audiograms, as they believed that these five audiograms exemplified typical differences between prescriptive methods. The five audiograms are presented in the top portion of Figure 1, labeled A-1 through A-5. In addition to fitting hearing aids for the rehabilitation of sensorineural hearing losses, audiologists also fit hearing aids to patients with conductive and mixed hearing losses. Therefore, a severe mixed loss (A-6) and a predominantly conductive hearing loss of moderate degree with a 40 dB conductive component (A-7) were included. These two audiograms are presented in the bottom portion of Figure 1. While these are only seven audiograms, the configuration and magnitude of the losses represent a sizable range of hearing losses commonly found within a patient population.

Software Options and Resultant Insertion Gains

Insertion gains for the each of the seven hearing losses were taken from the most recent software program of each prescriptive method (NAL-NL1 version 5.0.149, NAL-NL2 version 1.927, DSL m[i/o] version 5.021, and CAMEQ2-HF version date July 2010). Each software program was configured in a consistent manner based

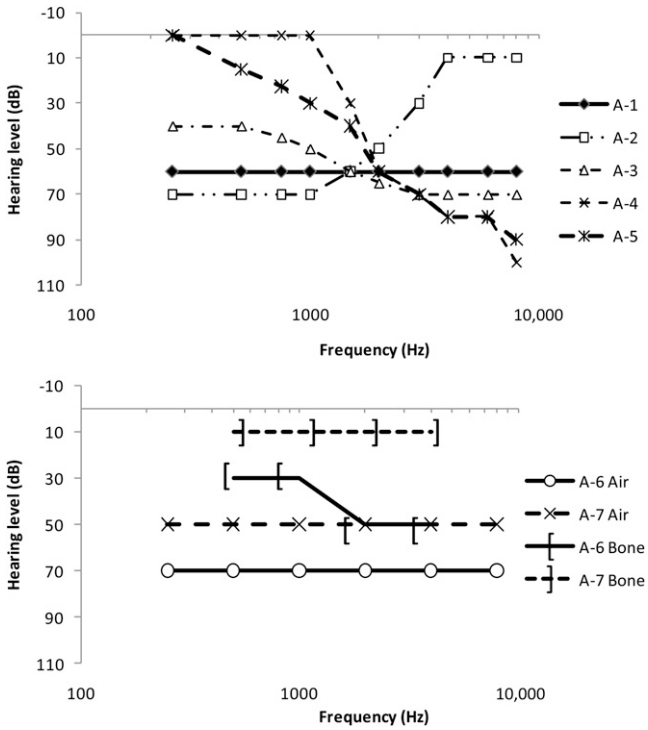

Figure 1. Top panel: Audiograms 1–5 (A-1 through A-5)—same sensorineural hearing losses as in Byrne et al (2001). Bottom panel: Audiograms 6–7 (A-6 through A-7)—mixed and conductive hearing losses.

on characteristics of a hypothetical patient and hearing aid. That is, for all audiograms the patient was considered to be of adult age. For the DSL m[i/o] targets, the target type associated with "acquired" (i.e., adult rather than pediatric) hearing loss was chosen. Additionally, the number of compression channels chosen was discussed with the developers of each prescriptive method and thought to not significantly affect prescribed insertion gains for any method and hence, the main findings reported herein. Thus, hearing aid compression options were set to a two-channel, wide dynamic-range compression behind-the-ear device with a crossover frequency of 1024 Hz. Output limiting was set to two channels also. A bilateral fitting option was available within each software program and was always selected. A unilateral fitting option would be expected to yield similar differences between prescriptive methods as discussed herein provided the use of a similar binaural summation effect. For the NAL-NL1, NAL-NL2, and CAMEQ2-HF methods, compression threshold defaults were set to 52 dB SPL for the wideband rms level of speech. For DSL m[i/o], compression threshold varies with the hearing threshold level, ranging from 48 to 52 dB SPL for mild to moderate hearing losses up to about 65 dB SPL for severe hearing losses (Scollie et al, 2005). In addition, where available, probe microphone verification options were set to head surface (or above the pinna) for the reference microphone position

and 45 degrees for the soundfield speaker placement, assuming a speech-shaped input signal; however, neither probe microphone options affect prescribed insertion gains (used in this study) but, rather, real-ear aided gains and responses. Transducer tips for obtaining audiometric thresholds were always selected as insert earphones. A generic 3 mm vent size was selected, when possible, without consequence, as selected vent size does not impact prescribed insertion gains. To clarify this point, vent size impacts achieved insertion gain in the ear but not the desired insertion gain of a prescriptive method.

Because NAL-NL2 has introduced variations in prescribed gain associated with other characteristics, the default values of unknown patient gender, experienced hearing aid user, fast compression, and non-tonal language user were selected within its software program. Within the NAL-NL2 software, the selection of unknown gender results in an insertion gain 1 dB lower than for males and 1 dB higher than for females. The choice of experienced hearing aid user assigns more gain than that resulting from the theoretical derivation for hearing loss greater than 50 dB HL, with a plateau at 3 dB for 70 dB HL or greater. The new user choice assigns less gain for hearing loss greater than 35 dB HL, with a plateau at –7 dB for 60 dB HL or greater. The choice of non-tonal language makes use of the average band importance function for determining insertion gain (i.e., Pavlovic, 1994), whereas tonal languages have more reliance on lower-frequency information (i.e., a higher band importance function at lower frequencies), which results in allocation of more insertion gain to lower frequencies and less to higher frequencies. The non-tonal language option in NAL-NL2 is expected to be most similar to the band importance functions assumed by other prescriptive methods.

For all prescriptive methods except CAMEQ2-HF, insertion gains were provided for 50, 65, and 80 dB SPL speech input levels. CAMEQ2-HF provided insertion gains for the levels of 50, 65, and 85 dB SPL. Frequency-specific insertion gains for an 80 dB SPL for CAMEQ2-HF were interpolated from the prescribed insertion gains.

Both DSL m[i/o] and NAL-NL2 allowed for insertion gains to be exported in 1/3-octave band levels. For NAL-NL1 and CAMEQ2-HF, insertion gains were available in the form of a line graph or a text table, respectively. From the graph or table, the insertion gains at octave and interoctave frequencies were extracted and then interpolated and extrapolated to 1/3-octave band levels. When insertion gains for NAL-NL1 were missing at low or high frequencies, the gain was assumed to drop off at +6 dB/octave or –6 dB/octave, respectively, from the closest neighboring frequency with a present insertion gain prescription. Insertion gains were obtained in 1/3-octave levels from 200 to 8000 Hz (a frequency range that encompasses the vast majority of modern-day hearing aids) for all prescriptive methods.

Compression Ratios

For each of the four prescriptive methods, compression ratios were calculated as the change in input divided by the change in output. The input range was 30 dB (bounded by wideband rms speech levels of 50 and 80 dB SPL), with spectral shape equal to the international long-term average speech spectrum (ILTASS) of Byrne et al (1994). The compression ratios are presented at a frequency, 500 and 2000 Hz, within each of the two compression channels utilized.

Loudness

Specific loudness is calculated by frequency in equivalent rectangular bandwidths (ERBs) from the amount by which excitation at each frequency exceeds the threshold excitation at that frequency (Moore and Glasberg, 1997, 2004). ERBs are approximations of the filters used by the human cochlea for hearing, with bandwidth as a function of frequency (f) given by the formula $0.108f + 24.7$ (Glasberg and Moore, 1996). Overall loudness (in the units of sones and phons) is then calculated by summing across ERBs.

The specific loudness calculation includes the effect of hearing loss on the transfer function of the inner and outer hair cells. Default assumptions of the model partitioning loss between the inner and outer hair cells were adopted: outer versus inner hair cell damage was 0.9 versus 0.1, up to the maximum outer hair cell loss of 57.6 dB HL. Altering these frequency-specific weightings on outer and inner hair cell loss does affect the outcome of predicted loudness (Moore and Glasberg, 2004); however, these weightings have provided the best fit to previous loudness data (Moore and Glasberg, 2004) and were chosen accordingly. In practice, the amount of underlying outer versus inner hair cell loss is usually unknown.

For the conductive hearing loss, no outer or inner hair cell loss was assumed. In addition, because the loudness model was intended for cochlear hearing losses only, the output levels prescribed by the prescriptive methods for the mixed and conductive losses were attenuated by the amount of the conductive component prior to inputting them to the loudness model. This process of attenuation accounted for the outer and middle ear components of the mixed and conductive losses; as a result, loudness could be calculated in the same manner as for the sensorineural hearing losses using bone-conduction hearing thresholds for the mixed and conductive losses. Last, for comparative purposes, the loudness was modeled for a person with normal hearing sensitivity of 0 dB HL with no outer or inner hair cell loss.

Following the "readme" file instructions provided by Moore and Glasberg for their 2004 loudness model, the "input" file was changed for each audiogram and prescribed output levels in 1/3-octave bands for each of the prescriptive methods over the range of 200–8000 Hz for a 65 dB SPL ILTASS input signal. The frequency range of 200–8000 Hz was chosen because this was the range provided by all four prescriptive methods. Next, the loud16k.exe program was called for each input file and saved to an "output" file. This particular program allowed for hearing loss threshold inputs up to 14,000 Hz. Thresholds at 10,000, 12,500, and 14,000 Hz were assumed equal to the 8000 Hz threshold; this assumption is considered of little significance because the frequency range modeled for loudness was from 200 to 8000 Hz. The loudness was computed for each combination of the seven hearing losses and four prescriptive methods.

