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Invited Paper

A comparison of NAL and DSL prescriptive methods for paediatric hearing-aid fitting: Predicted speech intelligibility and loudness

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Abstract

Objective: To examine the impact of prescription on predicted speech intelligibility and loudness for children. *Design:* A between-group comparison of speech intelligibility index (SII) and loudness, based on hearing aids fitted according to NAL-NL1, DSL v4.1, or DSL m[i/o] prescriptions. A within-group comparison of gains prescribed by DSL m[i/o] and NAL-NL2 for children in terms of SII and loudness. *Study sample:* Participants were 200 children, who were randomly assigned to first hearing-aid fitting with either NAL-NL1, DSL v4.1, or DSL m[i/o]. Audiometric data and hearing-aid data at 3 years of age were used. *Results:* On average, SII calculated on the basis of hearing-aid gains were higher for DSL than for NAL-NL1 at low input level, equivalent at medium input level, and higher for NAL-NL1 than DSL at high input level. Greater loudness was associated with DSL than with NAL-NL1, across a range of input levels. Comparing NAL-NL2 and DSL m[i/o] target gains revealed higher SII for the latter at low input level. SII was higher for NAL-NL2 than for DSL m[i/o] at medium- and high-input levels despite greater loudness for gains prescribed by DSL m[i/o] than by NAL-NL2. *Conclusion:* The choice of prescription has minimal effects on speech intelligibility predictions but marked effects on loudness predictions.

Key Words: Hearing-aid prescription; children; speech intelligibility; SII; loudness; DSL v4.1; DSL m[i/o]; NAL-NL1; NAL-NL2

Early detection of hearing loss via universal newborn hearing screening has made it possible to provide amplification to children at a very young age. For prescribing hearing-aid gain, the National Acoustic Laboratories (NAL) procedures (NAL-NL1, Byrne et al, 2001; NAL-NL2, Dillon et al, 2011) and the desired sensation level (DSL) procedures (DSL v.4, Seewald et al, 1997; DSL m[i/o], Seewald, 2005; Scollie et al, 2005) have been used widely. As the NAL and the DSL procedures are based on different principles and formulae, the target gain-frequency responses for many hearing losses differ markedly between prescriptions (Byrne et al, 2001; Johnson & Dillon, 2011). A recent cross-over comparison of prescriptions for 48 school-aged children with mild to moderately severe hearing loss showed that gains were significantly higher in hearing aids fitted with DSL v.4 than with NAL-NL1 (Ching et al, 2010a). Despite the difference in overall gains, the hearing aids were similarly effective for children with regard to laboratory and real-life performance and preference (Ching et al, 2010b, 2010c). The gain differences resulted in initial variation in subjective loudness ratings, but rating differences became non-significant after extended periods of familiarization with each prescription (Scollie et al, 2010a). In real-world trials, some children reported loudness discomfort with the DSL v.4 in some environments (Ching et al, 2010d). Whether the comments were due to gains exceeding comfort levels or to the prior use history of the children could not be delineated. Double-blind measurement of preferences revealed that even though some choices were related to acoustic environments, overall listening preferences were driven by auditory experience or years spent in development with each prescription (Scollie et al, 2010b). These findings call for an evaluation of the impact of choice of prescription on fitting infants and young children who are newly identified with hearing loss.

Evidence to guide the choice of prescription for young children is lacking, in part because it is difficult to evaluate outcomes of amplification at a young age using subjective measures (Stelmachowicz, 1999). Given that a major goal of amplification is to provide an audible signal across speech frequencies to maximize intelligibility within the range of comfortable loudness, models of predicted speech intelligibility and loudness provide a basis for comparing prescriptive methods. Based on prescribed gain targets, real-ear aided response levels can be calculated and used to predict speech intelligibility and loudness.

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Abbreviations

4FA	Four-frequency average, across 0.5, 1, 2, and 4 kHz
ANSI	American National Standards Institute
ANOVA	Analysis of variance
dBHL	Decibel hearing level
dBSPL	Decibel sound pressure level
DSL	Desired sensation level
DSL v4.1	Desired sensation level procedure version 4.1
DSL m[i/o]	Desired sensation level multi-stage input-output algorithm, aslo known as DSL v5
ERB	Equivalent rectangular bandwidth
HA2-2cc	Type 2 hearing-aid coupler with 2 cubic centimeter volume
HSD	Honest significant difference test
HTL	Hearing threshold level
ILTASS	International long-term average speech spectrum
LOCHI	Longitudinal outcomes of children with hearing impairment study
MPO	Maximum power output
MPL	Modified power law
NAL	National Acoustic Laboratories
NAL-NL1	National Acoustic Laboratories' prescription for non-linear hearing aids, version 1
NAL-NL2	National Acoustic Laboratories' prescription for non-linear hearing aids, version 2
REAG	Real-ear aided gain
REAR	Real-ear aided response
REUR	Real-ear unaided response
RECD	Real-ear-to-coupler difference
SII	Speech intelligibility index

The speech intelligibility index (SII) model is a standardized method of calculating audibility of a speech signal (ANSI, 1997) for predicting speech intelligibility. The SII is represented by the following equation:

$$\mathrm{SII} = \sum I_i A_i \tag{1}$$

where I_i is the function which characterizes the importance of the ith frequency band for speech intelligibility, and A_i expresses the proportion of the speech dynamic range in the ith frequency band that is above the listener's hearing threshold.

