Focus 40

The NAL-NL2 Prescription Procedure

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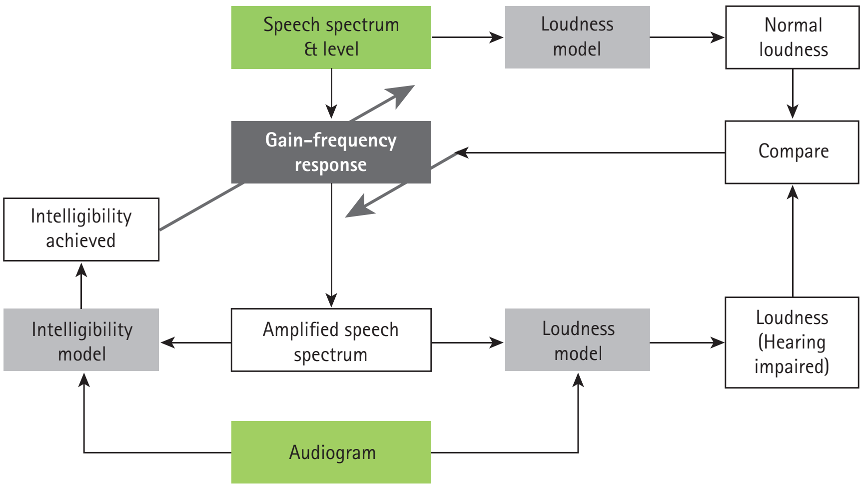
After a long gestation period, the NAL-NL2 prescription formula has been derived and is now in the process of being incorporated into software that enables it to be used. Like its predecessor, the NAL-NL2 prescription aims to maximize speech intelligibility whilst keeping overall loudness no greater than that perceived by a normal-hearing person listening to the same sound.

The adaptive process by which the gain-frequency response is adjusted to achieve these two aims is illustrated in Figure 1. The two basic inputs are the input speech spectrum and level at the top, and the audiogram at the bottom (green boxes), for which a prescription is required. The output, or the prescription, is expressed as the gain-frequency response. Two feedback loops operate in tandem to optimize this gain-frequency response. The loop on the left uses an intelligibility model (light grey box) to find the gain frequency response that maximizes speech intelligibility. If left unchecked, this loop would produce very large gains, and hence loud speech, even for weak input sounds, which would not give the hearing aid wearer an acceptable representation of the auditory world. The loop on the right calculates the loudness (light grey boxes) that would be perceived by the hearing-impaired person, compares this to the loudness that would be perceived by the normal-hearing person, and decreases the overall gain whenever the impaired-hearing loudness exceeds the normal-hearing loudness. This procedure was used to derive optimal amplification characteristics for 240 audiograms covering a wide range of severity and slopes, each at seven speech levels from 40 to 100 dB SPL. Finally, the prescriptions from all the audiograms and all the input levels were drawn together into a single composite formula so that the result is useable for any new audiogram and any speech level.The derivation of NAL-NL2 differs from that of NAL-NL1 in two main ways.

Figure 1
The adaptive process used to derive the optimal gain-frequency response for a single audiogram and input speech spectrum and level.



First, we now have available more extensive data on how much information people with hearing loss can extract from speech once it has been made audible. This has enabled the development of an improved model for predicting speech intelligibility for people with different degrees and configurations of hearing loss. Second, we have the benefit of many experiments where participants were fitted with NAL-NL1. The way these experiments were designed, made it possible to determine how much gain the hearing aid wearers preferred and therefore in which direction the prescription should be changed. These two aspects of NAL-NL2 are described briefly in the remainder of this paper.

