The NAL-NL2 prescription procedure

Harvey Dillon, Matt R. Flax, Teresa Y.C. Ching, Gitte Keidser, Scott Brewer

Conducted as part of The Hearing CRC

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, for which a prescription is required. 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 (see below) 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 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.

The derivation of NAL-NL2 differs from that of NAL-NL1 in two main ways. 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 method for predicting speech intelligibility for people with different degrees and configurations of hearing loss. Second, we have the benefit of many experiments where NAL-NL1 has been used, often in such a way that it has been possible to determine in which direction the prescription should be changed. These two aspects of NAL-NL2 are described briefly in the remainder of this report.

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

![Figure 1. The adaptive process used to derive the optimal gain-frequency response for a single audiogram and input speech spectrum and level.](image-url)
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 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.
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 known whether there are any dead regions.

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. 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**
The modified SII calculation method, combined with an unmodified loudness calculation method (Moore and Glasberg, 2004) was used to derive optimal amplification characteristics using the
process shown in Figure 1 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, adjusted where necessary for compression speed (see below), from all the audiograms and all the input levels, must be drawn together into a single composite formula so that the result is usable for any new audiogram and any speech level. The “formula” chosen for NAL-NL2 was in fact a neural net. The input parameters to the neural net are the audiogram values at each octave and several half-octave frequencies, and the overall level of the speech signal. The output values are 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: 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. For severe-profound losses, 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). Prescribed gains for fast- and slow-acting compression are approximately equal for a 65 dB SPL input level. 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 prefer more gain at low input levels, and less gain at high input levels. That is, compression ratios greater than those prescribed by NAL-NL1 are preferred.

Age: A study of the fitting results from 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. 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., in press). 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.

Gender: Males have been shown to prefer about 2 dB more gain than females with the same degree of hearing loss (Keidser & Dillon, 2006). 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 
such people, 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 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 4.

**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 5.

**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. Our aim is that it provides the best possible first start to hearing aid adjustment.

References