The SII model has been used successfully to predict speech scores for different types of speech material for listeners with normal hearing sensitivity and milder hearing impairment (Pavlovic, 1986; Studebaker et al, 1997; Ching et al, 1998). However, the model overestimated performance for listeners with increased amounts of hearing loss (Pavlovic, 1986; Studebaker et al, 1997; Ching et al, 1998). As shown in those previous studies, the amount of speech information that can be extracted from an audible signal decreases as hearing loss increases. This decreased ability of the impaired ear is commonly referred to as hearing loss desensitization. Speech intelligibility will be over-estimated if the SII calculation does not allow for desensitization when the hearing threshold at any frequency exceeds about 60 dB HL. Therefore, the SII model needs to be modified to include hearing loss desensitization (Ching et al, 2001, 2011).

In applying the SII model to estimating speech intelligibility for children, speech scores would be lower for children than for adults at a given SII (Scollie, 2008; Gustafson & Pittman, 2011; McCreery & Stelmachowicz, 2011). This observed discrepancy between adult and child performance does not vary across frequencies, suggesting that the frequency importance functions (e.g. Pavlovic, 1994) in the standard method would not need to be modified for children (McCreery & Stelmachowicz, 2011).

Although the SII method has been used to compare amplification options for children (Stelmachowicz et al, 1994), the SII on its own is not a reliable way to choose between different options. Given that the major determinants of audibility or SII are hearing thresholds and the amplified speech spectrum—assuming that there is no noise present—an amplification scheme that applies enough gain at each frequency to make speech at that frequency entirely audible will give a higher SII. Even if the technology makes this possible, it may result in excessive saturation of the hearing aid. In practical applications, the scheme with a higher SII may result in excessive loudness (e.g. Rankovic, 1991) and potential threshold shifts as a consequence of hearing aid usage (Macrae, 1994, 1995, 1996). These considerations require any modeling approach to hearing aid evaluation to include not only calculations of audibility but also estimations of loudness.

In this paper, we used the standard SII model and a modified SII model described in detail in the methods section that allowed for hearing loss desensitization to quantify the importance-weighted proportion of speech that is audible when alternative prescriptions were used in selecting hearing aids.

The perception of loudness has been estimated for individuals with normal hearing and cochlear hearing loss by the Moore and Glasberg (2004) model. As explained by Moore et al (2010), the model relies on two key concepts: (1) Excitation pattern along the basilar membrane transformed into an equivalent rectangular bandwidth ($\mathrm{ERB_N}$) scale to represent frequency, and (2) Specific loudness, of the frequency-specific loudness density, measured in sones per ERB. The ERBs are approximations of the filters in the human auditory system, with bandwidth as a function of frequency (f) given by the formula $0.108f + 24.7$ (Glasberg & Moore, 1986). The formula relating $\mathrm{ERB_N}$ to frequency, f (in kHz) is given in Glasberg & Moore (1990) as: $\mathrm{ERB_N}$ − number = $21.4\log_{10}(4.37f + 1)$.

Specific loudness is calculated by frequency in $\mathrm{ERB_N}$ scale from the amount by which excitation at each frequency exceeds the threshold excitation at that frequency (Moore & Glasberg, 1997, 2004). When specific loudness, N`, equals 0.00537 in any $\mathrm{ERB_N}$, the energy level (E) of the input sound is sufficient to excite the cochlea and a threshold response (Ethrq) is reached, *i.e.* $\mathrm{E} = \mathrm{E_{THRQ}} = 2.31$. Overall loudness (in units of sones and phons) is then calculated by summing specific loudness across ERBs.

The calculation of specific loudness 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 (Moore & Glasberg, 2004). In clinical practice, the amount of underlying outer versus inner hair cell loss is usually unknown.

The loudness model has been derived from adult data, but there is no evidence to suggest that it needs to be modified when applied to children (Moore, personal communication, 2012). Indeed, data from Serapanos and Gravel (2004) revealed no significant difference in loudness functions between children and adults with normal hearing. As children who had auditory experience of high in-ear sound pressure levels from amplification preferred listening at those levels (Scollie et al, 2000, 2010a,b), gains should be selected to take into account loudness limits when amplification is first provided early in life to avoid potential deterioration of hearing loss due to amplification (Macrae, 1996).

Both the DSL and the NAL procedures have been revised in recent years to take into account empirical verification and collaborative evaluations by the two research groups (DSL m[i/o], Scollie et al, 2005; NAL-NL2, Dillon et al, 2011). Each procedure provides gain targets separately for adult-aged and child-aged populations. A comparison of the adult versions of the DSL m[i/o] and NAL-NL2 for five hypothetical audiograms was reported by Johnson and Dillon (2011). They found that NAL-NL2 and DSL m[i/o] provided equivalent calculated loudness and predicted speech intelligibility at medium input levels, despite variations in gain-frequency response shapes prescribed by the two procedures (Johnson & Dillon, 2011). These findings cannot be generalized to the child-aged versions, however, because prescriptive gain targets for children differ from those for adults with the same audiogram. Prescriptive gain targets are always higher for children than adults because children have need for greater stimulus and sensation levels than adults to reach the same speech recognition performance (see Scollie, 2005 for review; Scollie, 2008).

There were no studies that compared the gains prescribed by the revised prescriptive methods for young children in terms of estimated speech intelligibility and loudness, which are important considerations with regard to amplification outcomes for children. To meet this need, the present paper adopted a modeling approach to examine the impact of gain differences between prescriptions for children. Specifically, two research questions were addressed:

1. In what way does application of the DSL v.4, or DSL m[i/o] or NAL-NL1 in hearing-aid fitting of young children impact on estimates of speech intelligibility and loudness?
2. In what way do gain differences between the DSL m[i/o] and NAL-NL2 prescriptions for children impact on estimates of speech intelligibility and loudness?

