

What's New in Prescriptive Fittings Down Under?

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Introduction

In 1999, the National Acoustic Laboratories (NAL) introduced a procedure, NAL-NL1, for fitting non-linear hearing devices (Dillon 1999). The aim of this procedure is to maximize intelligibility of speech at all input levels while ensuring that the overall loudness of speech does not exceed normal overall loudness. The formula was derived by fitting an equation to the optimum gain levels calculated for 52 different audiogram configurations and 11 input levels from 40 to 90 dB SPL. The calculations were based on a modified version of the speech intelligibility index (SII) formula (ANSI 1997) and loudness calculations using the loudness model of Moore and Glasberg (1997). The assumed input signal was represented by the one-third octave levels of the international long-term average speech spectrum (ILTASS) published by Byrne et al. (1994). Modifications to the SII calculations consisted of the introduction of an *effective* audibility factor (Ching, Dillon, Katsch and Byrne 2001) that accounts for the fact that as the hearing loss becomes more severe, less information is extracted from the speech signal, even when the signal is fully audible (Hogan and Turner 1998; Ching, Dillon and Byrne 1998).

As with its predecessors, the validity of the NAL-NL1 target has been monitored since the procedure was released, and the underlying principles of its derivation further evaluated. In particular, the appropriateness of

the rationale has been evaluated in adults and in children, further knowledge about the prediction of speech intelligibility has been sought, and issues such as gain acclimatization in new hearing aid users and the preferred compression characteristic by hearing aid users with severe to profound hearing loss have been investigated. These data are being used to modify the optimization procedure and to further refine the optimized gains, which in turn are leading to a revised formula called NAL-NL2. As hearing aids become increasingly able to adapt to the acoustic environment, it is becoming increasingly possible to fit hearing aids that have no volume control. For these hearing aids, it is just as important to correctly prescribe the average gain as it is to prescribe the correct frequency response shape if additional appointments to adjust the hearing aid are to be minimized or avoided. This paper will summarize the empirical findings that have led to the revisions and will conclude by showing the anticipated changes to the prescribed insertion gain for a few hypothetical clients.

Maximizing Speech Intelligibility

The rationale of maximizing speech intelligibility resulted in optimized gain that, across frequencies, equalized rather than normalized the loudness of speech bands, especially for higher input levels. For lower input levels, maximization of calculated intelligibility usually gave greatest weight to those (mid) frequencies that made the greatest contribution to intelligibility. Consequently, the shape of the NAL-NL1 targets can be very different from those derived by fitting procedures aiming at frequency-specific loudness normalization (e.g. Byrne, Dillon, Katsch, Ching and Keidser 2001; Keidser and Grant 2001, 2003). In particular, NAL-NL1 tends to prescribe less gain in the low frequencies for flat hearing

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loss configurations and less gain in the high frequencies for sloping high-frequency hearing loss configurations, and to generally prescribe lower compression ratios.

In an evaluation study conducted at NAL, 24 adult hearing aid users with either a flat or a steeply sloping high-frequency hearing loss compared NAL-NL1 with the Independent Hearing Aid Fitting Forum (IHAF) prescription procedure (Cox 1995; Valente and Van Vliet 1997), which is based on a pure loudness normalization rationale. While the prescribed frequency response shape for a 65 dB SPL input was matched in the best possible way, the overall gain for each prescription was always adjusted to match the participants' preferred loudness. In some cases, the adjustment of overall gain significantly reduced differences between the two prescribed targets (Keidser and Grant 2003). The outcome of this study was that both in the laboratory and in the field there was an increasing preference for the NAL-NL1 prescription over IHAF as the root-mean-square (RMS) difference between the fitted responses increased. That is, when the overall loudness was equalized across the two prescriptions and the difference in prescribed response shape was sufficiently different, there was a significant preference for equalizing over normalizing loudness of frequency-specific speech bands (Keidser and Grant 2001).

Similarly, data from NAL (Ching 2003) show an overwhelming preference by adult hearing aid users for NAL-NL1 over the Desired Sensation Level Input-Output (DSL[i/o]) prescription (Cornelisse, Seewald and Jamieson 1995), a procedure that also largely restores fre-

quency-specific loudness to normal. In this study, however, differences in both prescribed frequency response shape and overall gain were maintained in the fittings, and the preferences for NAL-NL1 seemed to derive more from the greater loudness of DSL[i/o] than from the difference in frequency response shape. It also should be noted that an extensive evaluation of the NAL-R prescription for linear devices (Byrne and Dillon 1986), which specifically aims at equalizing loudness of speech bands, showed that in comparison to various alternative responses, the NAL-R prescribed response shape was appropriate for 60 out of 67 ears (Byrne and Cotton 1988). On this basis the speech intelligibility maximization rationale is maintained in the derivation of NAL-NL2.