Calculation of speech intelligibility

Speech intelligibility, assessed with a VCV nonsense syllable test and the CUNY sentence test, was measured for 55 adults with hearing loss covering a wide range of audiometric profiles, and for 20 adults with normal hearing. Each set of speech test material was low-pass filtered at 700, 1400, 2800 and 5600 Hz, and high-pass filtered at 700, 1400, and 2800 Hz. Measurements were made at two levels in quiet and one level in the presence of noise. Various other measures collected included psychoacoustic tuning curves, the TEN test for dead regions (Moore, 2004), transient-evoked otoacoustic emissions, cognitive ability, and age. As with our previous investigation of the speech intelligibility of people with hearing loss (Ching et al., 1998), the greater the hearing loss, the greater was the tendency of the Speech Intelligibility Index (SII) method (ANSI, 1997) to overestimate speech intelligibility. Consequently, the SII method was modified such that its

Figure 2
Growth of effective audibility with sensation level for normal hearing people (dashed line) and hearing-impaired people (green line).

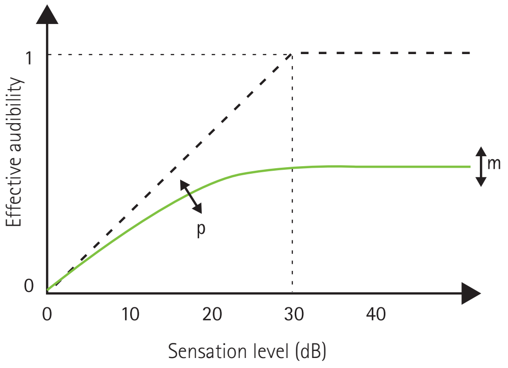
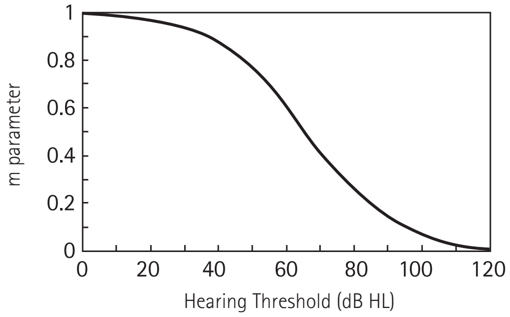


Figure 3
Variation of the m parameter with hearing threshold

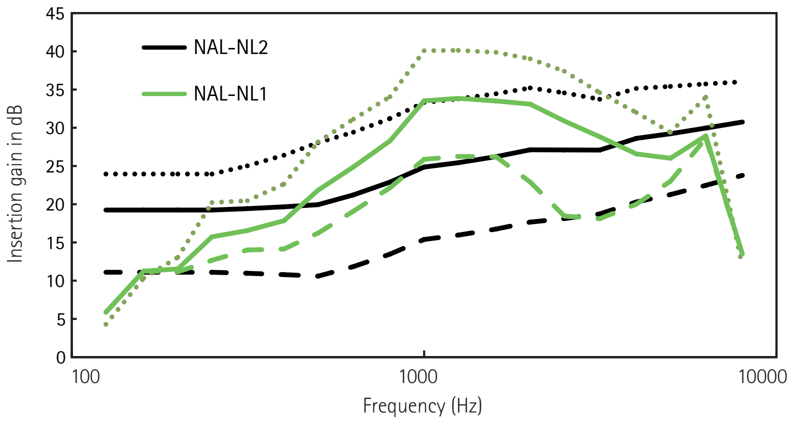


predicted speech intelligibility best matched the measured speech intelligibility. This modification was achieved by changing the relationship between sensation level and effective audibility. For normal hearing, the SII assumes that audibility increases from 0 to 1 as the sensation level of the maximum short-term rms levels of speech increase from 0 to 30 dB, as shown by the dashed line in Figure 2.

The modified model allowed this relationship to curve (controlled by the parameter p), and reach an asymptotic value m, as shown by the solid line in Figure 2. The parameters p and m were given the freedom to vary smoothly with frequency and hearing loss. In fact, the optimal values of m did not vary significantly with frequency, so the model was simplified such that it varied only with hearing loss. The resulting variation of m with HL is shown in Figure 3 and indicates that when hearing loss reaches 66 dB HL, only half of the information in speech can be recovered, even for very large amounts of amplification. When there is good audibility at all frequencies, this corresponds to an SII of 0.5, which is sufficient to achieve high speech intelligibility for materials with high redundancy, such as sentence test material. In adverse situations (noise, soft speech), intelligibility, even with amplification, is much lower than is achieved by normal hearing people. The result depicted in Figure 3 appears robust, in that the curve derived from the sentence test results was almost identical to that derived from the nonsense syllable results. Furthermore, the same parameter fitting process was applied to the data we collected over a decade ago using BKB sentence material (Ching et al., 1998) and the same result was again obtained.