Bandwidth of Cochlear Excitation and Effective Audibility

From the Moore and Glasberg (2004) loudness model the bandwidth of cochlear excitation can be obtained. The model states that when specific loudness $N' = 0.00537$ in any ERB_N, the energy level (E) is such that the input sound is sufficient to reach hearing threshold, that is, $E = E_{THRQ} = 2.31$. This amount of specific loudness indicates excitation in the cochlea that is sufficient to cause a threshold response.

As a separate indication of effective audible bandwidth, the parameter k from the ANSI S3.5-1997 (American National Standards Institute, 2007) Speech Intelligibility Index (SII) method was used. This parameter equals the amount by which short-term speech maxima exceed the greater of hearing threshold and external masking noise. That is, when $k > 0$, then the 1/3-octave bandwidth contained audible speech information considered usable for speech understanding.

Predicted Speech Intelligibility in Quiet and in Noise

For each of the seven hearing losses and four prescriptive methods, the predicted SII based on the real-ear aided response was calculated for a 65 dB SPL input over the range of 200–8000 Hz for speech in quiet and in noise. For speech in quiet, two versions of the 1/3-octave band SII were used, assuming the average band importance function of Pavlovic (1994). The first SII method is that described in ANSI S3.5-1997. The second method includes much of the same transforms and steps as ANSI S3.5-1997, with the exception of using a greater desensitization factor that was determined by NAL for derivation of the NAL-NL2 prescriptive method. Specifically, the desensitization factor used reduces effective audibility across all frequencies dependent upon the amount of hearing loss (in dB HL). The desensitization is governed by frequency-specific variables of m and p, that is, desensitized audibility,

$$k' = \left[\left(\frac{k}{30}\right)^p + m^p\right]^{1/p},$$

in which

$$m = \frac{1}{1 + e^{0.075(T-66)}}$$

$$p = \frac{T}{8} - 15$$

and in which T equals the amount of frequency-specific hearing loss in dB HL.

The SII from the first method is labeled herein as ANSI SII, and the second method, using the further desensitized audibility, k, is labeled NAL SII. For the mixed and conductive losses, the desensitization factor is based on the magnitude of the bone-conduction (BC) thresholds rather than the air-conduction (AC) thresholds, and SII is reported for the NAL method only. For the mixed and conductive losses, only NAL SII values are reported because there is only slight sensorineural hearing loss that would yield a small amount of desensitization. Hence, the difference between the ANSI SII and NAL SII is much less negligible for primarily conductive hearing losses than for more severe sensorineural hearing losses.

NAL SII values were also calculated for each of the four prescriptive methods and seven audiograms at three signal-to-noise ratios of –10 dB, 0 dB, and +10 dB using four separate background noise stimuli selected for variation in frequency response. The background noise stimuli selected, following a review of 12 stimuli published in Figure 2 of Keidser et al (2002), were Traffic, Office, Babble, and Toilet flushing. Respectively, these noises have a frequency spectrum consisting of a low-frequency emphasis, low- and high-frequency emphasis with midfrequency reduction, minimal to no change, and a high-frequency emphasis relative to the ILTASS of Byrne et al (1994) at an overall level of 65 dB SPL (Fig. 2). Through the use of both speech in quiet and speech in noise intelligibility calculations, frequency response differences between prescriptive methods allowed for the determination of whether one prescriptive method consistently offered better or poorer speech understanding than other methods.

RESULTS

Insertion Gains

The amount of frequency-specific prescribed amplification for each of the seven hearing losses for a 65 dB SPL ILTASS input is shown in Figures 3–4. In addition to showing insertion gains over the 200–8000 Hz range,

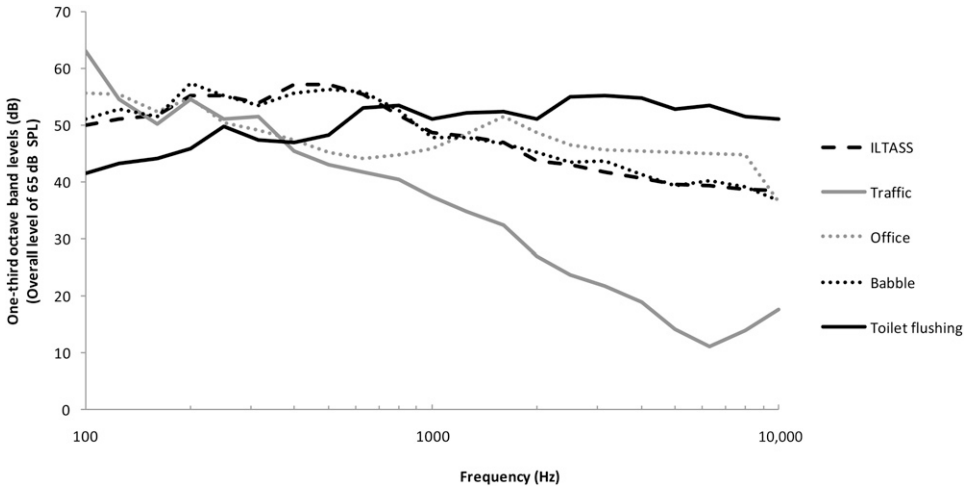

Figure 2. The 1/3-octave band level frequency spectrum of four stimuli taken from Keidser et al (2002) utilized in the calculation of predicted speech intelligibility in the presence of background noise; the international long-term average speech spectrum is included to serve as a reference.

these graphs present insertion gains prescribed at 160 Hz by each prescriptive method except for DSL m[i/o] and insertion gains prescribed at 10 kHz by CAMEQ2-HF as made available by the software program of each prescriptive method.

An adjustment was made to the insertion gains prescribed by DSL m[i/o] when implementing speech intelligibility and loudness modeling. Note the large negative insertion gains for DSL m[i/o] for Audiograms 4 and 5 in the bottom of Figure 3 and top of Figure 4, respectively.

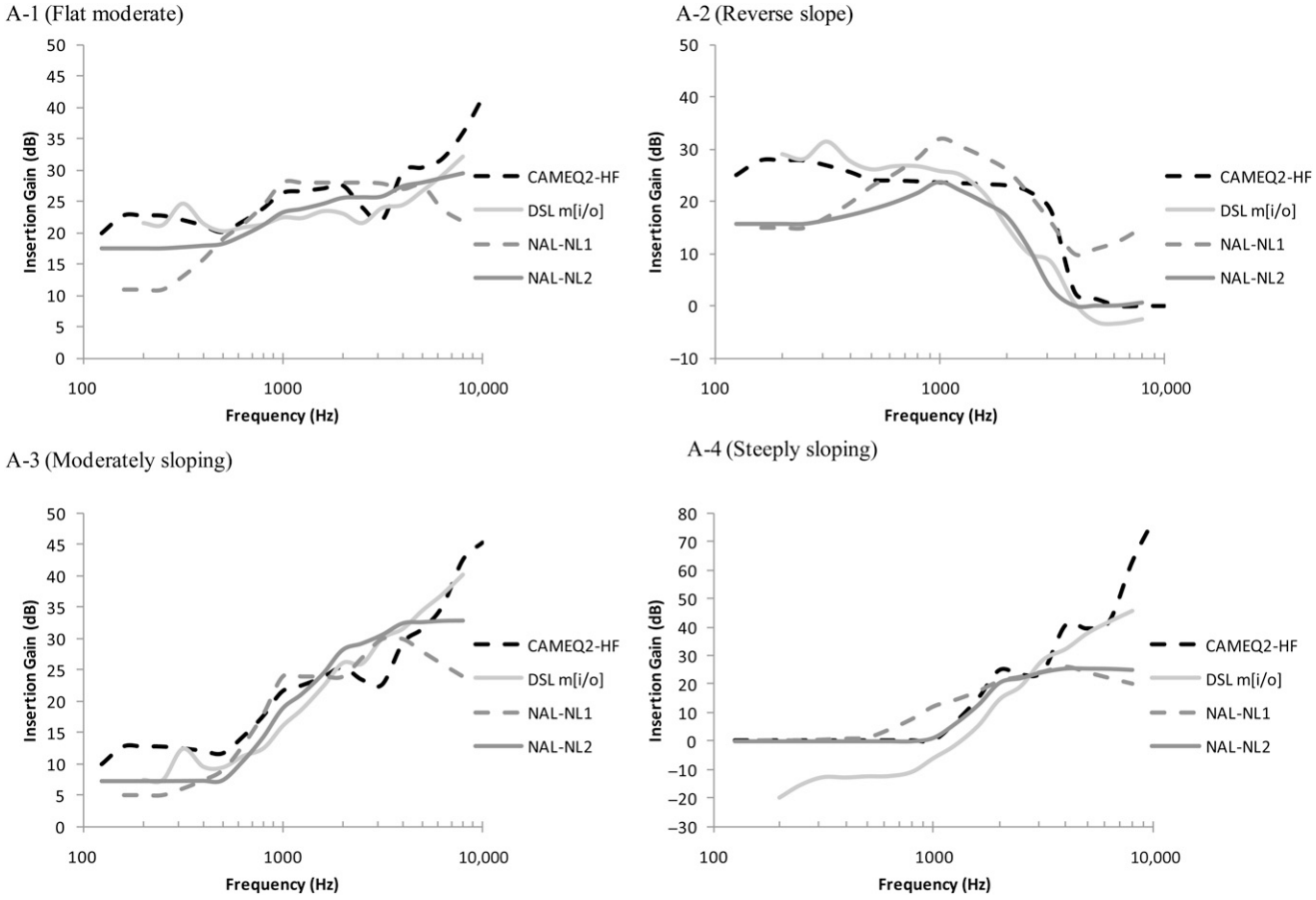

Figure 3. Insertion gain values for A-1, A-2, A-3, and A-4 for a 65 dB SPL soundfield input level.

