

# The DSL Method for Pediatric and Adult Hearing Instrument Fitting: Version 5

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## Abstract

The Desired Sensation Level (DSL) Method was originally developed to provide clinicians with a systematic, science-based approach to pediatric hearing instrument fitting that ensures audibility of amplified speech by accounting for factors that are uniquely associated with the provision of amplification to infants and young children who have hearing loss (Seewald, Ross and Spiro, 1985; Ross and Seewald, 1988; Seewald and Ross, 1988). This article summarizes a series of revisions that have been incorporated in the new Version 5 of the DSL Method including compatibility with auditory brainstem response (ABR) measurements; updates to Real-Ear-to-Coupler Difference (RECD) values and procedures; description of the multistage input/output algorithm for use with children and adults; and accommodating advances in hearing instrument technology and electro-acoustic verification procedures for use with DSL v5 target hearing instrument performance criteria.

## Introduction

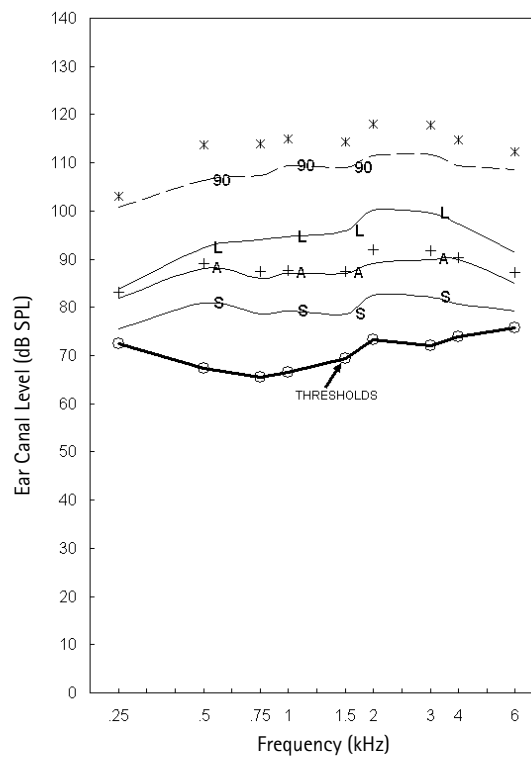
Initial publications on the development of the Desired Sensation Level (DSL) Method describe the electroacoustic fitting goal as the provision of frequency/gain characteristics that would deliver amplified speech to a child that was audible, comfortable and undistorted across the broadest relevant frequency range possible (Seewald, Ross and Spiro, 1985; Seewald, Stelmachowicz and Ross, 1987; Ross and Seewald, 1988; Seewald and Ross, 1988). The earliest versions of the DSL Method used tables of values that specified target sensation levels for amplified speech as a function of frequency and hearing level. These desired sensation levels, or DSLs, were based on data describing the speech sensation levels that were associated with comfortable listening levels across hearing levels (e.g., Kamm, Dirks and Mickey, 1978; Pascoe, 1978) and, more importantly, ceiling speech recognition performance in children with sensory hearing impairment (e.g., Gengel, Pascoe and Shore, 1971; Erber and Witt, 1977; Macrae, 1986; Smith and Boothroyd, 1989). The DSL Method also provided hearing instrument output limiting targets appropriate for use with young children that also varied as a function of frequency and hearing level (Seewald, 1991; Seewald, Ramji, Sinclair, Moodie and Jamieson, 1993). These look-up table of values and accompanying paper/pencil worksheets made clinical implementation of the DSL Method cumbersome. In 1991, the DSL Method (DSL v3.0) was made available as a software program making it the first published computer-assisted implementation for hearing instrument fitting for young children (Seewald, Zelisko, Ramji and Jamieson, 1991).

In 1995, Cornelisse, Seewald and Jamieson described an electroacoustic fitting algorithm

called the DSL input/output formula (DSL[i/o] v4.0) (Cornelisse, Seewald and Jamieson, 1995). This device-independent enhancement of the original DSL Method provided prescriptive targets for the fitting of wide-dynamic-range compression hearing aids which had become readily available by this time. The DSL[i/o] algorithm applied loudness data and a curvilinear fit to map a wide range of input levels to target hearing instrument output levels across frequencies. It has been used in DSL® software systems for v4.0 and v4.1 and in most hearing instrument, real-ear systems and manufacturers software implementations.

**Figure 1**

An SPLogram display showing hearing aid fitting results for a 6-month old child in dB SPL (re: TM) as a function of frequency (in kHz). The child's thresholds (circles) and upper limits of comfort (asterisk) outline the residual dynamic range to be fitted. The measured performance for aided average conversational speech (70 dB SPL) is shown (A) relative to the DSL targets (plus signs). Measured output for aided soft speech (S) and aided loud speech (L) are also shown, as is the measured hearing aid maximum output with a 90 dB input (90).