As a result of the new modifications made to the standard SII formula, NAL-NL2 prescribes a different gain-frequency response shape than NAL-NL1. Specifically, relative to the NAL-NL1 prescription, NAL-NL2 prescribes relatively more gain at the low and high frequencies than at the mid frequencies, see Figure 4.

Figure 4
Comparison of the NAL-NL1 and NAL-NL2 prescriptions for a flat 60 dB HL hearing loss for input levels of 50 dB SPL (dotted lines), 65 dB SPL (solid lines), and 80 dB SPL (broken lines).

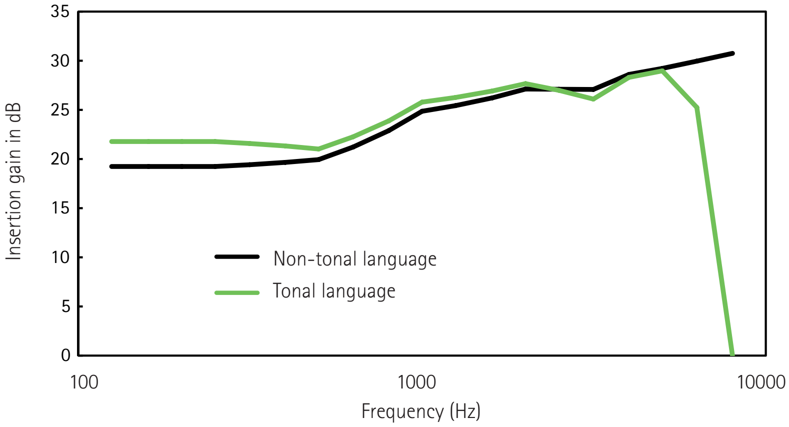


Effect of psychoacoustic measures

Speech intelligibility, with SII calculated in the traditional way held constant, was found to be statistically related to each of the psychoacoustic measures. It deteriorated with tuning curve sharpness, threshold elevation of the TEN test, otoacoustic emission strength, cognitive ability and age. However, after the SII was modified in the method described above (which lowers the predicted speech intelligibility as hearing thresholds increase) only cognitive ability and age consistently correlated with the discrepancies between the measured and predicted speech intelligibility. Consequently, although the presence of dead regions unquestionably affects the frequency range over which amplification should be provided, and presumably the amount of amplification provided (Baer et al., 2002), our analysis suggests that the increase in ability to predict speech intelligibility may not be sufficient to require that clinicians routinely test for dead regions, provided the prescription used has already incorporated an allowance for the diminishing effectiveness of audibility as hearing thresholds increase. NAL-NL2, like its predecessors, therefore is based primarily on hearing thresholds. Of course, this decision does not preclude clinicians from assessing the presence of dead regions (Moore et al., 2004) and modifying the prescription away from the NAL-NL2 prescription when it is known whether there are any dead regions.

Figure 5

The effect of language on the NAL-NL2 prescription shown here for a flat 60 dB HL hearing loss at 65 dB SPL input.



Tonal languages

The original, and our modified, SII method have been derived from studies performed using the English language. Unlike English, tonal languages, such as Mandarin or Cantonese, use fundamental frequency to convey information about the meaning of words. As the acoustic cues to fundamental frequency lie in the frequency region below about 800 Hz, the importance function for these languages should be more weighted towards the low frequencies than is the case for English. Consequently, the derivation process was repeated using an importance function that has been derived for Cantonese (Wong et al., 2007). This produced very similar prescriptions, but as anticipated, the prescriptions had more gain in the low frequencies and less gain in the high frequencies, than the prescription for non-tonal languages such as English (Figure 5). In NAL-NL2, the results of either optimization process can be selected to produce a prescription optimized for either tonal or non-tonal languages.