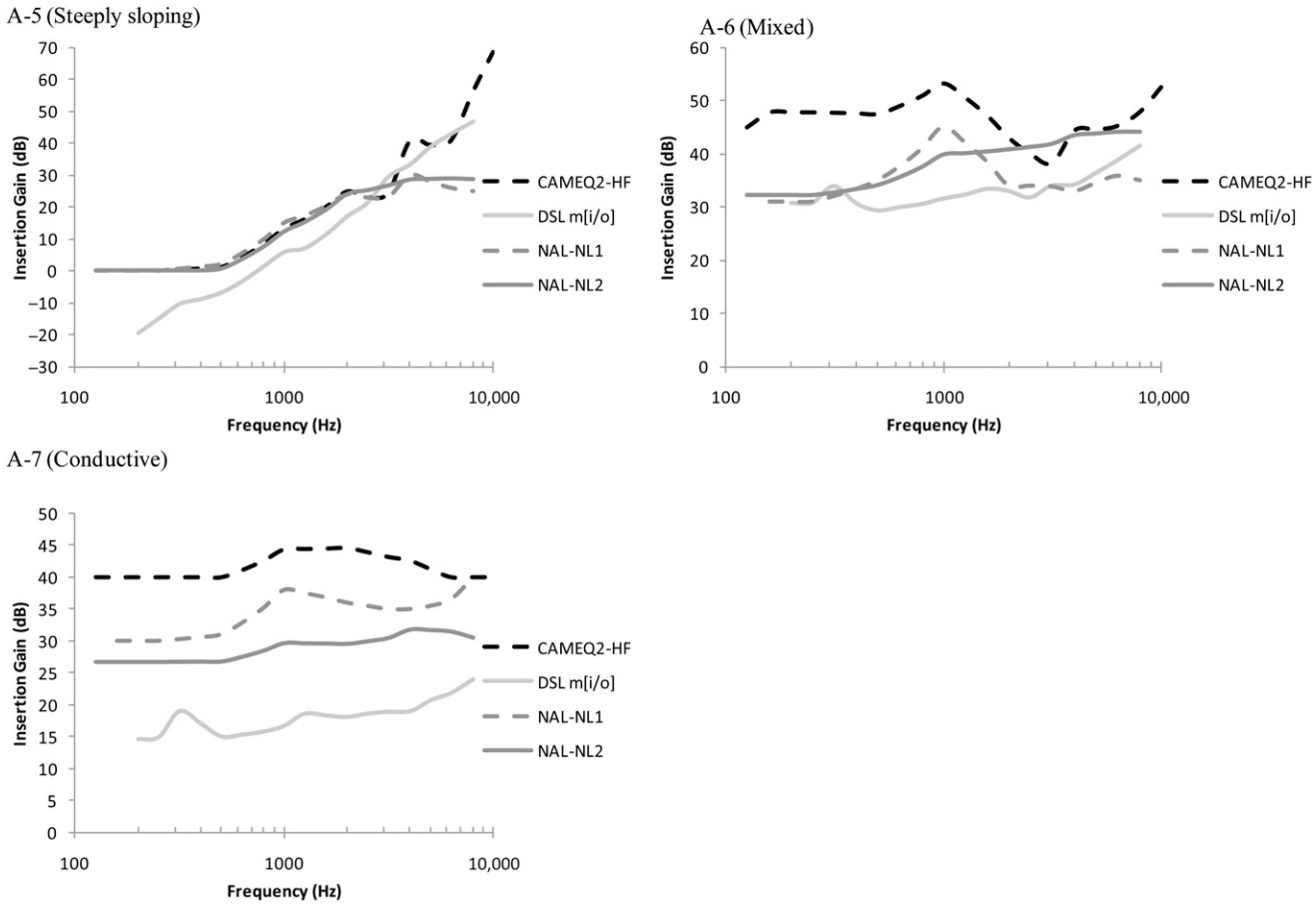

Figure 4. Insertion gain values for A-5, A-6, and A-7 for a 65 dB SPL soundfield input level.

While these insertion gains do correspond to the DSL targets, in actuality such negative insertion gains are likely unobtainable in a hearing aid fitting; therefore, the negative insertion gains were set to 0 dB. Using the negative gains significantly lowered the predicted speech intelligibility and loudness, whereas the adjustment enabled a more realistic comparison of the DSL m[i/o] with the other prescriptive methods.

Compression Ratios

The compression ratios for each prescriptive method at frequencies of 500 and 2000 Hz are shown in Table 1. In general, for all prescriptive methods, compression ratios were reasonable and appropriate in the typical range of 1.1:1 to 3:1 (Dillon, 2001). Compression ratios in this range have been shown to maintain speech recognition scores and speech quality adjustments as compared with linear gain (Boike and Souza, 2000) as well as preserve relative distance judgments (Akeroyd, 2010).

Loudness

The overall loudness and specific loudness of each prescriptive method for a 65 dB SPL ILTASS input signal, as calculated by the Moore and Glasberg (2004) loudness model, are shown in Figures 5 and 6 for each of the five sensorineural hearing losses. Also shown in Figures 5 and 6 is calculated loudness for a normal-hearing individual for the same input signal. For normal hearing, the loudness of the ILTASS at the eardrum given a 65 dB SPL diffuse soundfield input was 18.6 sones, agreeing well with the calculated loudness of the revised speech spectrum of Moore et al (2008), whose loudness of a 65 dB SPL input is 20.7 sones (Moore et al, 2010).

DSL m[i/o] and NAL-NL2 provided the least overall loudness, then CAMEQ2-HF, followed by NAL-NL1. With regard to overall loudness averaged across Audiograms 1–5 (Fig. 7), NAL-NL1 and CAMEQ2-HF provided about 14 sones, and DSL m[i/o] and NAL-NL2 provided about 8 sones. For Audiogram 2, the overall loudness difference between NAL-NL1 (19.3 sones) and NAL-NL2 (5.8 sones) is significantly larger than the typical difference between the two methods. For this audiogram, much of the overall loudness of NAL-NL1 arises from the high-frequency area, whereas the lack of loudness for NAL-NL2 is a result of smaller insertion gains in the lower frequencies.

With regard to specific loudness, the four prescriptive methods generally equalized loudness across the

Table 1. Compression Ratios for Each Prescriptive Method Over the Range of 50–80 dB SPL Input Levels Assuming the International Long-Term Average Speech Spectrum of Byrne et al (1994)

Audiogram and Prescriptive Method	500 Hz	2000 Hz
A-1		
Cambridge Method for Loudness Equalization 2—High-Frequency (CAMEQ2-HF)	1.5	2.3
Desired Sensation Level Multistage Input/Output (DSL m[i/o])	1.3	1.5
National Acoustic Laboratories—Non-linear 1 (NAL-NL1)	1.2	2.3
National Acoustic Laboratories—Non-linear 2 (NAL-NL2)	2.6	2.7
A-2		
CAMEQ2-HF	1.6	2.3
DSL m[i/o]	1.3	1.1
NAL-NL1	1.3	2.1
NAL-NL2	1.6	1.4
A-3		
CAMEQ2-HF	1.3	2.0
DSL m[i/o]	1.2	1.5
NAL-NL1	1.2	2.3
NAL-NL2	2.0	2.5
A-4		
CAMEQ2-HF	1.1	1.9
DSL m[i/o]	1.0	1.8
NAL-NL1	1.0	1.9
NAL-NL2	1.0	1.7
A-5		
CAMEQ2-HF	1.1	1.9
DSL m[i/o]	1.0	1.8
NAL-NL1	1.0	2.0
NAL-NL2	1.1	2.1

midfrequencies, particularly for Audiograms 1 and 3. For Audiograms 2, 4, and 5 the specific loudness across prescriptive methods varied more. NAL-NL1 and NAL-NL2 tend to prescribe less loudness where greater amounts of hearing loss existed. CAMEQ2-HF provides the greatest loudness for most sensorineural audiograms (1–5), particularly at the highest frequencies, relative to other methods. The specific loudness for DSL m[i/o] generally fell between that of NAL-NL2 and CAMEQ2-HF, particularly at high frequencies for Audiograms 4 and 5.