To address the first question, hearing-aid gains of a sample of children who were fitted with DSL v.4 or DSL m[i/o] or NAL-NL1 were used in calculations. The sample was drawn from the population-based cohort of a prospective study on outcomes of early- and late-identified children in Australia, the 'longitudinal outcomes of children with hearing impairment' or LOCHI study (Ching et al, this issue). The real-ear aided responses were used to calculate estimates of speech intelligibility and loudness perception.

To address the second question, prescriptive targets for the DSL m[i/o] and the NAL-NL2 were derived for a subset of the sample. Prescribed real-ear aided responses were used to calculate predicted speech intelligibility and loudness.

Methods

Sample

The sample comprised 200 children who enrolled in the LOCHI study prior to initial fitting of hearing aids. Following enrollment, individual children were randomly assigned to either the NAL prescription (NAL-NL1; Byrne et al, 2001) or the DSL prescription (DSL[i/o] v4.1; Seewald et al, 1997) for first fitting of hearing aids.

Audiological services after diagnosis, including hearing assessment and hearing-aid selection, fitting, and verification for all children were provided by audiologists at Australian Hearing (AH, the national government funded organization that provided hearing services to all children with hearing loss under the age of 26 years in Australia). All children were fitted bilaterally with multi-channel hearing aids that have wide-dynamic range compression capabilities. In accordance with the AH national pediatric amplification protocol (King, 2010), the individual hearing thresholds and real-ear-to-coupler differences (RECD) were used to derive gain targets in an HA2-2cc coupler by using the standalone software of the respective prescriptions. Hearing aids were adjusted and verified in an HA2-2cc coupler by comparing the measured values to custom targets. A broadband speech-weighted stimulus was used to verify gain-frequency responses at input levels of 50, 65, and 80 dB SPL; and a swept pure tone presented at 90 dB SPL was used as stimulus to verify maximum output of hearing aids.

The hearing thresholds and hearing-aid gains of children were retrieved by research audiologists from clinical records held at AH service centers, with written parental permission. Measurements of hearing aids reported in this paper were completed by AH audiologists within 6 months of the children's outcomes evaluations at 3 years of age (as part of the LOCHI study). At that time, the hearing aids of some children who were initially fitted with DSL v4.1 had been updated with the DSL m[i/o] as part of the routine service provision by AH, whereas others were still to be updated. None of the children initially fitted with NAL-NL1 had been updated with NAL-NL2 yet. Table 1 gives the hearing threshold levels of participants.

Study 1: SII and loudness calculated for hearing aids fitted using NAL-NL1, DSLv4.1, and DSL m[i/o]

This study used a between-group design to compare calculated SII and loudness for hearing-aid gains for 200 children: 35 of them were using hearing aids fitted with DSL v4.1, 57 with DSL m[i/o], and 108 with NAL-NL1. About 13% of the participants' audiograms demonstrated asymmetry of greater than 10 dB HL across octave frequencies between 0.5 and 2 kHz. The remaining participants had symmetrical hearing losses.

For calculations of SII and loudness, the hearing thresholds in the better ear for children with asymmetrical loss and the right ear for children with symmetrical loss were used as input data. There was no rationale for choosing the right ear. Rather, thresholds from one ear were used as the loudness prediction model is set up to

Table 1. Mean, standard deviation (SD), and range (Min-Max) of hearing threshold levels of 200 children, grouped according to the prescription used for fitting hearing aids at 3 years of age. Audiometric data of the ear used in calculations are included.

	Frequency (kHz)				
Group	*0.25*	*0.5*	*1.0*	*2.0*	*4.0*
DSL v4.1 (n = 35)					
Mean	37.5	44.5	49.7	55.5	54.4
SD	19.7	19.5	22.6	22.4	23.5
Min-Max	10–90	10–80	15–95	15–110	10–110
DSL m[i/o] (n = 57)					
Mean	36.0	43.7	48.4	53.6	56.7
SD	17.9	18.1	18.5	19.3	20.2
Min-Max	0–85	10–95	15–100	10–110	15–105
NAL-NL1 (n = 108)					
Mean	37.5	43.9	47.8	54.6	56.9
SD	17.6	16.8	18.2	16.6	19.4
Min-Max	0–80	5–80	10–95	15–100	5–115

handle only threshold input from a single ear with an assumption of symmetric thresholds for a binaural calculation; the speech intelligibility index model is set up to return better ear SII, so in the case of symmetric hearing thresholds either the left or right ear thresholds could have been used. There were 52 left ears and 148 right ears. Across the three prescription groups, the four-frequency pure-tone average (4FA, average of thresholds at 0.5, 1, 2, and 4 kHz) was not significantly different ($F(2, 197) = 0.026$, $p = 0.97$). Also, the audiometric slope between 0.5 and 4 kHz was not significantly different between groups ($F(2, 197) = 0.29$, $p = 0.75$). Furthermore, the spread of audiometric thresholds for children fitted with each of the prescriptive methods was not statistically different. This was confirmed with a Levene's test of equality of variances for the 4FA ($F(2, 197) = 2.62$, $p = 0.08$), as well as for the audiogram slope ($F(2, 197) = .52$, $p = 0.59$). On average, there were no significant difference in mean hearing thresholds, audiogram slope, and spread of thresholds across groups.

Study 2: SII and loudness calculated for gain targets of NAL-NL2 and DSL m[i/o]

This study used a within-group design to compare prescribed targets. Audiometric data in the better ear (for asymmetric loss) or right ear (for symmetric loss) of the sub-sample of 57 children who were fitted with DSL m[i/o] were used. The audiograms (17 left ears and 40 right ears) were used to derive custom targets for DSL m[i/o] and NAL-NL2 using the respective standalone software.