One of the primary traits of the DSL Method is the now well-recognized SPLogram display (Figure 1). The goal of packaging amplified speech within the residual auditory area can be best observed by plotting all thresholds using an ear canal dB SPL reference scale. A sample SPLogram is shown in Figure 1 for a child with a moderate hearing loss from .25 to 6 kHz. Unaided hearing thresholds and predicted thresholds of discomfort define the residual auditory area in a dB SPL reference level. Targets for amplified conversation-level speech are also plotted. Measured responses for amplified soft, average and loud conversational speech are shown, as is the hearing aid maximum output for a 90 dB narrowband input. Note that the extent of the child's residual auditory area and resulting location of aided speech and hearing aid maximum output are easily observable and compared with each other.

### **DSL Method for Children: Validation Studies**

Many studies have shown that children with normal or impaired hearing require greater stimulus levels, greater signal-to-noise ratio levels and broader bandwidth than adults in order to achieve similar levels of performance (Elliott, Connors, Kille, Levin, Ball and Katz, 1979; Elliot and Katz, 1980; Nozza, 1987; Nabelek and Robinson, 1982; Neuman and Hochberg, 1982; Nittrouer and Boothroyd, 1990; Nozza, Rossman, Bond and Miller, 1990; Nozza, Miller, Rossman and Bond, 1991; Nozza, Rossman, and Bond, 1991; Kortekaas and Stelmachowicz, 2000; Serpanos and Gravel, 2000; Fallon, Trehub and Schneider, 2002). This may be related to several factors including maturation of the auditory and phonological systems (Nittrouer and Boothroyd, 1990; Hnath-Chisholm, Laipply and Boothroyd, 1998; Blamey et al., 2001; Nittrouer, 2002). Based on these facts, development of the DSL Method and its associated algorithm has focused on a

habilitative audibility approach to the provision of amplification (Scollie, 2005). The goal is to accurately fit infants and young children with the appropriate electroacoustic characteristics so that they will be provided with audibility of the full bandwidth and envelope of conversation-level speech for auditory learning (e.g., Seewald and Ross, 1985; Ling, 1989). Recently, several validation studies of the DSL Method v4.0 and v4.1 for children have been conducted in our laboratory (Jenstad, Seewald, Cornelisse and Shantz, 1999; Jenstad, Pumford, Seewald and Cornelisse, 2000; Scollie, Seewald, Moodie and Dekok, 2000). The findings of these studies will be briefly reviewed within the following sections.

### **Preferred listening levels of children who use hearing aids: Comparison to prescriptive targets**

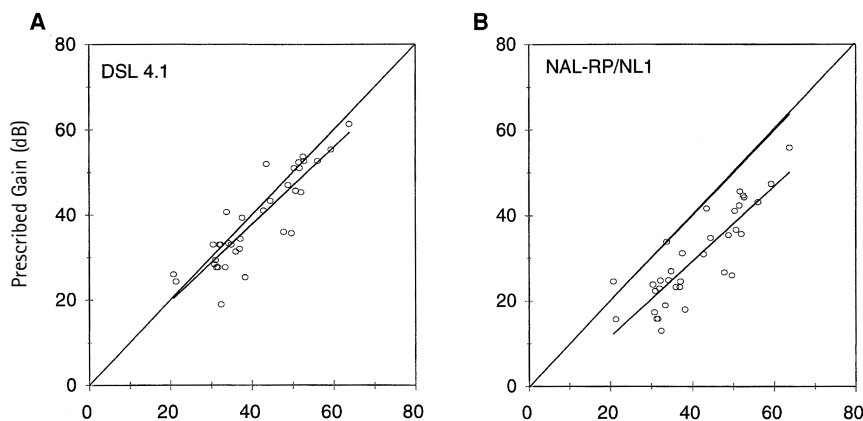
Scollie et al. (2000) measured the preferred listening levels (PLLs) of 18 children (mean age of ~10 years) with various degrees of sensorineural hearing loss using conversation-level speech heard through the children's own hearing aids. The purpose of the study was to determine if hearing aids fitted using DSL[i/o] v4.1 would amplify conversation-level speech to the children's PLLs. A second purpose was to compare the children's PLLs to prescriptive targets generated by the National Acoustics Laboratory (NAL) formulae (Byrne and Dillon 1986; Byrne, Parkinson and Newall, 1990; Dillon and Storey, 1998). Results of the study indicated that the DSL[i/o] algorithm appeared to more closely approximate pediatric user PLLs than did the NAL-RP/NL1 algorithm in children who were users of DSL-fitted hearing aids regardless of the level of hearing loss. The targets from DSL[i/o] v4.1 and NAL-RP/NL1 are plotted against the PLLs in Figure 2 (A) and 2 (B) respectively. Linear regressions of each fitting algorithm onto the PLL are shown. The 95 percent confidence intervals showed that the DSL targets