For the mixed and conductive hearing losses, the specific loudness and overall loudness of each prescriptive method are shown in Figure 6. DSL m[i/o] provided the least loudness, followed by NAL-NL2 and NAL-NL1, while CAMEQ2-HF provided the most loudness. The loudness for CAMEQ2-HF was observed to match closely that of an individual with normal hearing.

Bandwidth of Cochlear Excitation and Effective Audibility

Given the insertion gains of each prescriptive method in the frequency range of 200–8000 Hz, the excitation bandwidth of a 65 dB SPL ILTASS input signal yielded a lowermost and uppermost excited frequency within the cochlea referred to herein as the bandwidth of cochlear excitation (top half of Table 2). In general, audible low-frequency excitation extended below 200 Hz for all prescriptive methods, excluding most notably Audiogram 1 and 2, as these audiograms had the most severe low-frequency hearing loss. For Audiogram 2, NAL-NL2 provided cochlear excitation only down to 443 Hz. The uppermost excited frequencies were commonly above 5500 Hz, excluding most notably Audiograms 4 and 5. For Audiograms 4 and 5, significant high-frequency hearing loss was present, and as a result, cochlear excitation was limited to 2812 and 3158 Hz, respectively, with both NAL-NL1 and NAL-NL2. Note that cochlear excitation often occurred well beyond the frequency input range of 200–8000 Hz for levels prescribed by the CAMEQ2-HF. For example, frequencies receiving cochlear excitation were up to 8705 Hz for Audiograms 4 and 5, up to 12,115 Hz for Audiogram 1, and up to 13,520 Hz for Audiogram 2.

To accompany the data on cochlear excitation, the frequency bandwidth giving rise to effective audibility ($k > 0$) also was analyzed. The range of frequencies with effective audibility based on the SII modeling is shown in the bottom half of Table 2. The patterns of any prescriptive method providing more or less of a frequency range relative to other methods were similar to those of cochlear excitation. CAMEQ2-HF provided the widest frequency range of effective audibility, followed closely by DSL

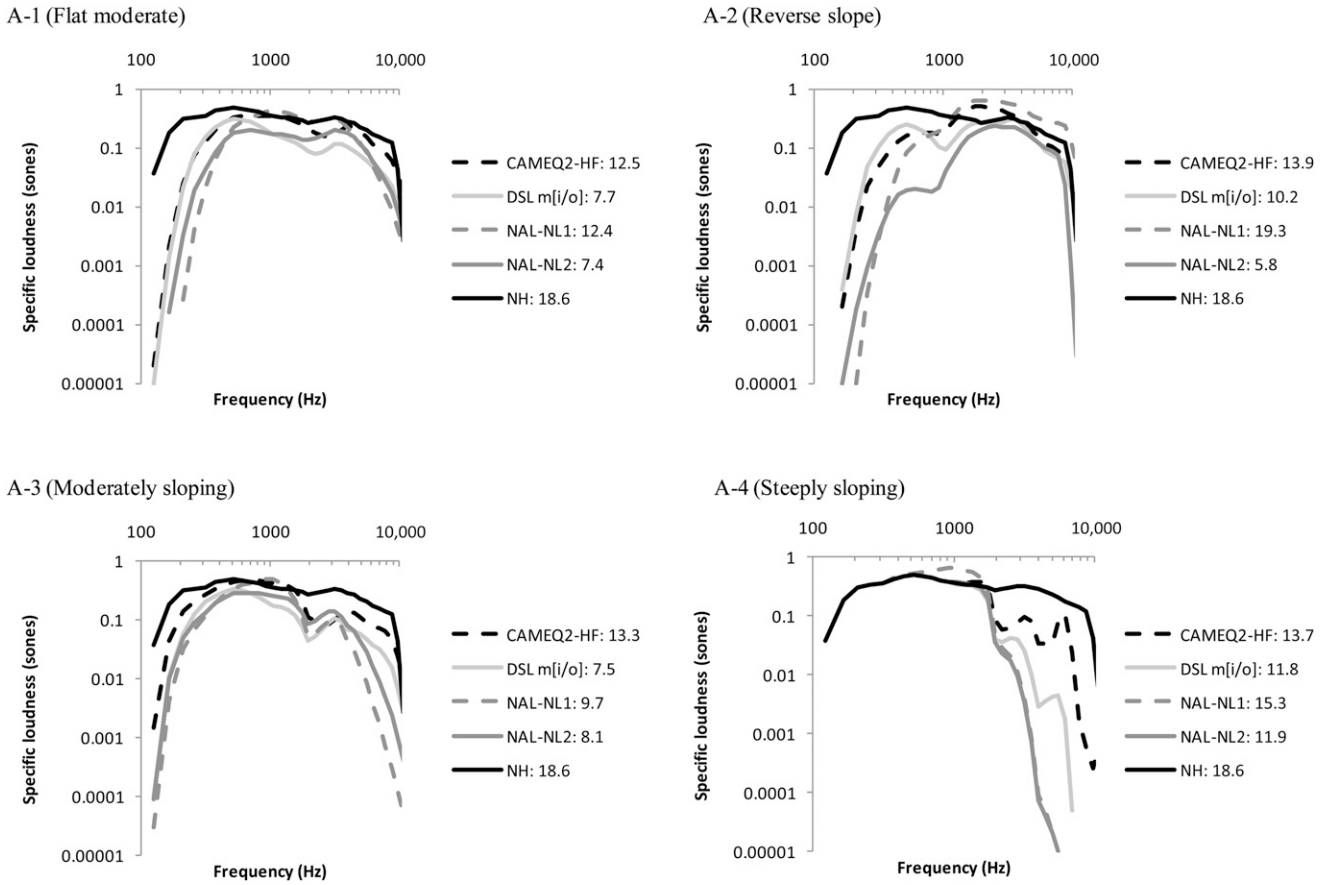

Figure 5. Specific loudness for A-1 through A-4 based on a 65 dB international long-term average speech spectrum input in quiet. Overall loudness is shown to the right of the prescriptive method in the legends (NH designates normal hearing).

m[i/o]. The audiograms receiving the narrowest frequency range effectively providing audibility were Audiograms 4 and 5 by the NAL-NL1 and NAL-NL2 methods.

The more restricted cochlear excitation and effective audibility high-frequency bandwidths occur for NAL-NL1 and NAL-NL2 because of the desensitized SII methods they are based on, which predict that extending amplification to frequencies at which hearing loss is more severe does not create worthwhile improvements in speech understanding. In contrast, CAMEQ2-HF seeks to make high frequencies audible whether the information is effective or not. Therefore, the upper cochlear excitation frequency of 8705 Hz with CAMEQ2-HF was achieved with 55 dB and 48 dB of insertion gains at 8000 Hz for Audiograms 4 and 5, respectively. The insertion gain prescribed by NAL-NL1 and NAL-NL2 at 8000 Hz for Audiogram 4 was only 20 and 25 dB, respectively. For Audiogram 5, NAL-NL1 and NAL-NL2 prescribed insertion gains at 8000 Hz of only 25 and 29 dB, respectively, for a 65 dB SPL ILTASS input signal.

Predicted Speech Intelligibility in Quiet

The predicted SII values for the sensorineural losses of Audiograms 1–5 are shown in Table 3 for both the ANSI method and the NAL modification. Recall that these analyses were completed for a 65 dB SPL ILTASS input only. The patterns of results with regard to differences or similarities among the four prescriptive methods were, in large part, unaffected by which method was used (Fig. 8). The greater desensitization factor of NAL SII reduced the average overall SII values by the least amount of 0.10 for DSL m[i/o] and by the largest amount of 0.14 for CAMEQ2-HF. The predicted SII values of the NAL-NL1 and NAL-NL2 prescriptive methods experienced reductions of 0.13 and 0.11, respectively.

To examine whether any prescriptive method consistently provided better or worse SII values than other methods, we examined SII values for individual audiograms as well as the average SII values of the five sensorineural audiograms. The examination indicated no clear separation in predicted SII scores among DSL m[i/o], NAL-NL1, and NAL-NL2. That is, the SII values tend to be within ± 0.02 of one another for these three methods. On the average though, CAMEQ2-HF tended to outperform the other three prescriptive methods by only approximately 0.05 SII. Across all five audiograms, the lowest SII value occurred for Audiogram 1 for NAL-NL1 at 0.48. Despite this, applying the transfer function of Humes (2002) for the Connected Speech Test