Prescription of gain

To derive the optimal amplification characteristics that provided the data for the NAL-NL2 formula, a modified SII calculation method was used to predict speech intelligibility, and an unmodified loudness calculation method (Moore and Glasberg, 2004) was used to calculate the overall loudness. The final "formula" chosen for NAL-NL2 was a neural net. The input parameters to the neural net were the audiogram values at each octave and several half-octave frequencies, and the overall level of the speech signal. The output values were the gains at each of the same frequencies. A neural net was an appropriate choice as the gain at any frequency depends in a complex manner on the hearing loss at all frequencies. Also, the gain at any frequency should monotonically increase as hearing loss increases, and monotonically decrease as speech level increases, behaviours that fit well with the characteristics of the perceptrons within each layer of a neural net. Training of the three-layer neural net was accomplished using the gains resulting from the derivation process described in Figure 1, after they were adjusted to prevent excessively high compression ratios.

Application of empirical evidence for optimal amplification

A range of experiments have provided information on the amplification characteristics that people prefer, and/or perform best with. Consequently, we need to over-ride the theoretical prescription whenever it departs from what we understand to be optimal on the basis of empirical studies.

Compression speed and ratios

It might appear desirable to provide people with severe-profound loss with fast-acting multi-channel compression with a high compression ratio, as such a combination would provide a good combination of audibility and comfort over a wide range of input levels for people with a narrow dynamic range between threshold and discomfort. This is certainly the result that the process depicted in Figure 1 leads to when the prescriptions for different input levels are combined. We have long known, however, that people with severe loss prefer much less compression (lower compression ratios and/or higher compression thresholds) than this line of thinking would predict (DeGennaro, 1986; Barker et al., 2001; Keidser et al., 2007), and we can infer that this is because fast-acting multi-channel compression destroys spectral information, even as it makes the energy audible. It is also possible that lower compression ratios further preserve the prosodic cues for this population. Consequently, for severe-profound losses, the compression ratio is constrained to be less than 3:1 in the high frequencies and less than 2:1 in the low frequencies (Keidser et al, 2007) during the formula extraction for fast-acting compressors. As we have no reason to believe that somewhat higher compression ratios are not appropriate for this population when the compression parameters act like an automatic volume control, the constraint was increased to 5:1 across all frequencies during the formula extraction for slow-acting compressors. For both fast- and slow-acting compressors, compression was constrained to 1:1 for those with no hearing loss, which means that compression speed mainly affects the compression ratios prescribed for those with more severe and profound hearing loss. In all cases, the prescribed gains for fast- and slow-acting compression are approximately equal for a 65 dB SPL input level (Figure 6).

Data on gain preferences in real life at different input levels (Zakis et al.,2007; Smeds et al, 2006) indicates that, relative to the gain preferred at average input levels, adults with mild or moderate hearing loss prefer more gain at low input levels, and less gain at high input levels than prescribed by NAL-NL1. That is, compression ratios greater than those prescribed by NAL-NL1 are preferred by this population. This change in prescription can be observed in the example depicted in Figure 4.

Figure 6

The effect of compression speed on the NAL-NL2 prescription for a severe 80 dB HL flat hearing loss. The prescriptions are shown for input levels of 50 dB SPL (dotted lines), 65 dB SPL (solid lines), and 80 dB SPL (broken lines).