Predicting Speech Intelligibility

The speech perception data collected at NAL that lead to the modified speech intelligibility index calculations also suggested that speech proficiency was highly correlated with both frequency and temporal resolution (Ching, Dillon and Byrne 1997). However, as these parameters also were highly correlated with the degree of hearing loss, which was found to be the more contributing factor to speech intelligibility, NAL-NL1 remained a threshold-based prescription procedure like its linear predecessors NAL-R and NAL-RP (Byrne, Parkinson and Newall 1991). Since the development of NAL-NL1, it has been questioned whether the presence of a cochlear dead region (Moore 2001, 2004) affects speech intelligibility (Baer, Moore and Kluk 2002; Rankovic

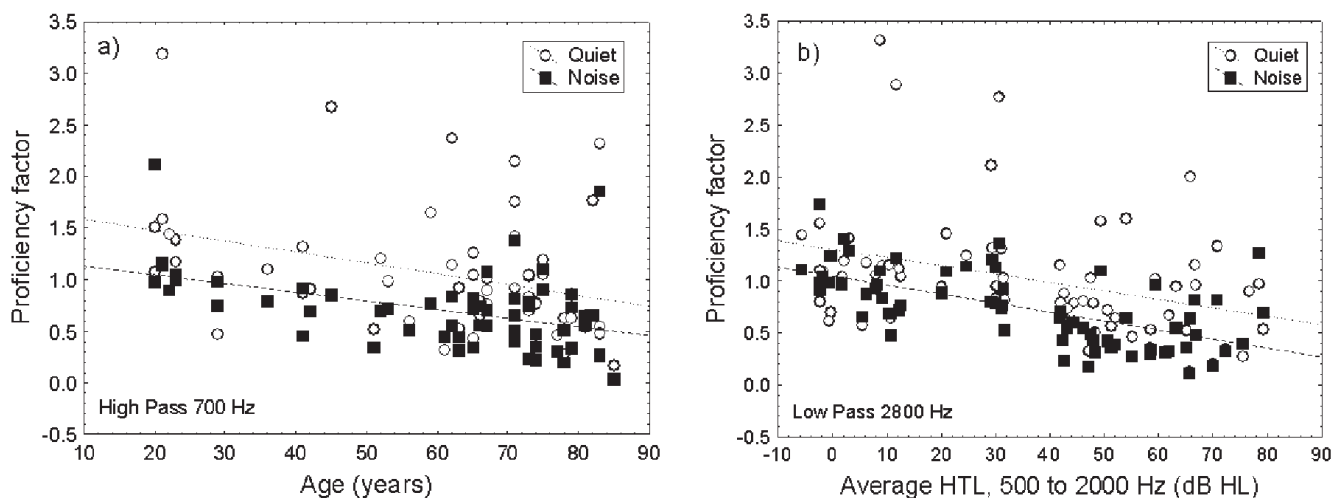


Figure 1. The proficiency factors extracted from the speech scores obtained in quiet and in noise with the a) low pass filtered speech at 0.7 kHz as a function of age, and b) high pass filtered speech at 2.8 kHz as a function of the hearing threshold level averaged across 0.5, 1.0, and 2.0 kHz.

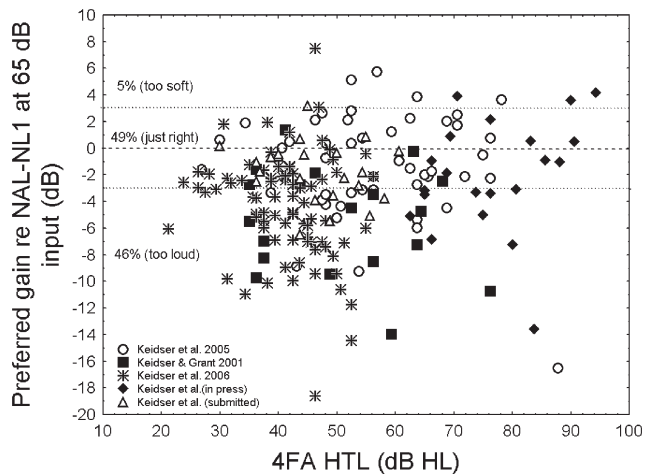


Figure 2. The overall gain preference relative to NAL-NL1 prescribed gain for a 65 dB input as a function of the 4FA HTL for 189 hearing-impaired people participating in five different research studies.