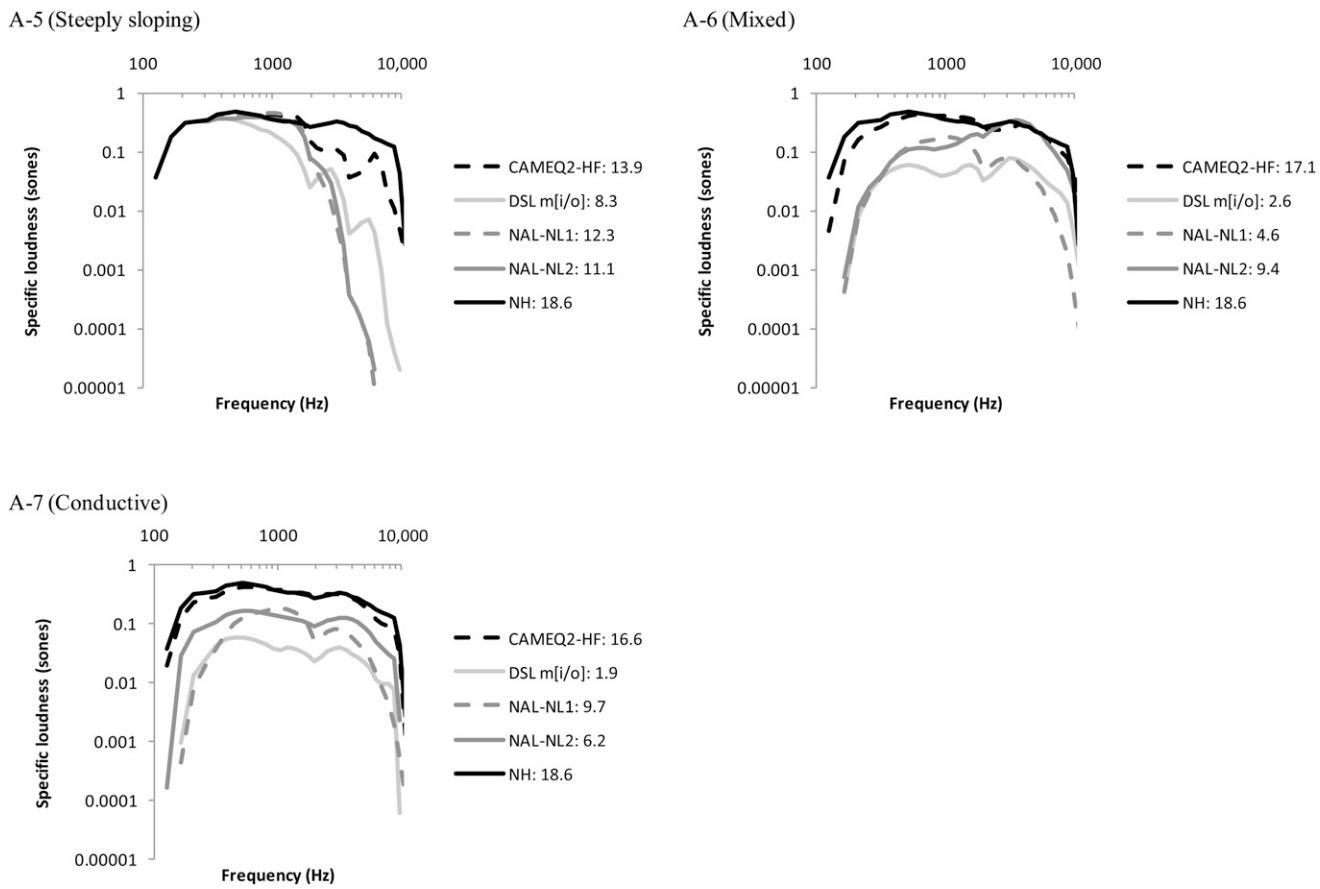

Figure 6. Specific loudness for A-5 through A-7 based on a 65 dB international long-term average speech spectrum input in quiet. Overall loudness is shown to the right of the prescriptive method in the legends (NH designates normal hearing).

(Cox et al, 1987) predicts recognition performance of 91% correct for connected speech in the form of sentences. Therefore, for each of the audiograms and prescriptive methods predicted performance was considered favorably high. The predicted recognition performance of the average SII across the five sensorineural hearing losses is shown by the data labels in Figure 8. Evidenced is the fact that an average increase of 0.05 SII gave rise to less than a 1% improvement in recognition, as performance was already near 100%.

In Figure 9, the predicted SII values for Audiogram 6 (mixed) and Audiogram 7 (conductive) are shown. Despite the differences in prescribed insertion gain between the prescriptive methods for the mixed and

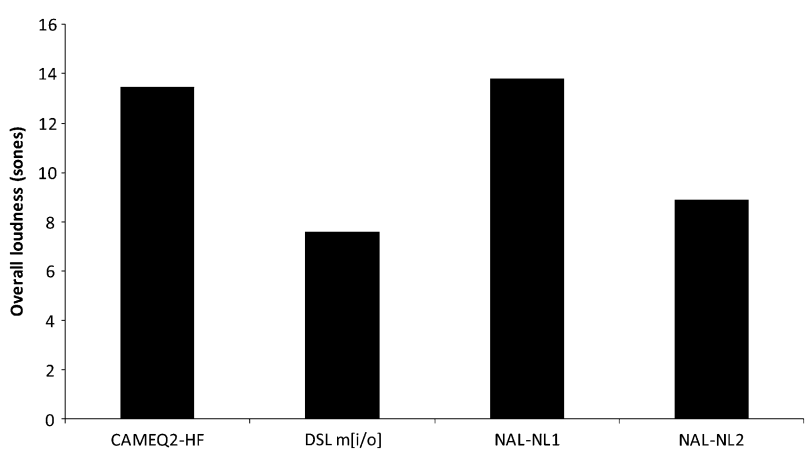

Figure 7. Overall loudness of each prescriptive method averaged across the five sensorineural hearing losses (A-1 through A-5) based on a 65 dB international long-term average speech spectrum input in quiet.

Table 2. Bandwidth (Hz) of Cochlear Excitation and Bandwidth (Hz) of Effective Audibility for Each Audiogram and Prescriptive Method According to the Moore and Glasberg (2004) Loudness Model and ANSI S3.5-1997 Speech Intelligibility Index Model Incorporating a Revised NAL Desensitization Factor

Bandwidth and Audiogram	CAMEQ2-HF	DSL m[i/o]	NAL-NL1	NAL-NL2
Bandwidth of cochlear excitation				
A-1	208–12115	208–9722	313–8705	257–9722
A-2	257–13520	208–13520	375–13520	443–9722
A-3	163–10854	163–9722	208–5576	163–6973
A-4	123–6973	123–3543	123–2812	123–2812
A-5	123–8705	123–5576	123–3158	123–3158
A-6	163–12115	208–8705	208–6973	208–10854
A-7	123–9722	208–8705	163–9722	163–8705
Bandwidth of effective audibility				
A-1	200–8000	200–8000	250–6300	200–8000
A-2	200–8000	200–8000	315–8000	250–8000
A-3	200–8000	200–8000	200–5000	200–6300
A-4	200–8000	200–6300	200–4000	200–4000
A-5	200–6300	200–6300	200–4000	200–4000
A-6	200–8000	200–8000	200–8000	200–8000
A-7	200–8000	200–8000	200–8000	200–8000

conductive loss, the differences in predicted SII were again small. The largest difference between any two prescriptive methods was 0.04 for the mixed loss and 0.05 for conductive loss. Moreover, the magnitude of the predicted SII values was again high. Using the transfer function of Humes (2002) for the Connected Speech Test, near perfect performance of at least 97% and 99% or better was predicted with all prescriptive methods for the mixed and conductive losses, respectively.

Predicted Speech Intelligibility in Noise

Predicted SII values using the NAL desensitization factor for each prescriptive method, background noise stimulus, and signal-to-noise ratio condition are represented in Figure 10. The bars represent the mean SII across all seven hearing losses included in this study. A three-way repeated-measures analysis of variance indicated the presence of two significant main effects, background noise ($F[3,18] = 77.091, p < .001$) and signal-to-noise ratio ($F[2,12] = 283.157$, $p < .001$). There was no significant effect of the prescriptive method on predicted SII ($F[3,18] = 3.402$, $p = .0888$). Mean data for these three main effects are shown in Figure 11. The only significant interaction was a two-way effect of signal-to-noise ratio and background noise stimuli ($F[6,36] = 57.149$, $p < .001$).

DSL m[i/o] Versus NAL-NL2

For several reasons, the differences in the prescribed insertion gains of DSL m[i/o] and NAL-NL2 are shown in Figure 12 for an average level input of 65 dB. The first reason is the popularity of these two fitting methods in the United States and expected demand for this information. The second reason is that the results yielded such similar modeled speech intelligibility and loudness values despite differences in prescribed insertion gain. These differences are of interest perhaps in regards to how they might, for example, impact ratings of speech quality. Therefore, clear reporting of these differences is of expected interest to a number of various parties including hearing aid manufacturers and clinical audiologists who choose between these prescriptive methods when fitting patients with hearing aids. Frequency-specific differences were calculated as DSL m[i/o] – NAL-NL2; the negative insertion gain values of DSL m[i/o] in the low frequencies for Audiograms 4 and 5 were set to 0 dB prior to calculation consistent with the procedure used when conducting the speech intelligibility and loudness models. In general, Figure 12 shows that DSL m[i/o] prescribes less gain in the low and middle frequencies up to 4000 Hz and more gain at 6300 and 8000 Hz than NAL-NL2 for Audiograms 1, 3, 4, and 5. For Audiogram 2, DSL m[i/o] prescribes more gain in the low frequencies up to 1 kHz and less gain above 4000 Hz. For Audiograms 6 and 7, DSL m[i/o] prescribes less gain than NAL-NL2 at all frequencies.