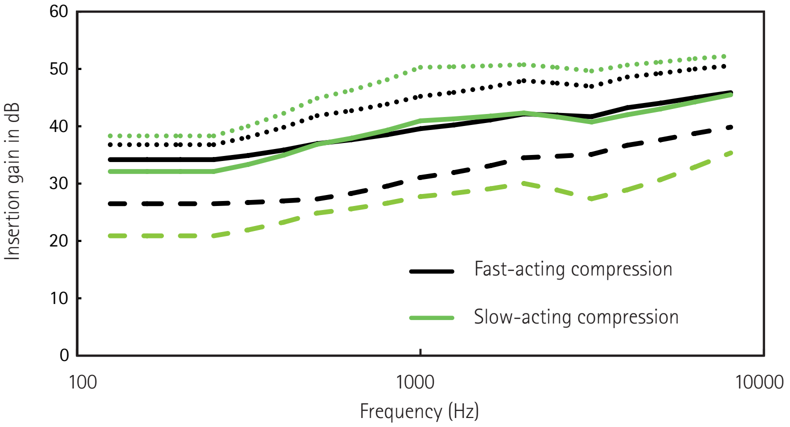


Figure 7
The effect of age on the NAL-NL2 prescription when the adult and the child have the same gently sloping hearing loss. The prescriptions are shown for input levels of 50 dB SPL (dotted lines), 65 dB SPL (solid lines), and 80 dB SPL (broken lines).

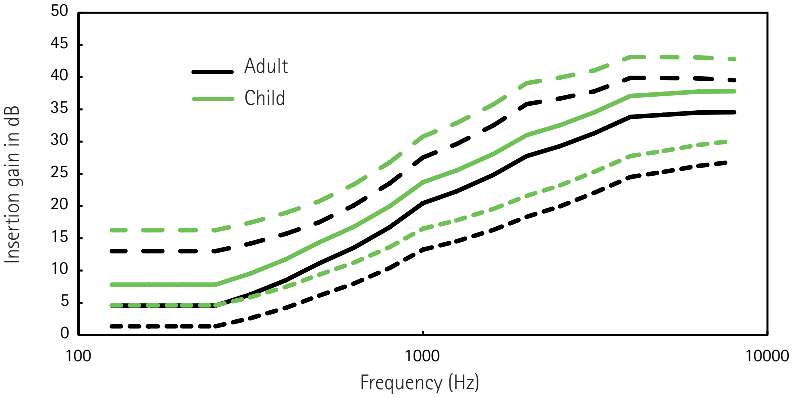
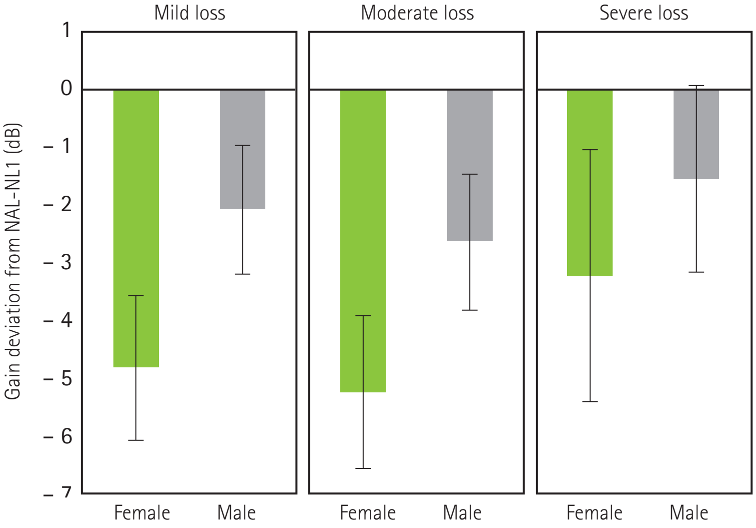


Figure 8
The average gain deviation selected from NAL-NL1 by female and male hearing aid users with mild (N = 47), moderate (N = 93), or severe to profound hearing loss (N = 47). The bars show the 95% confidence interval.