Procedure

Calculations of speech intelligibility and loudness for different fitting methods were completed using published models. The models required data on hearing thresholds and speech spectra as input. We used the speech spectra with overall levels of 52, 65, and 76 dB SPL to represent soft, medium, and loud speech. The spectral shapes of the soft and loud speech were taken from Scollie et al (2005) to reflect those in current use by DSL m[i/o], and the spectrum of medium level speech was that of the international long-term average speech spectrum (ILTASS; Byrne et al, 1994) utilized by NAL-NL1 and NAL-NL2.

For estimating speech intelligibility and loudness of hearing-aid gains for low, medium, and high input levels (Study 1), the REAG data were added to the respective speech spectrum for each prescriptive method to yield real-ear-aided responses (REAR). For estimating speech intelligibility and loudness of target gains (Study 2), the REAG targets were added to the speech spectra to yield prescribed REAR. Available octave and inter-octave frequency hearing thresholds and REAR were interpolated and extrapolated to one-third octave band levels or otherwise, as needed for subsequent modeling input data requirements.

Speech intelligibility index (SII) modeling

Speech intelligibility was calculated using the speech intelligibility index (SII) model. This modeling was completed with two approaches:

1. The American National Standards Institute (ANSI) S3.5 (1997) method, and
2. The ANSI S3.5 (1997) method with a revised desensitization factor.

The second method included the same transforms and steps as ANSI S3.5 (1997), but with the addition of a hearing loss desensitization factor. The desensitization factor was empirically derived (Ching et al, 2011) and adopted in the derivation of the NAL-NL2 prescriptive method (Dillon et al, 2011). Specifically, the desensitization is governed by variables of m and p, which are frequency-specific but not frequency-dependent. The desensitized audibility,

$$k' = \left[\left(\frac{k}{30} \right)^{p} + m^{p} \right]^{1/p} \tag{2}$$

in which,

$$m = \frac{1}{1 + e^{0.075(T-66)}}, \tag{3}$$

$$P = \frac{T}{8} - 15, \tag{4}$$

and in which T equals the amount of frequency-specific hearing loss in dB HL; and k is the amount by which the maximum short-term rms speech levels exceed the disturbance level, which is effectively the greater of hearing thresholds and masking noise, as specified in ANSI SII. The average speech importance function was used in all calculations of SII.

To provide a normative reference, SII values were also calculated for a hypothetical audiogram with 0 dB HL across frequencies and an average real-ear unaided response (REUR, Bentler, 1994).

In this paper, the SII value calculated with the first method is labeled as ANSI SII, and the value calculated with the second method is labeled as Desensitized SII.

Loudness modeling

To estimate loudness for low-, medium-, and high-level speech input, the Moore and Glasberg (2004) loudness model was utilized. The model allowed for input data for only one ear and assumed typical binaural summation to calculate binaural loudness. Relevant input variables were hearing thresholds (in dB HL) and energy levels of the input speech spectra (in dB SPL). Specific loudness was calculated by frequency in ERB_N scale from the amount by which excitation at each frequency exceeds the threshold excitation at that frequency (Moore & Glasberg, 1997, 2004). Overall loudness (in units of sones) was then calculated by summing specific loudness across ERBs. To estimate overall loudness for a normal-hearer as a reference, loudness was also calculated for a hypothetical audiogram with 0 dB HL and average real-ear unaided response (REUR, Bentler, 1994).

Statistical analysis

Results are summarized in terms of means and standard deviations. Analysis of variance with repeated measures was used to determine significance of difference between means. Where significant interactions were found, post-hoc analysis was carried out using the Tukey's honest significant difference test.

Results

Study 1: SII and loudness calculated for hearing aids fitted using NAL-NL1, DSLv4.1, and DSL m[i/o]

The deviation of hearing-aid gains from prescribed gains is shown in Table 2. The deviation in frequency response slopes achieved in hearing aids compared to prescribed slopes is shown in Table 3. On

Table 2. Mean deviation of four-frequency-average gain (averaged between 0.5 and 4 kHz) measured in users' hearing aids compared to prescriptive targets for three groups of hearing-aid fittings (User gain minus target gain). Deviations are shown for low (50 dB SPL), medium (65 dB SPL), and high (80 dB SPL) input levels. Also shown are standard deviations (SD) and range (Min-Max).

	Input level		
Group	*Low*	*Medium*	*High*
DSL v4.1 (n = 35)			
Mean	− 0.1	− 1.5	− 1.1
SD	2.2	2.1	2.7
Min-Max	− 9.0 to 3.3	− 8.5 to 1.5	− 11.0 to 2.7
DSL m[i/o] (n = 57)			
Mean	− 0.3	− 0.8	− 1.0
SD	2.1	2.5	3.0
Min-Max	− 9.0 to 2.8	− 10.0 to 4.5	− 9.5 to 4.5
NAL-NL1 (n = 108)			
Mean	− 0.2	0.4	0.9
SD	2.2	1.9	2.2
Min-Max	− 7.5 to 5.3	− 8.5 to 6.3	− 10.3 to 6.8

average, prescribed target 4FA gains were matched within ± 1.5 dB across input levels and prescription groups; and frequency response slopes were approximated within ± 1.2 dB/octave.

Speech intelligibility

The SII values calculated for hearing-aid fittings of the three groups of children are shown in Figure 1, a. The left panel represents values obtained with the ANSI SII method and the right panel shows those obtained with the desensitized SII method.

Analysis of variance (ANOVA) with ANSI SII as dependent variables, prescription (DSL v.4 vs DSL m[i/o] vs. NAL-NL1) as a between-group factor, input level (50, 65, 80 dB) as repeated measures, and 4FA hearing thresholds as a covariate, indicated that the effect of prescription was significant ($F(2,196) = 11.96$, $p < 0.001$).