DISCUSSION

Model-based studies, such as the one reported here, are regarded as both a time- and resource-efficient process for ascertaining the expected impact of differing

Table 3. Speech Intelligibility Index (SII) Value for the A-1 Through A-5 Sensorineural Losses Using Both the ANSI S3.5-1997 and National Acoustic Laboratories (NAL) SII Methods

	A-1		A-2		A-3	
Prescriptive Method	ANSI SII	NAL SII	ANSI SII	NAL SII	ANSI SII	NAL SII
CAMEQ2-HF	0.71	0.51	0.74	0.61	0.76	0.55
DSL m[i/o]	0.67	0.51	0.71	0.61	0.71	0.55
NAL-NL1	0.69	0.48	0.71	0.58	0.70	0.53
NAL-NL2	0.67	0.5	0.64	0.59	0.73	0.54
	A-4		A-5		Average	
Prescriptive Method	ANSI SII	NAL SII	ANSI SII	NAL SII	ANSI SII	NAL SII
CAMEQ2-HF	0.77	0.67	0.77	0.63	0.75	0.62
DSL m[i/o]	0.75	0.67	0.72	0.63	0.70	0.59
NAL-NL1	0.79	0.65	0.71	0.61	0.70	0.57
NAL-NL2	0.71	0.66	0.72	0.62	0.69	0.58

prescribed insertion gains for the typical hearing-impaired listener on select evaluation criteria in comparison with the more lengthy and costly traditional subject recruitment and behavioral research process. In this study, five configurations of sensorineural hearing loss as well as a conductive and a mixed hearing loss were included with the insertion gain recommendations of four prescriptive methods. The impacts of the prescribed insertion gains on the evaluation criteria of predicted loudness, high-frequency bandwidth, and speech intelligibility will be discussed. The discussion is partitioned into sections pertaining to hearing losses with a conductive component followed by hearing losses with only a sensorineural component. We will begin briefly with reference to Byrne et al (2001), as that study provided the impetus and initial framework for the undertaken endeavor. Also, because these study results pertain to adults, for prescriptive methods where the prescription varies with the age of the client (e.g., DSL m[i/o] and NAL-NL2), the specific prescription and observed trends for children may differ from those reported herein.

Although NAL-NL2 and DSL m[i/o] are more similar to one another now than the predecessors of NAL-NL1 and DSL i/o compared in Byrne et al (2001), the current state of prescriptive methods continues to indicate variation among methods in the amount of frequency- and level-specific insertion gain to apply when compensating for the effects of hearing impairment based on pure-tone hearing loss. The variation evidenced by Byrne et al (2001), who included prescriptive methods based on both loudness equalization and loudness normalization, was perhaps more expected than the variation in current methods. That is, the rationale of loudness normalization is not at the core of the prescriptive methods examined in this study. Instead, there is a fair amount of consensus among the prescriptive methods examined that maximizing speech intelligibility while controlling overall loudness and loudness perception across frequency (loudness equalization) is a good rationale for prescribing amplification. Hence, discrepancies among the methods in the prescription of insertion gain are all the more intriguing, with more divergent discrepancies for mixed and conductive losses than for sensorineural losses.

Mixed and Conductive Hearing Losses

Note the difference in prescribed insertion gain for Audiograms 6 and 7 by CAMEQ2-HF and DSL m[i/o] (Fig. 4). The differences, however, yielded only minimal change in predicted speech intelligibility (Fig. 9) but rather divergent loudness perception values (Fig. 6). The similarity in predicted speech intelligibility owed to the effect of the level distortion factor, at least in part, which decreased from an average of 0.93 for DSL m[i/o] to 0.78 for CAMEQ2-HF for 200–8000 Hz, which effectively reduced audibility (k_i). Thus, the prescriptive targets of DSL m[i/o] prescribed enough gain to provide similar effective audibility at lower loudness levels than CAMEQ2-HF for an average level input of 65 dB SPL. It is quite noteworthy to point out that the difference in prescribed insertion gains between DSL m[i/o] and CAMEQ2-HF did make a larger difference in the intelligibility of speech for a softer input level of 50 dB SPL. Specifically, for Audiogram 6, the predicted SII with CAMEQ2-HF was 0.59, whereas with DSL m[i/o] the predicted SII was 0.25. These SII values equate to an expected performance of 97.5% versus 27.1%, respectively, assuming the transfer function of Humes (2002). For Audiogram 7, the predicted SII with CAMEQ2-HF was 0.81, whereas with DSL m[i/o] the predicted SII was 0.45. These SII values equate to an expected performance of 99.8% versus 87.9%, respectively.

In practice, given the difference among prescriptive methods, it is not surprising that audiologists often debate the initial prescription for mixed and conductive losses. Rationales for different ways of deriving a good starting prescription have had various proponents.

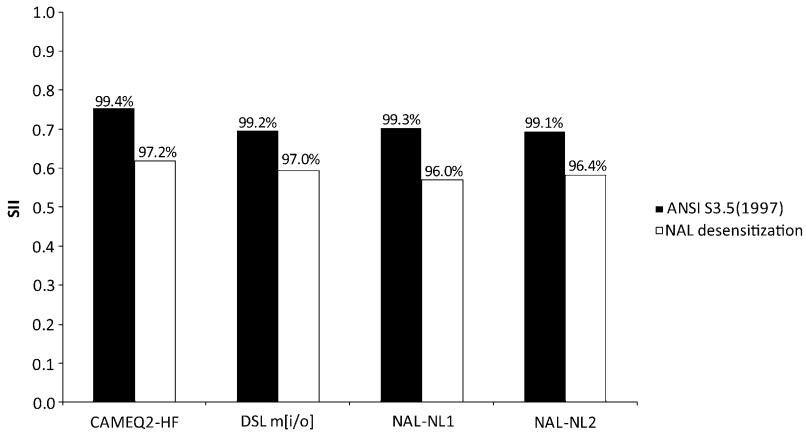

Figure 8. Average Speech Intelligibility Index (SII) value for speech in quiet across the five sensorineural hearing losses for each prescriptive method using both the ANSI S3.5-1997 and the National Acoustic Laboratories SII methods. Also shown is the SII transformed value into a predicted speech recognition score (% correct) for the Connected Speech Test (Cox et al, 1987) using the transfer function of Humes (2002).

Irrespective of the prescriptive method used, some audiologists use both AC and BC thresholds and allow the prescriptive method to dictate the prescribed levels. Others propose the use of BC thresholds with the addition of an arbitrary amplification factor (e.g., 10 dB) to the prescribed levels, whereas others propose using the BC thresholds and adding one half to three-quarters of the air–bone gap (ABG) to the prescribed levels. Because of these differing rationales, this discussion seemed an appropriate place to explicitly state the assumptions of generic prescriptive methods for hearing losses with a conductive component.

The earlier NAL formulas for linear hearing aids (NAL, NAL-R; Byrne and Tonisson, 1976; Byrne and Dillon, 1986) prescribed average gain approximately equal to half the sensorineural hearing loss, which is similar to the half-gain rule of Lybarger (1963). For hearing losses with a conductive component, Lybarger also proposed that gain should equal half the AC threshold plus one-quarter the ABG. This can be expressed algebraically as 1/2AC + 1/4ABG. In turn, this formula can be expressed as 1/2(BC + ABG) + 1/4(ABG), which simplifies to 1/2BC + 3/4ABG.

The NAL-NL2 procedure, like its predecessors, has the principle of applying its sensorineural loss rule to the BC thresholds and then applying three-quarters of the ABG to determine insertion gain. The decision to compensate for less than the full amount of the conductive component has also been supported by the work of Walker (1997, 1999). The tendency for patients to prefer less than full restoration of the conductive component was, at least in part, owing to the maximum output of the hearing aid being too low in comparison with the gain required for full restoration (Walker, 1997). Accordingly, using enough gain to restore fully the conductive component caused the hearing aid to saturate, frequently resulting in distortion with no actual increase in gain (Walker, 1997).

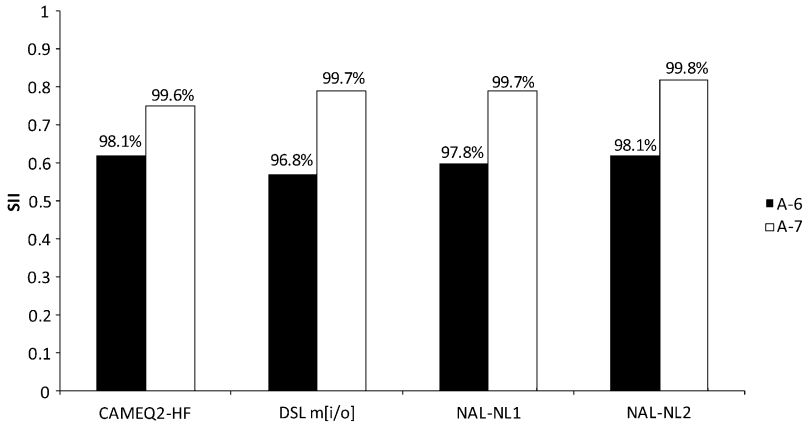

Figure 9. Speech Intelligibility Index (SII) value for speech in quiet for the A-6 (mixed) and A-7 (conductive) hearing losses and each prescriptive method using the National Acoustic Laboratories SII method. Also shown is the SII transformed value into a predicted speech recognition score (% correct) for the Connected Speech Test (Cox et al, 1987) using the transfer function of Humes (2002).