2002; Vestergaard 2003). It also has been questioned whether the effective audibility of high frequency information in noise may be greater than in quiet when compared at the same sensation level (Hogan and Turner 1998; Turner and Henry 2002). An affirmative result on both accounts would suggest that a prescription that aims at maximizing speech intelligibility must take individual dead regions into account and must consider optimized gain in both quiet and noise.

To investigate these issues, an extensive study involving 75 listeners with hearing ranging from normal to profound loss was conducted at NAL (Ching, Dillon, Lockhart, van Wanrooy and Carter 2005). All participants were tested for dead regions using the threshold equalizing noise (TEN) test by Moore (2001) at audiometric frequencies from 0.25 to 8.0 kHz and psychophysical tuning curves at octave frequencies from 0.5 to 4.0 kHz. In addition, speech perception was measured in quiet and in babble noise using sentence material and a consonant test low-pass filtered at 0.7, 1.4, 2.8, and 5.6 kHz and high-pass filtered at 0.7, 1.4, and 2.8 kHz. The data showed no consistent correlation between speech proficiency for the different filter bands in quiet or in noise and the TEN elevation in the same frequency regions. That is, the knowledge of individual dead regions according to the TEN test seemed unlikely to improve the prediction of speech intelligibility once hearing thresholds were known. Speech proficiency decreased as both age and hearing threshold level increased, as shown in figure 1, but for any particular combination of age and hearing threshold, speech profi-

ciency was lower in noise than in quiet. That is, there is at least as much need to allow for the impact of hearing loss on the ability to extract information (i.e., hearing desensitization) in noise as there is in quiet. This information and the new speech intelligibility data are currently being used to refine the frequency specific desensitization factors and hence the effective audibility parameter in the SII formula.

Additional data were collected in this study, none of which have as yet demonstrated a convincing need for making NAL-NL2 dependent on suprathreshold psychoacoustic data in addition to its existing dependence on hearing threshold levels. There are, however, some analyses yet to be carried out, and we are leaving open the option of a clinician applying a suprathreshold test, the result of which would create a correction to the insertion gain prescribed on the basis of hearing thresholds alone. Someone with a dead region, for example, would be prescribed less gain in the dead region than the average person with that loss, whereas someone proven not to have a dead region would be prescribed more gain than average.

Desired Loudness

Another rationale behind the optimization procedure used to derive NAL-NL1 is to ensure that the overall loudness of speech does not exceed normal overall loudness. However, clinical anecdotes worldwide would suggest that the NAL-NL1 prescribed gain is too high. But, by how much and to what extent is any preferred gain variation from target related to input level or frequency band, or to some characteristic of the client, such as age and previous experience with amplification?

Adults

For Medium Input Levels (65 dB SPL)

Figure 2 shows for 189 adults the preferred four-frequency-average (4FA – measured across 0.5, 1.0, 2.0, and 4.0 kHz) gain deviation from the NAL-NL1 prescription for a 65 dB SPL input level in everyday life as a function of their 4FA hearing threshold level (HTL). For those who were bilaterally fitted, the values were averaged across ears while the values for the fitted ear were used for those who were fitted unilaterally. These data, from five different studies, were partly collected clinically through the Australian Hearing network (Keidser et al. 2005; Keidser, O'Brien, Carter, Froehlich and

Dillon 2006) and partly at NAL (Keidser and Grant 2001; Keidser et al. 2006; Keidser, Dillon, Dyrland, Carter and Hartley 2007; Keidser, Carter, Chalupper and Dillon submitted). The aims of the five studies varied and in all but one study the calculated preferred gain refers to the resulting fine-tuned gain that was arrived at after an adjustment period of 1-4 weeks in the field. Only in the Keidser et al. (2006) study are the measurements based on the participants' self-adjusted gain levels in their everyday environments.