Table 3. Mean deviation of user frequency response slope (averaged over 0.5 to 4 kHz, expressed in terms of dB/octave) from prescribed response slopes (user slope minus target slope). Deviations are shown for low (50 dB SPL), medium (65 dB SPL), and high (80 dB SPL) input levels. Also shown are standard deviations (SD) and range (Min-Max).

	Input level		
Group	*Low*	*Medium*	*High*
DSL v4.1 (n = 35)			
Mean	0.9	− 0.7	− 0.4
SD	1.6	1.7	1.6
Min-Max	− 3.0 to 3.0	− 4.7 to 2.0	− 6.3 to 2.3
DSL m[i/o] (n = 57)			
Mean	− 0.6	− 1.2	− 0.6
SD	2.4	2.5	2.0
Min-Max	− 9.7 to 3.7	− 10.0 to 2.7	− 6.3 to 2.7
NAL-NL1 (n = 108)			
Mean	0.3	0	0.5
SD	1.7	1.5	1.5
Min-Max	− 5.3 to 5.3	− 5.3 to 4.3	− 3.7 to 5.3

The effect of input level was also significant ($F(2,392) = 124.28$, $p < 0.001$). There was significant interaction between prescription and input level ($F(4,392) = 46.47$, $p < 0.001$). Post-hoc analysis indicated that at low input levels, the ANSI SII values of NAL-NL1 were on average significantly lower than those of DSL v4.1 by 0.09 units ($p < 0.001$) and lower than those of DSL m[i/o] by 0.11 units ($p < 0.001$). At medium input level, the ANSI SII values for NAL-NL1 were significantly lower than DSL v4.1 by 0.03 units ($p < 0.01$) and also lower than DSL m[i/o] by 0.03 ($p = 0.01$). At high input level, the ANSI values for NAL-NL1 were on average higher by 0.01 units than those for the DSL groups, but the difference was not significant (for DSL v4.1: $p = 0.05$; for DSL m[i/o]: $p = 0.08$).

A separate ANOVA was carried out with the desensitized SII values as dependent variable, prescription as a between-group factor, input level as repeated measures, and 4FA hearing loss as a covariate. The main effect of prescription was not significant ($F(2,196) = 1.56$, $p = 0.21$). The main effect of input level was significant ($F(2,392) = 92.06$, $p < 0.001$). The interaction between input level and prescription was significant ($F(4,392) = 65.93$, $p < 0.001$). Post-hoc analysis revealed that at low input level, the desensitized SII for NAL-NL1 was significantly lower than those for DSL v4.1 by 0.04 units ($p < 0.001$) and lower than DSL m[i/o] by 0.05 units ($p < 0.001$). At medium input level, there was no significant difference between NAL-NL1 and DSL v4.1 ($p = 0.30$), or between NAL-NL1 and DSL m[i/o] groups ($p = 0.62$). At high input level, desensitized SII for NAL-NL1 was significantly higher than DSL v4.1 by 0.03 units ($p = 0.002$) and higher than DSL m[i/o] by 0.01 units ($p = 0.02$), suggesting that greater reduction in SII was associated with the DSL prescriptions than with the NAL prescription.

For the normative reference audiogram, both the ANSI and desensitized SII models return SII values of 0.98 for low input, 0.99 for medium input, and 0.94 for high input levels.

Loudness

The estimated loudness for hearing aids fitted according to the three prescriptive methods is displayed in Figure 2, a. An ANOVA with overall loudness as dependent variables, prescription as a between-group factor, input level as repeated measures and 4FA hearing thresholds as a covariate indicated a significant effect of prescription ($F(2,196) = 40.0$, $p < 0.001$). The effect of input level was significant ($F(2,392) = 18.43$, $p < 0.001$). There was significant interaction between prescription and input level ($F(4,392) = 29.07$, $p < 0.001$). Post-hoc analysis revealed that on average, the loudness estimated for NAL-NL1 was significantly lower than that for DSL v4.1 at low ($p = 0.002$), medium ($p < 0.001$) and high input levels ($p < 0.001$). In a similar vein, the loudness estimated for NAL-NL1 was significantly lower than that for DSL m[i/o] at low ($p < 0.001$), medium ($p < 0.001$) and high input levels ($p < 0.001$). Using an average REUR and hearing thresholds of 0 dB HL to represent a listener with normal hearing as a reference, the calculated loudness for low-, medium-, and high-level speech were 8.5, 18.6, and 41.7 sones respectively.

Study 2: SII and loudness calculated for gain targets of NAL-NL2 and DSL m[i/o]

The same audiograms from the 57 children who were fitted with DSL m[i/o] in Study 1 were used in the comparison of targets from NAL-NL2 and DSL m[i/o] for Study 2. For these 57 children, the mean REAG targets prescribed by the NAL-NL2 and DSL m[i/o] for low, medium, and high input levels are shown in Figure 3. For low input level, NAL-NL2 prescribed less gain than DSL m[i/o] for