Age

A study of the fine-tuned gain-frequency responses measured on 189 adults participating in several studies (Keidser & Dillon, 2006) has indicated that NAL-NL1, on average, overprescribes gain by about 3 dB at average input levels for adults with mild and moderate hearing loss. This finding has since been confirmed in a study that specifically aimed at determining the overall gain preferred by hearing aid users (Keidser et al., 2008). By contrast, a study on children's preferences and performance enables us to infer that children on average prefer a few dB more gain than that prescribed by NAL-NL1 (Ching et al., 2010). They benefit from this for low input levels, and the danger of causing noise-induced hearing loss is least at low input levels, so the increase relative to NAL-NL1 should be greatest at low levels. That is, for children too, a compression ratio higher than that prescribed by NAL-NL1 seems optimal. Note that the higher compression ratio is for children achieved by increasing gain relative to the NAL-NL1 prescription across the lower input levels while the same compression ratio is achieved for adults by reducing gain relative to the NAL-NL1 prescription across the higher input levels. Figure 7 shows the effect of age on the NAL-NL2 prescription for experienced hearing aid users.

Gender

Males have been shown to prefer, on average, 2 dB more gain than females with the same degree of hearing loss (Keidser & Dillon, 2006). This trend was measured across 74 female and 113 male hearing aid users and it appears robust across the degree of hearing loss as shown in Figure 8. Consequently, the gains from the neural net are increased by 1 dB for males, and decreased by 1 dB for females. For coupler gain prescriptions, these small differences in real-ear gain are compounded by the larger ears that males have. Real-ear-to-coupler differences for males are therefore smaller than for females, so coupler gains for males need to be larger by the same amount to achieve the same real-ear gain. The difference caused by ear size increases with frequency, up to 1.4 dB at 6 kHz.

Experience

Experienced hearing aid wearers have been shown to prefer more gain than people receiving their first hearing aids (Keidser et al., 2008). The difference between the two groups increases from 0 dB for mild hearing losses up to around 10 dB for severe hearing losses. For people with more severe hearing loss, the sudden provision of amplification is a much bigger change in audibility than for a person with mild loss receiving a low-gain hearing aid, particularly as the former is likely to have had hearing loss for much longer than the latter. The amount by which the gain was decreased for new users and increased for experienced users was determined from experimental observations on 76 participants of how much gain each group of people preferred relative to NAL-NL1, and by how much gain NAL-NL2 was prescribing compared to NAL-NL1. These corrections are shown in Figure 9. An example of the combined effect of gender and experience on the NAL-NL2 prescription can be seen in Figure 10.

Binaural listening

Listening with two ears produces greater loudness than listening with one ear, though recent evidence suggests that the binaural to monaural loudness ratio is less than 2:1 (Epstein & Florentine, 2009). NAL-NL2 still provides greater gain for unilateral fittings than for bilateral fittings, but the difference is less than was applied for NAL-NL1. For symmetrical hearing loss, the difference progressively increases from 2 dB for input levels below 50 dB SPL up to 6 dB for input levels above 90 dB SPL. As hearing asymmetry increases, the bilateral correction is progressively reduced. The corrections applied for a symmetrical hearing loss are shown in Figure 11. As a result of the progressive increase in gain, bilaterally fitted hearing aid users will be fitted with higher compression ratios than those with unilateral hearing loss.

Figure 9

Gain adjustments for experienced listeners (dashed line) and inexperienced listeners (solid line) provided for different degrees of four-frequency average hearing loss.

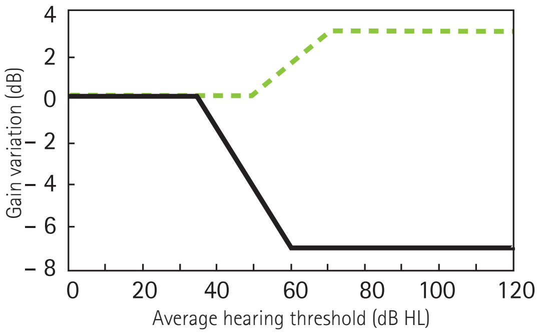


Figure 10

The combined effect of gender and experience on the NAL-NL2 prescription at 65 dB SPL input for a male experienced hearing aid user and a female new hearing aid user who both have a four-frequency-average hearing loss of 55 dB HL with a gently sloping configuration.