The data confirm that it is much more common for clients to want a gain decrease than a gain increase relative to the NAL-NL1 prescription. If clients were to rate a gain level within 3 dB of the prescribed gain as just right, then the prescribed overall gain appears to be right for nearly half of the study participants (48%), while 5% found the prescription too soft and 47% found the prescription too loud. Based on this data set, the average preferred overall gain deviation from NAL-NL1 is -3.2 dB, with a standard deviation of 4.2 dB. This value is in reasonable agreement with the average preferred overall gain deviation from NAL-R of -4.3 dB found across studies by Byrne and Cotton (1988), Cox and Alexander (1992), Horwitz and Turner (1997), Humes, Wilson, Barlow and Garner (2002) and Convery, Keidser, and Dillon (2005). The lower preferred gain deviations from NAL-NL1 are likely due to non-linearity reducing gain further for high input levels and the fact that NAL-NL1 for a 65 dB SPL input level prescribes less gain than NAL-RP for bilateral fittings (the proportion of bilateral to unilateral fittings in the data in figure 3 is nearly 3 to 1). Reducing the overall gain for a 65 dB SPL input by 3 dB would change the proportion of participants who found the prescription too soft, just right, and too loud to 20%, 60%, and 20%, respectively, for a ± 3 dB tolerance criterion.

Smeds et al. (2006a, 2006b) conducted an experiment in which normal-hearing and hearing-impaired participants made loudness judgements and volume adjustments to preferred loudness for a range of listening environments presented in the laboratory. The same participants also performed volume adjustments in their everyday environments. On average, the hearing-impaired participants (including experienced and inexperienced hearing aid users) preferred less gain than prescribed by NAL-NL1. The median gain variation based on field test data was -8 dB re NAL-NL1 for input levels between 60 and 70 dB SPL. This deviation is somewhat larger than seen in figure 3 and may be explained by factors such as a wider frequency range pro-

vided by the test device used and occlusion, as all participants were fitted with unvented earmolds. Of particular interest, however, Smeds et al. further found that 1) NAL-NL1 tended to prescribe less than normal loudness according to the Moore and Glasberg (1997) loudness model, especially for input levels below 65 dB SPL; 2) the hearing-impaired participants, when aided with NAL-NL1, rated loudness higher than normal-hearing listeners despite the calculated loudness of NAL-NL1 being less than normal; and 3) while both normal-hearing and hearing-impaired participants preferred less than normal loudness in the laboratory environment, normal-hearing listeners aided with 0 dB insertion gain and having access to a volume control selected close to normal loudness in the field. These results would suggest that the hearing loss component is not appropriately accounted for in the 1997 Moore and Glasberg loudness model, at least with the default assumptions about how much of the loss is due to inner hair cell loss, and how much is due to outer hair cell loss. Smeds, Smeds and Leijon (2004) have presented data showing that if the relative portions of loss are deduced from the elevation of loudness discomfort level that occurs in sensorineural hearing loss, calculated loudness increases by a few dB. This modified assumption, together with a revised version of the loudness model, is being used in the derivation of NAL-NL2, and is the primary mechanism that will lead to the lower gain prescriptions that our empirical data tell us are necessary.

Table 1. The average change in overall gain deviation in dB from NAL-NL1 preferred at low and high input levels relative to the preferred gain for a medium input level of 65 dB SPL.

Study :	50 dB SPL	80 dB SPL
Smeds et al. (2006a)	1.1	-1.5
Zakis et al. (submitted)	0.9	-1.5

For Low and High Input Levels

According to Smeds et al. (2006a, 2006b) and Zakis, Dillon and McDermott (submitted), the magnitude of the average preferred gain reduction below NAL-NL1 increases with increasing input level, suggesting that hearing aid users prefer a compression ratio higher than prescribed. Both studies used the same research device, a master programmable hearing aid that could be worn in the field (Zakis, McDermott and Fisher 2004) that allowed the preferred volume control settings to be

Table 2. The average change in overall gain deviation in dB from NAL-NL1 preferred at low and high frequencies relative to that preferred in the mid frequencies (between 0.63 and 2.5 kHz) for three input levels by participants in Zakis et al. (submitted).