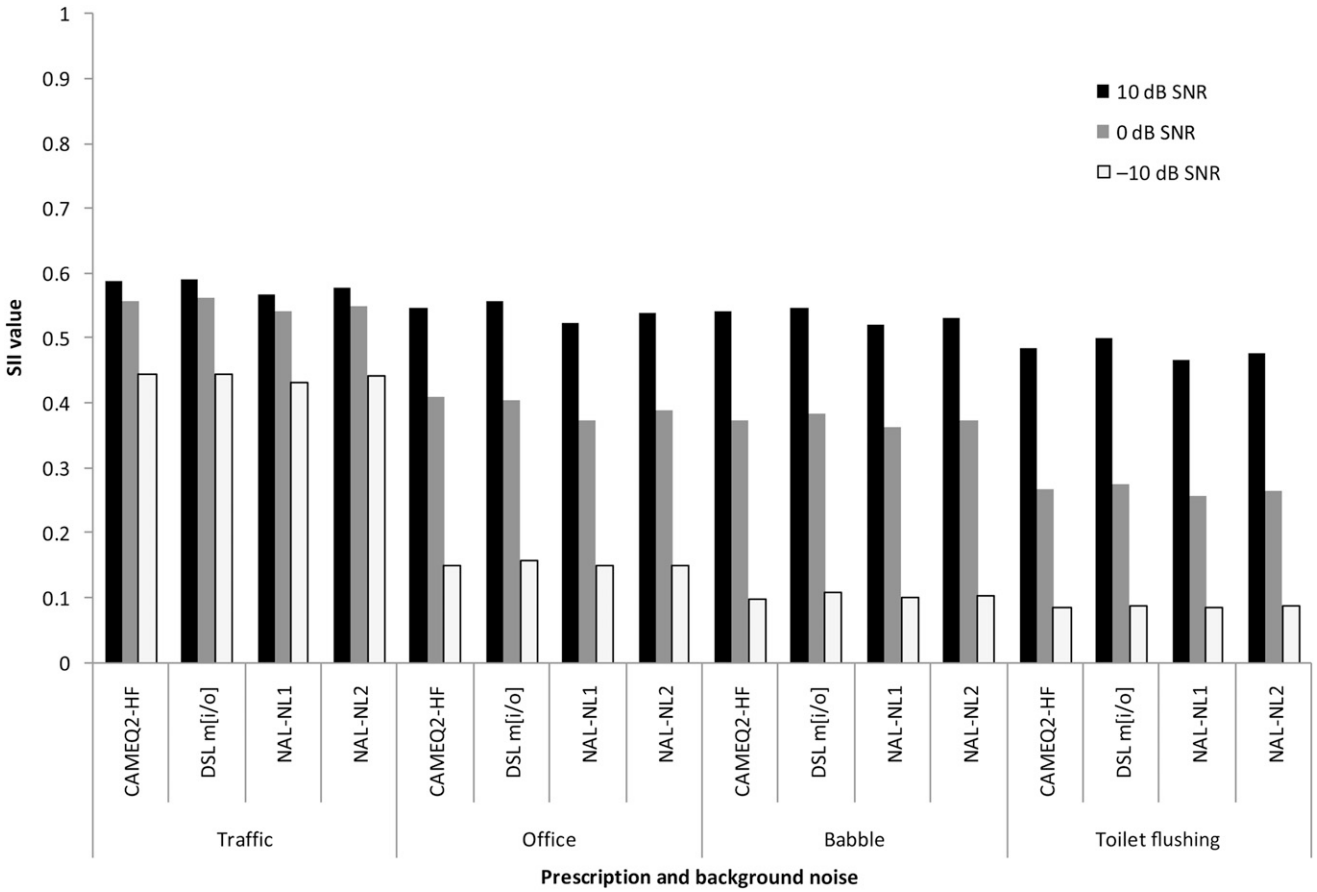

Figure 10. Average Speech Intelligibility Index values, as calculated with the ANSI S3.5-1997 method employing the most current National Acoustic Laboratories desensitization factor, across the seven hearing losses studied.

As for sensorineural hearing losses, CAMEQ2-HF also places as much of the speech spectrum above the absolute thresholds as possible for conductive hearing losses given an overall loudness constraint of 20.7 sones (Moore et al, 2010). Additionally, there is the expectation that loudness perception may be similar to that of normal hearing when the hearing loss is entirely conductive in nature, as loudness recruitment would not affect modeled loudness used for the generation of prescriptive targets. With the DSL m[i/o] general aim of maximizing comfortable audibility, for conductive hearing losses in particular the predicted upper limits of comfort (ULC) are increased, which in turn makes the input/output function more linear, applying more gain. Limits to this approach include not exceeding 140 dB SPL in the ear canal with the ULC increased by 25% of the audiometric ABG, averaged across 500–4000 Hz to a maximum 60 dB ABG (Scollie et al, 2005).

The prescriptive methods of NAL-NL1, NAL-NL2, CAMEQ2-HF, and DSL m[i/o] can be compared in Figure 4 for the mixed and conductive losses. The most striking result of the differences in the prescribed insertion gain is again not predicted speech intelligibility for average level speech but, rather, loudness. DSL m[i/o] prescribes the least loudness, followed by the NAL methods, with CAMEQ2-HF prescribing the most loudness.

Sensorineural Hearing Losses

Given the more frequent occurrence of sensorineural hearing loss relative to hearing losses with a conductive component, the remainder of the discussion will focus on generalities of the four prescriptive methods with regards to sensorineural hearing loss. First, the prescribed insertion gains are more similar among the methods for sensorineural hearing losses than for previously described losses with a conductive component. The differences that do exist among the prescribed insertion gains give rise to only small differences in predicted speech intelligibility in quiet. When considering predictions of speech intelligibility in noise, differences between prescriptive methods were again small and in statistical analysis did not reach significance.

Larger prescribed insertion gains did give rise to greater loudness for CAMEQ2-HF, followed by NAL-NL1, NAL-NL2, and DSL m[i/o]; NAL-NL2 and DSL m[i/o] were actually only about 1 sone different from

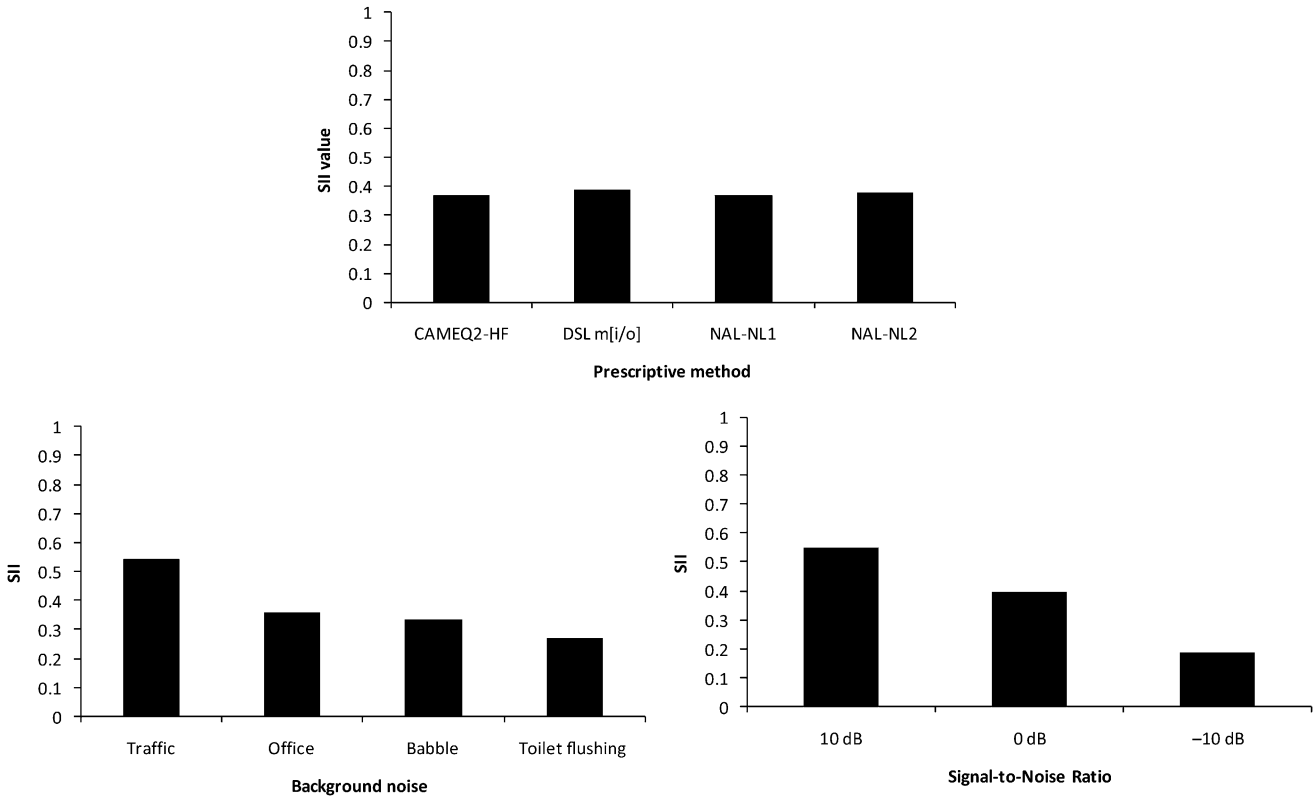

Figure 11. Average Speech Intelligibility Index (SII) value graphed separately as a function of the prescriptive methods, background noise, and signal-to-noise ratio collapsed across all other independent variables (i.e., statistical main effects). There was no effect of the prescriptive method on the predicted SII value for speech presented in the presence of noise; the background noise stimuli and signal-to-noise ratio did, however, significantly affect the predicted SII value.