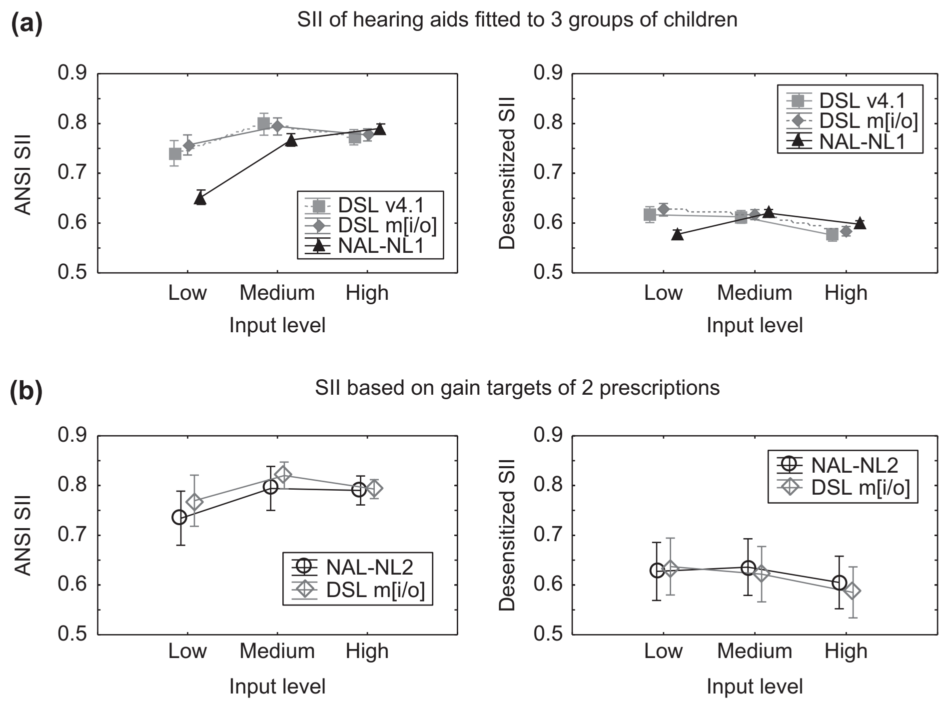

Figure 1. (a) depicts mean SII values for groups of children fitted according to NAL-NL1 (filled triangles), DSL v4.1 (filled squares), or DSL m[i/o] (filled diamonds) at low, medium, and high input levels. (b) depicts mean SII values for target gains prescribed by the NAL-NL2 (open squares) and the DSL m[i/o] (open circles) for 57 audiograms. The left panels show ANSI SII values, and the right panels show desensitized SII values that included hearing loss desensitization. Vertical bars denote 0.95 confidence intervals.

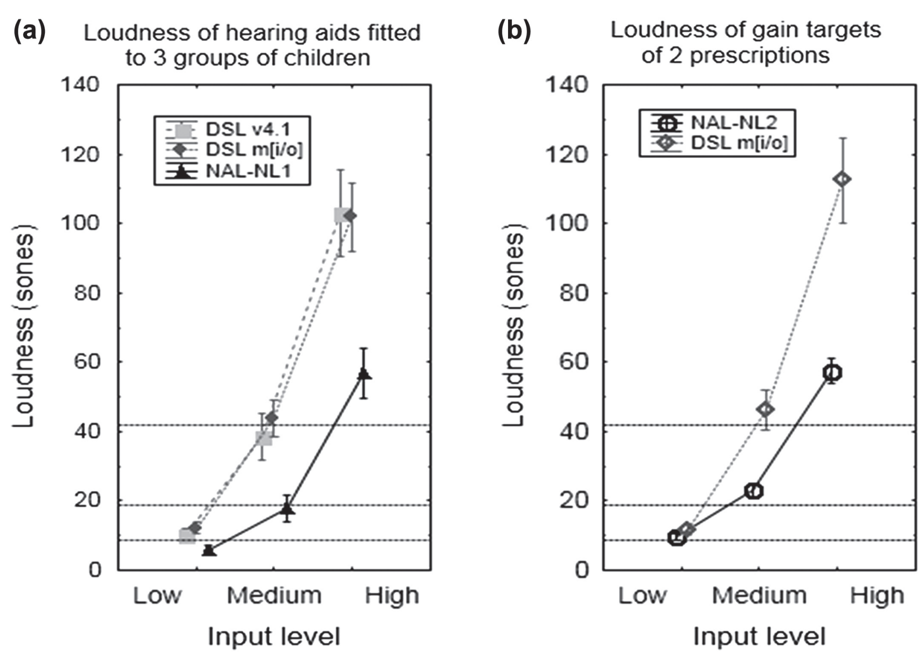

Figure 2. (a) shows calculated loudness for groups of children fitted according to NAL-NL1 (filled triangles), DSL v4.1 (filled squares) or DSL m[i/o] (filled diamonds) at low, medium, and high input levels. Vertical bars denote 0.95 confidence intervals. (b) shows calculated loudness for target gains prescribed by the NAL-NL2 (open circles) and the DSL m[i/o] (open diamonds) for 57 audiograms. The three horizontal lines at y-values of 8.5, 18.6, and 41.7 sones depict estimated loudness for normal hearers at low, medium, and high input levels respectively.