Input level :	Low-frequency band (<0.63 kHz)	High-frequency band (>2.5 kHz)
50 dB SPL	2.9	-0.4
65 dB SPL	3.1	-0.6
80 dB SPL	2.6	0.2

logged together with information about the level and spectrum of the environment at the time of the volume control adjustment. Both studies found that in the field, the hearing aid users, on average, required 2.5 dB greater reduction for 70-80 dB SPL input levels than for 50-60 dB SPL input levels (table 1). These data suggest that the increase in the compression ratio should be small, at least for adult hearing aid wearers with mild and moderate hearing loss. Data by Keidser et al. (2007) suggest that as the low-frequency hearing loss progresses from severe to profound, close to linear amplification is preferred in the low frequencies while the preferred compression ratio in the high frequencies remains between 2:1 and 3:1. Although these data are based on a small sample (21), adjustments will be made to NAL-NL2 to ensure that the compression ratio will not exceed 2:1 in the low frequencies and decreases toward linear as the hearing loss exceeds 70 dB HL.

For Low and High Frequencies

In the study by Zakis et al. (submitted), the participants were able to control various hearing aid parameters and log their preferences in different environments, thus training the hearing aid to predict their preferred gain-frequency responses as a function of some acoustic characteristic of the environment. The trained data revealed that the participants generally preferred relatively less gain than prescribed in the high frequencies than in the low frequencies across a wide range of input levels (table 2). This finding is supported by Keidser et al. (2006) who found that among both experienced and new hearing aid users who in a multi-memory device were fitted with NAL-NL1, a high cut response, and a low cut response (where possible), 60% preferred the program delivering NAL-NL1 with a high-frequency cut. Going back in time, when Byrne and Cotton (1988) evaluated NAL-R, they found that when comparing the NAL-R prescription with variations having increased or decreased low-frequency emphasis or increased high-frequency emphasis, there was an overwhelming preference for the NAL-R response. However, when compar-

ing NAL-R with a high cut response, a majority of listeners had no preference for either response. It would appear that the preference by many hearing aid users to reduce gain in the high frequencies is purely related to sound quality, as there is no evidence that less high-frequency gain improves performance. The changes made to the loudness calculations will produce slightly less gain at high frequencies for clients with sloping (high-frequency) hearing loss, as a higher contribution to loudness where the loss is greatest will cause the optimal response to move some gain from the high frequencies to the low frequencies. It is possible that the changes being made to the effective audibility will produce a further reduction in high-frequency gain.

Gain Acclimatization

Clinical anecdotes suggest that new hearing aid users prefer less gain than do experienced hearing aid users. A comprehensive literature review conducted by Convery et al. (2005) found no strong evidence to support this belief. Although new users, on average, generally did prefer less gain than experienced users, the difference in preferred gain levels relative to the NAL-R prescription did not exceed 2 dB. This difference was not statistically significant and it was independent of the time at which gain preferences were measured (up to 12 months after fitting) and the acoustic environment in which the measurements were obtained. Smeds et al. (2006b) also found no statistically significant difference in preferred gain deviations from NAL-NL1 between new and experienced hearing aid users. On average, across a range of input levels, the new hearing aid users preferred 1.4 dB less gain than experienced hearing aid users. When excluding six extreme observations in figure 2 (one preference for more than 6 dB more gain than prescribed and five preferences for a reduction of more than 12 dB below the prescription), the combined data collected at NAL suggest that new users prefer, on average, 2 dB less gain than participants who had worn amplification for more than 3 years. Overall, these findings suggest that the observed small difference between new and experienced users is