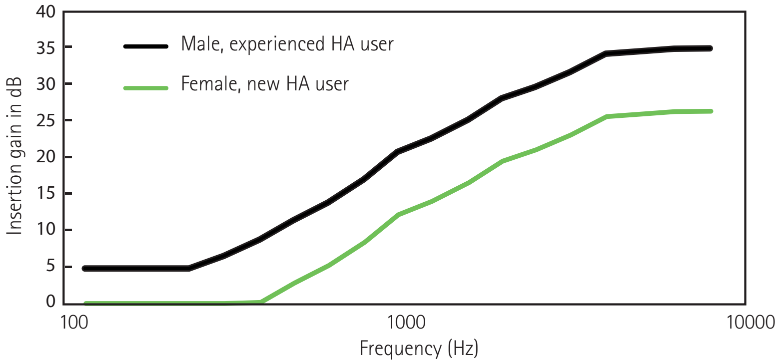
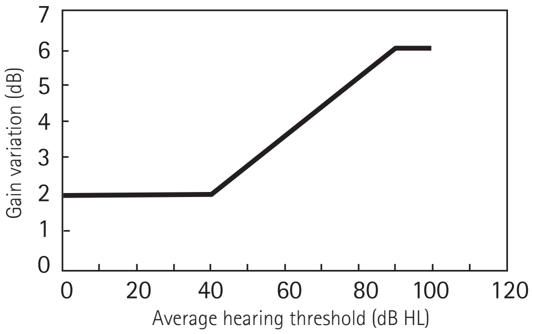


Figure 11

Gain difference between unilateral and bilateral fittings.



Conclusion

Like its predecessors, NAL-NL2 is based on a combination of theory and empirical evidence. Because NAL-NL1 has been so extensively used in experiments, and its limitations examined, the extent of empirical evidence underpinning NAL-NL2 is greater than that underpinning any of its predecessors. NAL-NL2 uses available evidence to prescribe performance depending on a range of factors other than the audiogram. It prescribes language dependent gain-frequency response shapes, compression speed dependent compression for those with severe or profound hearing loss, and varies the overall gain with age, gender, and experience. Our aim is that it provides the best possible first start to hearing aid adjustment.

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Dr Harvey Dillon is Director of Research at the National Acoustic Laboratories. Dr Dillon has performed research into many aspects of hearing aids. At various times he has also been responsible for the design of hearing aids and for the co-ordination of clinical service provision. Most recently, his research has concerned signal processing schemes for hearing aids, prescription of hearing aids, evaluating the effectiveness of rehabilitation, electrophysiological assessment, auditory processing disorders, and methods for preventing hearing loss. Dr Dillon is the author of over 160 scientific publications and a text book on hearing aids and is frequently invited to give keynote addresses at international conferences. He has been closely associated with the various NAL prescription rules, COSI outcomes evaluation, the trainable hearing aid, the LiSN-S test of spatial hearing loss, and clinical cortical response testing.

Dr Gitte Keidser is a Senior Research Scientist at the National Acoustic Laboratories where she manages a team working on projects related to hearing devices and rehabilitation. Her own research and many publications have focused on hearing aid users' preference for different amplification characteristics in different listening conditions, loudness perception and overall gain preference, the effects of advanced signal processing strategies on user performance and preference, and trainable devices.

Dr Matthew R. Flax worked as a Research Engineer at the National Acoustic Laboratories for 18 months during which time he was responsible for the implementation and verification work leading to the NAL-NL2 formula.

Dr Teresa Y.C. Ching is head of Rehabilitation procedures research at the National Acoustic Laboratories. Her research interest and experience encompass many aspects of hearing rehabilitation for children and adults, including amplification requirements, relationship between speech intelligibility and psychoacoustic abilities, evaluation methods for effectiveness of amplification and cochlear implantation, bimodal hearing and bilateral cochlear implantation, and efficacy of early intervention and outcomes of children with hearing impairment.

Scott Brewer has worked for the National Acoustic Laboratories in Sydney for the past 14 years developing PC software for commercial and experimental applications, including the stand-alone software supporting NAL's non-linear prescription rules, as well as providing IT Support.

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