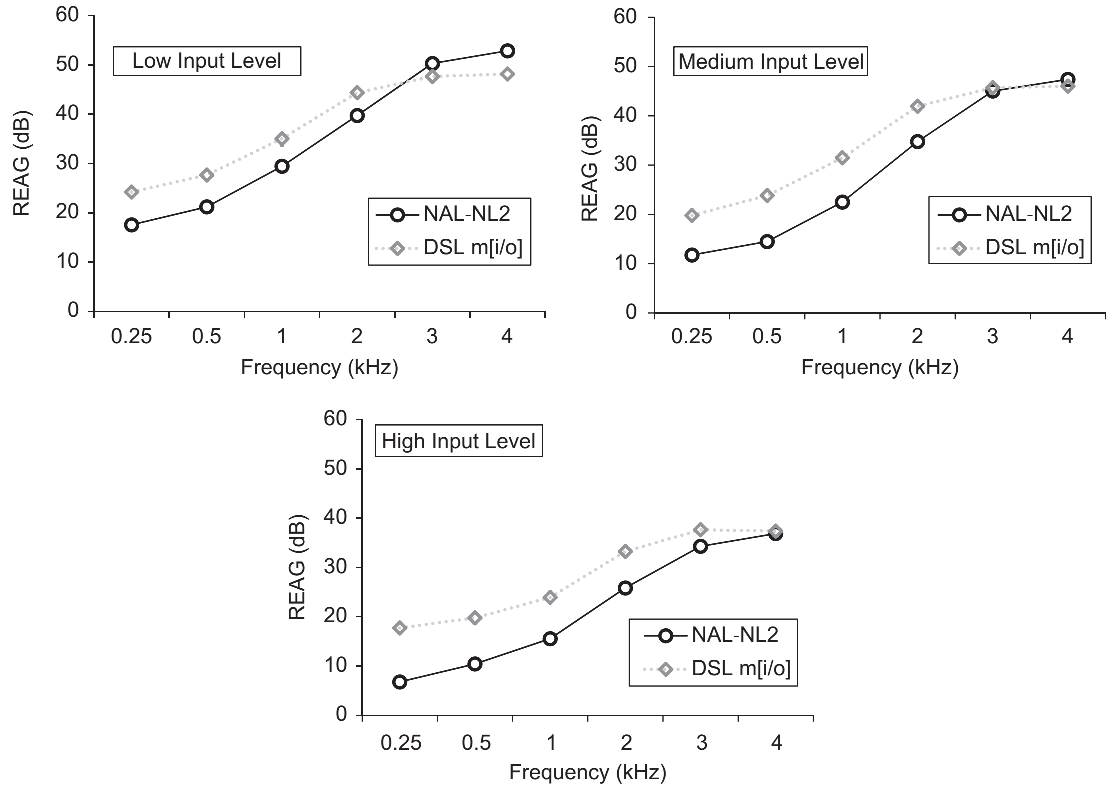

Figure 3. Mean audiogram for 57 audiograms is shown in the top panel; together with real-ear-aided gain (REAG) targets prescribed by NAL-NL2 (open circles and solid line) and DSL m[i/o] (open diamonds with broken line) prescriptions at low, medium and high input levels.

frequencies below 3 kHz but slightly more gain than DSL m[i/o] at 4 kHz. For medium and high input levels, NAL-NL2 prescribed less gain than DSL m[i/o] below 3 kHz but similar gain at 4 kHz.

Speech intelligibility

The mean ANSI SII and desensitized SII values for prescribed gains are shown separately in Figure 1, b. An ANOVA was conducted with ANSI SII values as dependent variables, prescription (NAL-NL2 vs. DSL m[i/o]) and input level (low, medium, high) as repeated measures. The main effect of prescription was present ($F(1,56) = 8.91$, $p = 0.004$). There was also a main effect of input level ($F(2,112) = 12.91$, $p < 0.001$). The interaction between prescription and input level was significant ($F(2,112) = 8.52$, $p < 0.001$). Post-hoc analysis indicated that the SIIs were significantly lower for NAL-NL2 than for DSL m[i/o] by 0.04 units at low input level, and by 0.03 units at medium input level ($p < 0.001$), but there were no significant differences in SII between prescriptions at high input level ($p = 0.99$).

A separate repeated measures ANOVA was completed for the desensitized SII values. The main effect of prescription was significant ($F(1,56) = 34.01$, $p < 0.001$), and the main effect of input level was significant ($F(2,112) = 121.47$, $p < 0.001$). There was significant interaction between prescription and input level ($F(2,112) = 122.12$, $p < 0.001$). Post-hoc analysis revealed that the desensitized SII values for NAL-NL2 were on average lower than those for DSL m[i/o] by 0.01 unit at low input level ($p < 0.001$), but higher than DSL m[i/o] by 0.01 at medium input level ($p < 0.001$), and higher than DSL m[i/o] by 0.02 units at high input level ($p < 0.001$). From low to medium input levels, the desensitized SII for NAL-NL2 increased by 0.01 units whereas DSL m[i/o] decreased by 0.02 units.

Loudness

The mean loudness estimates for gains prescribed by DSL m[i/o] and NAL-NL2 are shown in Figure 2, b. An ANOVA using loudness values in sones as dependent variables, prescription as between group factor, and input level as repeated measures indicated that there was a significant main effect of prescription ($F(1,56) = 74.97$, $p < 0.001$). The main effect of input level was significant ($F(2,112) = 487.33$, $p < 0.001$). There was significant interaction between prescription and input level ($F(2,112) = 62.48$, $p < 0.001$). Post-hoc analysis revealed no significant difference in loudness between prescriptions at low input level ($p = 0.99$). However, the loudness estimates for NAL-NL2 were significantly lower than those for DSL m[i/o] at medium input ($p < 0.001$) and at high input levels ($p < 0.001$). As shown in Figure 2, the loudness estimates for both prescriptions at low input levels were on average close to normal loudness levels. On the other hand, loudness estimates at medium and high input levels for both prescriptions were greater; considerably more so for DSL m[i/o]; than the reference loudness calculated for an assumed normal-hearing listener.

Discussion

The primary aim of this study was to assess the impact of prescription method on predicted speech intelligibility and loudness for children.

SII and loudness calculated for hearing aids fitted using NAL-NL1, DSL v4.1, and DSL m[i/o]

The consequence in applying the three prescriptive methods in hearing-aid fittings for predicted speech intelligibility and loudness was investigated using a between-groups design. The conclusion about which method optimizes speech intelligibility appears to depend on whether the SII calculations made allowance for hearing loss desensitization. The standard ANSI SII calculations suggest that speech at low and medium levels would be more intelligible for the groups fitted with the DSL prescriptions than for the group fitted with the NAL prescription. After allowing for hearing-loss desensitization, the predicted speech intelligibility for medium-level speech was no longer significantly different across prescription groups. This is in spite of the mean loudness estimates at medium levels for the DSL groups to be almost doubling that for the NAL group (see Figure 2).