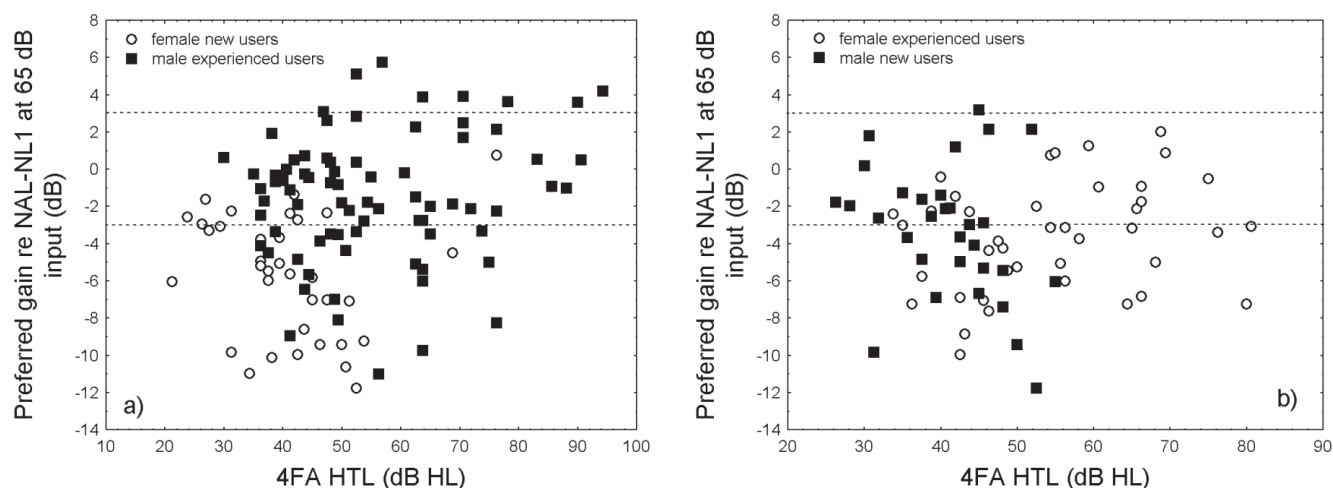


Figure 3. The distribution of preferred gain deviations from NAL-NL1 for a 65 dB input by a) new female and experienced male hearing aid users, and b) experienced female and new male hearing aid users.

quite consistent and do not explain the entire variability in preferred gain seen in figure 2.

There may therefore be factors other than experience that discriminate between those who find NAL-NL1 prescribed gain too soft, just right, or too loud. This was investigated in the data set depicted in figure 2. Using the degree of hearing loss (4FA HTL), configuration of hearing loss (slope), age, gender (female/male), aid configuration (unilateral/bilateral), and experience with amplification (new user, experienced user) as independent variables, a discriminant analysis revealed that a combination of five out of the six parameters could predict the gain preference better than pure chance ($p < 0.0002$). The only parameter not included in the model was the slope of the hearing loss. Younger, new, unilaterally fitted female hearing aid users with a mild hearing loss were more likely to find the NAL-NL1 prescription too loud. The model produced two discriminant functions of which only one was significant ($p < 0.00007$). This function accounted for 83% of the variability in data and correctly identified 61% of the 183 participants as preferring more, the same, or less gain than prescribed. Among the five parameters, gender produced the highest standardized weight and was the only parameter to reach significance within the model (see table 3). On its own, gender could significantly predict gain preference better than pure chance ($p < 0.0001$), also correctly identifying 61% of the participants. The female hearing aid users, on average, preferred 2.3 dB less gain than did male hearing aid users.

Figure 3 shows the combined effect of gender and experience. It can be seen that female new hearing aid users mostly prefer less gain than prescribed (-5.2 dB on

average), while male experienced hearing aid users generally prefer the prescribed overall gain within the ± 3 dB tolerance band (-1.5 dB on average). On the other hand, experienced female and new male hearing aid users prefer similar gain levels (-3.6 and -3.3 dB, on average, respectively). Data are currently being collected at NAL to study whether gain preferences of new female users will change over a period of 12 months. Based on this information, NAL-NL2 will provide gender- and experience-specific gain, prescribing 4.0 dB higher gain for males with hearing aid experience than for females with no hearing aid experience.

Children

In a collaborative study between NAL and the University of Western Ontario in Canada, DSL[i/o] and NAL-NL1 were fitted to 48 children, 24 at each site. At both sites, the performance and preference with each prescription were measured in the laboratory and in the field (Seewald 2002; Ching 2003). Although DSL[i/o] typically prescribes both higher overall gain and steeper slopes than NAL-NL1, the achieved fittings mainly differed in the overall gain. Performance data based on loudness measurements and speech perception tests revealed no significant difference between the two prescriptions. In terms of preference in the field, the vote was half and half for each prescription in Australia while the Canadian children primarily selected DSL[i/o]. That is, a greater proportion of the children studied preferred a gain somewhat higher than that prescribed by NAL-NL1.

The discrepancy in findings between this study and the study mentioned earlier involving adults suggest that gain preferences differ between either children and adults, or between congenitally and adventitiously impaired listeners. A review of 43 fittings performed on adults with a severe or profound hearing loss at NAL, of whom 15 had a congenital hearing loss and 28 had an acquired hearing loss, found no significant difference in gain preferences relative to the NAL-NL1 prescription (unpublished data). Consequently, it is currently assumed that the observed discrepancy applies to age, and thus NAL-NL2 will provide higher overall gain for children than for adults. The highest increase of 4 dB will be for low input levels, with a progressive decrease in increased gain with increased input level (i.e., an increase in compression ratio). Although the decision to increase the gain above NAL-NL1 for children is based on preferences expressed by the children, the nature of the increase comes from two overall considerations; 1) an increase of gain is far more likely to lead to greater speech intelligibility at low input levels, where intelligibility is most limited by audibility, than at high input levels, and 2) an increase in gain is far less likely to cause noise-induced hearing loss for low input levels than for high input levels.