one another. The insertion gains prescribed translate into the widest bandwidths for CAMEQ2-HF, followed by DSL m[i/o] and NAL-NL2, with the narrowest bandwidths for NAL-NL1. Applying this information to dispensing hearing aids, a prescriptive method like CAMEQ2-HF may be appropriate for patients expected to benefit from the widest bandwidths and who will accept louder hearing aid fittings, with the acknowledgment that the large insertion gains prescribed for more severe hearing loss may be difficult to obtain in commercial products. An assessment of individuals with mild to moderate hearing impairments using multichannel amplitude compression in a behind-the-ear-style hearing aid did lead to satisfactory loudness and sound quality in everyday life (Moore and Füllgrabe, 2010). These authors reported usually being able to achieve targets within ±3 dB of channel center frequencies, albeit encountering occasional difficulty at 7500 Hz. Other preliminary validation work with the CAMEQ2-HF method has been reported in Füllgrabe et al (2010). The ability to achieve DSL m[i/o] targets has also been demonstrated for 30 listeners with mild to severe sensorineural hearing losses for whom 95% of fittings were within 5.8 dB of target at 4000 Hz and 2.5 dB/octave slopes from 500 to 4000 Hz (Polonenko et al, 2010).

Based on the predicted usefulness of a frequency region to speech understanding in quiet (i.e., its effective audibility), the NAL-NL2 prescribed a range of frequency bandwidths dependent upon the audiogram. Also, NAL-NL2 prescribed less loudness than a CAMEQ2-HF prescription for the same hearing loss. Relative to NAL-NL2, DSL m[i/o] provided essentially equivalent predicted speech intelligibility, with slightly wider bandwidths and comparable loudness with less insertion gain in the midfrequencies and more insertion gain at lower and higher frequencies. NAL-NL2 prescribed less insertion gain in the midfrequencies and more insertion gain at lower and higher frequencies than NAL-NL1. This, too, had the effect of maintaining speech intelligibility and lowering overall loudness.

The DSL m[i/o] and NAL-NL2 prescriptive methods provided average loudness that agreed with laboratory and field trials regarding how much loudness was preferred by listeners (with and without hearing aid experience) with sensorineural hearing impairment. Smeds et al (2006a, 2006b) concluded that participants with hearing impairment preferred, in median, loudness levels of –14 phons re: normal for input levels of 50–89 dB SPL. Thus, as determined by the Moore and Glasberg (1997) loudness model used in Smeds et al (2006a, 2006b), if an ILTASS signal at 65 dB SPL giving rise

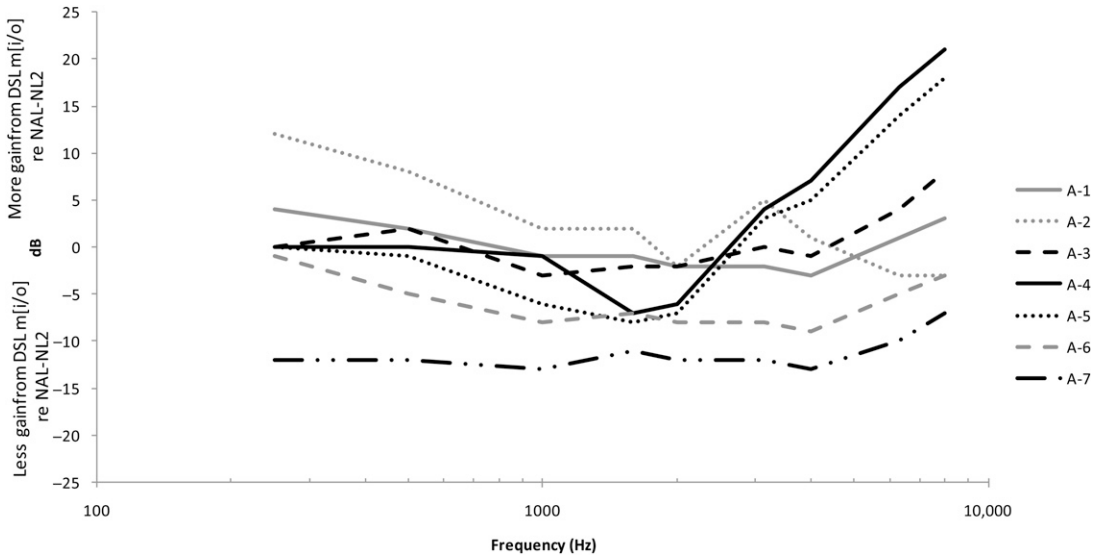

Figure 12. Frequency-specific differences in insertion gains prescribed by Desired Sensation Level Multistage Input/Output (DSL m[i/o]) and National Acoustic Laboratories—Non-linear 2 (NAL-NL2) for each of the seven hearing losses at select 1/3-octave bands. The data are reported as DSL m[i/o] – NAL-NL2. Negative numbers indicate less gain from DSL m[i/o], and positive numbers indicate more gain from DSL m[i/o], for a 65 dB SPL input re: NAL-NL2.

to 23.4 sones (85 phons) were reduced by 14 phons, then the expected preferred listening level of the median listener with hearing impairment would be 8.5 sones (71 phons). The expected preferred listening level of 8.5 sones agrees well with the average sone values prescribed by DSL m[i/o] and NAL-NL2 of 7.6 and 8.8 sones, respectively, for the five sensorineural audiograms included in this study. In conclusion, the DSL m[i/o] and NAL-NL2 methods prescribe insertion gain in such a way that loudness is likely preferred by typical hearing aid users while ensuring that speech intelligibility in quiet and noise remains comparable to that of the other prescriptive methods examined in this study. To support this conclusion, which is based on modeling, behavioral data from Polonenko et al (2010) demonstrated that DSL m[i/o] targets approximated, on average, the preferred listening levels of participants within 2.6 dB.

In brief, the differences in prescribed insertion gains from the four prescriptive methods for a conversational speech input level of 65 dB SPL yielded the following study conclusions:

- greater overall loudness for NAL-NL1 and CAMEQ2-HF,
- predicted overall loudness for NAL-NL2 and DSL m [i/o] that is more similar to the behavioral loudness preferences of hearing-impaired listeners in laboratory and field trials that were reported in Smeds et al (2006a, 2006b),
- a wider high-frequency bandwidth for CAMEQ2-HF, and
- similar predicted speech recognition in quiet and in noise among all methods.

Considerations and Future Research

The modeling performed in this study pertains to the typical listener of each hypothetical hearing loss examined. Such modeling is not applicable to all individuals with the same hearing loss due to intersubject variability. That is, a range of possible speech recognition scores (e.g., Rankovic, 1991; Studebaker et al, 1999; Humes, 2002) and loudness perception (e.g., Moore, 1995; Launer et al, 1997) is possible despite the prediction for a typical listener. Hence, modeling speech recognition scores and loudness perception for the individual remains a challenge. In the clinical setting, to accommodate more than the typical patient, the targets (e.g., insertion gain etc.) of any prescriptive method are generally fine-tuned to the preferences of the individual. Jenstad et al (2007) demonstrated that a range of 10 dB in both low (315–1000 Hz) and high frequencies (1250–4000 Hz) is sufficient to achieve both subjective and objective optimization on a range of outcome measures.

Future research, given the similar amount of loudness achieved by the differing frequency responses of NAL-NL2 and DSL m[i/o], may consider examining the preferred response shape for optimal speech quality in different listening environments as an extension beyond examination of preference for overall loudness and speech intelligibility optimization for quiet listening environments. Also, because the NAL-NL2 method specifically considers the impact of hearing loss on the ability to extract information from speech amplified so that it is audible, it is likely that differences among the procedures greater than those reported here are likely to emerge for more severe sensorineural hearing losses. That is, as

hearing loss proceeds further into the severe and eventually profound range, the NAL-NL2 (and NAL-NL1) prescriptive methods will relinquish achieving useful contributions to audibility before the other methods do and will focus amplification more on the frequencies for which there is less loss but greater ability to extract information. Hence, comparisons for more severe degrees of hearing loss should also be performed and reported.

Acknowledgments. The authors would like to thank Brian Moore, Susan Scollie, Jeff Crukley, Sheila Moodie, and Leonard Cornelisse for the comments and feedback on an earlier draft of this article. Also, thanks go to Ben Hornsby for allowing the use and modification of an Excel spreadsheet implementing the ANSI S3.5-1997 standard for calculating the Speech Intelligibility Index taught in a AUD 5377—Hearing Loss and Speech Understanding course at Vanderbilt University.

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