The conventional ANSI SII included a level distortion factor which reduces the contribution of an audible signal to speech intelligibility when the overall sound pressure level exceeds 73 dB SPL (ANSI, 1997). This factor caused the ANSI SII values for the DSL group to decrease with increase in input level. The additional allowance for hearing loss desensitization resulted in a significant reduction in predicted speech intelligibility as input level increased for the DSL group. At high levels, the desensitized SII values show that speech intelligibility for the NAL group was predicted to be slightly better than that for the DSL groups, even though the loudness resulting from the application of the DSL prescriptions was considerably greater than that of the NAL prescription (see Figure 2).

Taking the predicted speech intelligibility and loudness (Figures 1 and 2) together suggest that the NAL prescription has achieved its goal of maximizing speech intelligibility, subject to the overall loudness of speech being no more than that perceived by a normal-hearing person for medium-level speech (Dillon, 1999). For low-level input, the overall loudness was less than normal; and speech amplified by NAL-NL1 was predicted to be less intelligible than that amplified by the DSL prescriptions (Figure 1). On the other hand, the underlying rationale for the DSL procedure is to normalize loudness at each frequency (Cornelisse et al, 1995; Scollie et al, 2005). For low-level speech, the overall loudness resulting from applying the DSL v4.1 or the DSL m[i/o] was close to normal, and the predicted speech intelligibility was optimal. For medium- and high-level input, loudness increased considerably above normal loudness levels with a concomitant reduction in speech intelligibility. It appears that even at medium input level, hearing loss desensitization reduced the contribution of amplified speech to intelligibility.

The current findings suggest that the optimal gain for speech intelligibility at low input level is closer to that prescribed by the DSL procedures than the NAL-NL1 procedure. At medium and high input levels, the NAL procedure provides gain that maximizes speech intelligibility while keeping overall loudness to be closer to normal than the DSL procedures.

SII and loudness calculated for gain targets of NAL-NL2 and DSL m[i/o]

This within-group comparison of prescriptive targets revealed significant differences in SII, favoring DSL m[i/o] for low input level, but NAL-NL2 for medium and high input level. Across input levels, the effect sizes were small—of the order of less than or equal to 0.04 units of SII—suggesting that both prescriptions maximize speech intelligibility over a wide range of input levels.

Comparison of estimated loudness revealed that the two prescriptions approximated normal loudness for low-level input. However, the calculated loudness for DSL m[i/o] was significantly greater than NAL-NL2 for medium- and high-level inputs.

In contrast to these findings on children showing minimal differences in SII but vastly different loudness, the comparison of the adult versions (Johnson & Dillon, 2011) indicated that the two prescriptions were equivalent in SII and loudness. As the two prescriptions inherently prescribed less gain for adults than for children, it would not be surprising that conclusions about loudness for the two populations differ. It does suggest that the additional gain provided to children relative to adults with the same hearing loss contributes little to intelligibility. Because the usefulness of the audible signal for speech intelligibility is affected by level distortion and hearing loss desensitization, higher sensation level than is optimal for speech intelligibility at any frequency region contributes not to intelligibility but to loudness, which may result in sensations that are unacceptable to some individuals (Rankovic, 1991) and lead to potential deterioration of hearing due to hearing aid use (Macrae, 1995).

Implications

The current findings suggest that the choice of prescription for children may be guided by the acceptability of the loudness sensation resulting from the application of each prescription, as both appear to provide similar speech intelligibility. The suitability of gain and maximum output of hearing aids must be evaluated carefully to ensure that the hearing aids do not cause loudness discomfort. This evaluation should include observing a child for visible signs of discomfort when loud noises are made in the clinic; as well as soliciting parents' observations of the child in real-world situations using a systematic report tool such as the parents' evaluation of aural/oral performance of children (PEACH, Ching & Hill, 2007). Also, advice about the use of hearing protection when a child will be in noisy environments for extended periods of time should be provided to parents.

The current estimates of loudness differences between the DSL m[i/o] and NAL-NL2 were based on prescribed targets, and the real-life impact when children use hearing aids in real-world environments needs to be determined. Also, the effect of using the prescriptions in hearing aids on children's development of speech production and perception remains to be investigated. As the hearing-aid fitting of the cohort of 200 children is progressively being updated with the NAL-NL2 and the DSL m[i/o] via the routine service of AH, we expect to be able to examine these effects when the children will be evaluated at 5 years of age.

Conclusions

In summary, the findings are:

1. On average, predicting speech intelligibility that allowed for hearing loss desensitization revealed that hearing aids fitted using the DSL v4.1 and DSL m[i/o] prescriptions provided higher SII at low input levels than those fitted using NAL-NL1.
2. On average, the SII at medium input level was similar among groups fitted using NAL-NL1, DSL v4.1 or DSL m[i/o].
3. On average, the SII at high input level was better for NAL-NL1 than for DSL v4.1 or DSL m[i/o].
4. On average, applying the DSL v4.1 or DSL m[i/o] prescriptions in hearing aids resulted in greater loudness than applying the NAL-NL1 prescription, across a wide range of input levels.
5. The SII that allowed for hearing loss desensitization suggested that speech intelligibility would be better for targets of DSL m[i/o] than those of NAL-NL2 at low input level, but better for NAL-NL2 than DSL m[i/o] at medium and high input levels. The effect size was small.

6. The estimated loudness for the prescribed targets of DSL m[i/o] was significantly greater than that for NAL-NL2 at medium and high input levels, on average by a factor of 2.

In conclusion, the modeling approach adopted for comparing prescriptions for children suggest that the DSL m[i/o] and the NAL-NL2 maximize predicted speech intelligibility over a wide range of input levels. The prescriptions differ markedly in loudness estimates, especially at medium and high input levels.

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