Other Parameters

Other parameters prescribed by NAL-NL1 include a compression threshold of 52 dB SPL for a broadband speech signal and limiting for single and multiple channels. We are not aware of any direct evaluation of these recommendations, but neither are we aware of any evidence suggesting that the threshold or limiting is inappropriate. Consequently, we are not anticipating that there will be any changes made to these parameters.

A bilateral correction factor that introduces a level-dependent gain reduction (figure 6) also is prescribed. The reduction is greatest for high input levels, which results in an increase in the prescribed compression ratio for bilateral fittings. This is an area in which we would prefer to have further research data available. While some studies indicate considerable binaural loudness summation, on which figure 4 is based, other studies indicate only 1–2 dB of summation at high input levels (Dillon 2001).

NAL has not conducted any research into the dynamic characteristics of compression, but note the comprehensive findings by Gatehouse, Naylor and Elberling (2006), which showed that the performance of, and preference for, different time constants depends in part on the client's cognitive skills and listening environment. The NAL-NL2 prescription will therefore not make any prescription for specific compression time

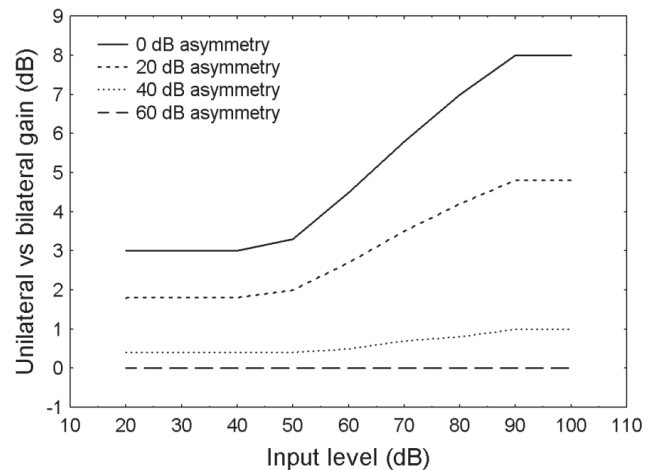


Figure 4. The difference between unilateral and bilateral gain, for different input levels and different degrees of asymmetry between the ears.

Table 3. The parameters that correctly predicted the preference for less, the same, or more overall gain than prescribed by NAL-NL1 and the standardized coefficient (β), the significance level (p), and the tolerance (T) obtained for each parameter.

Parameter :	β	p-level	T
Gender	-0.77	0.0003	0.99
4FA HTL	-0.16	0.06	0.78
Aid configuration	-0.35	0.10	0.99
Aid experience	-0.34	0.15	0.80
Age	-0.24	0.29	0.97

constants, but rather can be used with whichever time constants are selected or available.

Summary

In summary, we show how the NAL-NL2 prescription is likely to vary from the NAL-NL1 prescription based on the assumptions behind the development process that have been presented in this paper. Consider a gently sloping audiogram as shown in figure 5a. The likely NAL-NL2 prescriptions for a first-time female hearing aid candidate, an experienced male hearing aid user with a cochlear dead region, and a child are compared to the current NAL-NL1 prescription in figures 5b–d. In each case, a bilateral hearing aid fitting is assumed. While the NAL-NL1 prescription is the same irrespective of the person presenting the audiogram, this is not so with the NAL-NL2 prescription. Figure 5b shows that for a new female hearing aid candidate, the

loudness corrections, inexperience with amplification, and female gender have all led to a substantial gain reduction relative to NAL-NL1, with the most pronounced reductions at the highest input levels. Figure 5c shows the prescription for an experienced male wearer with a high-frequency dead region. The dead region correction (assuming it does become a part of NAL-NL2) has caused a pronounced gain reduction in the high frequencies, and an offsetting gain increase in the low and mid frequencies, so that the correction does not change overall loudness. When all the corrections are combined in the low frequencies, the gain is very similar to that of NAL-NL1. Finally, figure 5d shows the estimated prescription for a child. In contrast to the adults, the estimated NAL-NL2 gains are greater than those for NAL-NL1, particularly for low-level sounds. In this case, the compression ratio reaches a maximum value of 3.3:1 at 2 kHz. We do have some concerns about compression ratios this high if they are achieved totally with fast

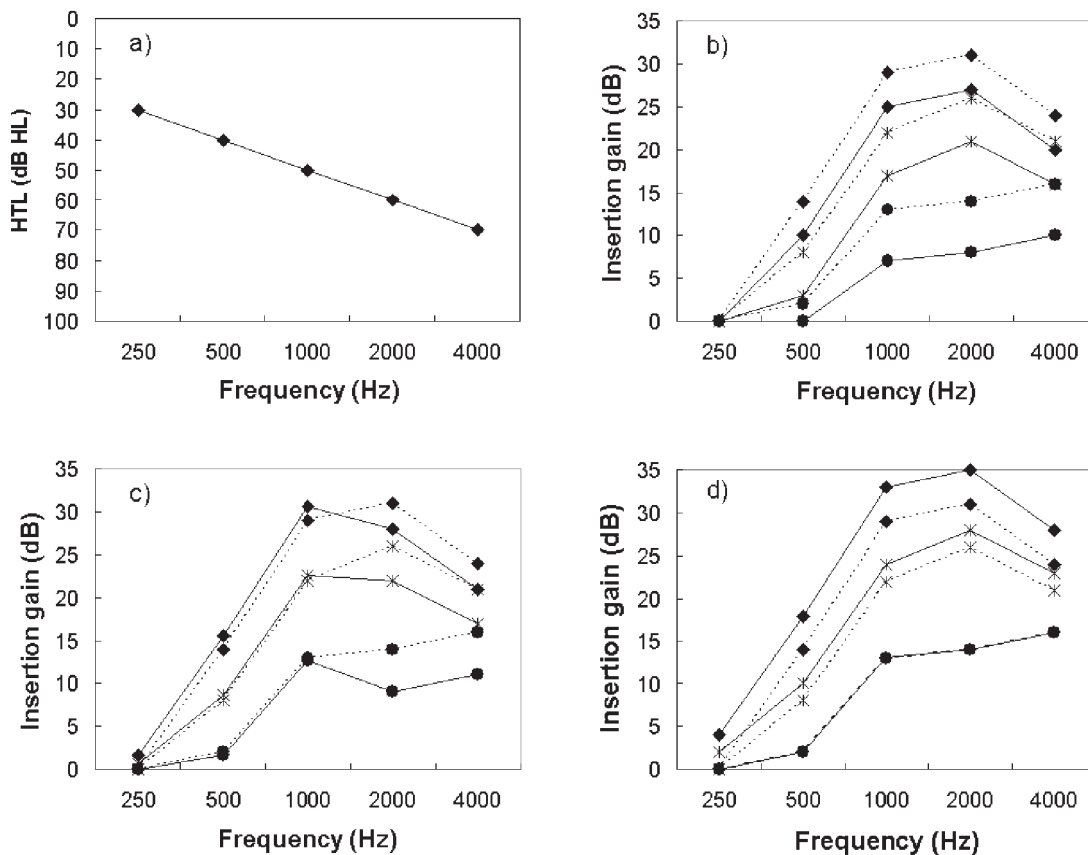


Figure 5. Assumed bilateral hearing loss (a), and the NAL-NL1 (dotted) and estimated NAL-NL2 (solid) insertion gain prescriptions for (b) a new female hearing aid candidate, (c) an experienced male hearing aid wearer with known cochlear dead regions at and above 2 kHz, and (d) a child. Prescriptions are shown for 50 (diamond), 65 (asterisk), and 80 (circle) dB input levels.

acting, multi-channel compression, in which case loss of spectral cues to place would most likely occur, offsetting the increased audibility that these higher compression values enable. Our expectation is that high compression ratios will not cause a flattening of spectral cues if they are achieved, at least partially, with slow acting compression. This is an area where further research is greatly needed.

Acknowledgement

Many of our colleagues have been involved in the process of collecting, analyzing, and interpreting the data that are behind NAL-NL2. In particular, we would like to thank Richard Katsch, Teresa Ching, Karolina Smeds, Justin Zakis, Elizabeth Convery, Anna O'Brien, and Lyndal Carter for managing the many projects referred to in this paper. We are also grateful to the Oticon Foundation, Bernafon, GN ReSound and Siemens, who have sponsored a number of the projects from which the data are presented.

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