resulted in recommended listening levels that were, on average, 2 dB lower than the children's PLL, with approximately seventy percent of PLLs falling within 5 dB of the DSL target. In contrast, it was found that the NAL prescribed listening levels were, on average, 10 dB lower than the children's PLL, with approximately nine percent of PLLs falling within 5 dB of the NAL target. These data indicate that the amplified levels of conversational speech prescribed by the DSL[i/o] algorithm more closely approximated the pediatric users PLLs relative to those prescribed by the NAL-RP/NL1 algorithm in children who were prior users of DSL-fitted hearing aids regardless of the degree of the hearing loss.

**Comparison of linear gain and wide dynamic range compression hearing aid circuits: Aided speech perception and aided loudness measures**

In the late-1990s, two studies (Jenstad et al., 1999; 2000) were conducted to compare aided speech perception measures and aided loudness measures for linear gain and wide-dynamic-range compression (WDRC) hearing aids. In the first study which examined aided speech perception measures, 12 subjects (mean age of ~16 years) with moderate to severe sensorineural hearing loss were fitted with hearing aids set to DSL v4 targets for both linear gain and WDRC processing. Speech intelligibility was measured in (a) the unaided; (b) the linear gain; and (c) the WDRC conditions using two tasks in quiet: nonsense words and sentences. Results indicated that for both speech tests, more subjects received benefit in the WDRC condition than the linear condition. Results also showed that WDRC hearing aids fitted to the DSL[i/o] targets achieved comfort and intelligibility of speech across a range of speech input levels. In the companion study, which examined aided loudness measures, 10 subjects (mean age ~16 years) with moderate to severe sensorineural hearing loss were

**Figure 2**  
DSL 4.1 and NAL-RP/NL1 recommended listening levels plotted against preferred listening levels, for individual ears, in the binaural listening condition. Linear regressions are also shown for each prescriptive formula (from Scollie, Seewald, Moodie and Dekok, 2000). Courtesy of the Journal of the American Academy of Audiology).



fitted with hearing aids set to DSL v4.0 targets for linear gain and WDRC processing (Jenstad et al., 2000). Threshold, upper limit of comfort and loudness growth were measured in the (a) unaided; (b) linear gain and (c) WDRC conditions for warble tones, environmental sounds and speech. Results of this study indicated that WDRC hearing aids fitted using the DSL[i/o] algorithm were able to normalize loudness perception for speech and other environmental sounds across a wide range of input levels.

In summary, for the fitting of amplification for children, the DSL Method and it's associated prescriptive algorithm has been shown to: (1) significantly improve children's speech recognition scores over unaided performance; (2) improve low-level speech recognition and normalize loudness when a nonlinear version of the DSL prescription is used; and (3) more closely approximate pediatric users PLLs than does the NAL-RP/NL1 algorithm in children who were prior users of DSL-fitted hearing aids regardless of the degree of hearing loss.

## Is it time for a new version of the DSL Method?

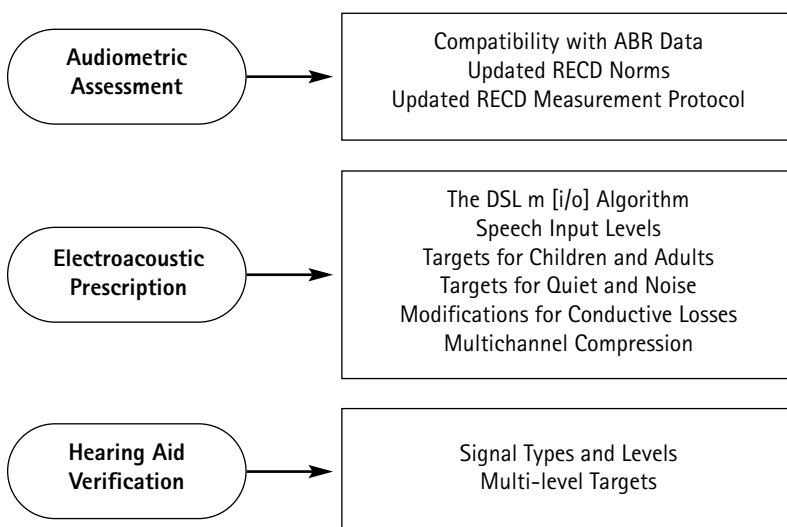
Recently several factors have made our laboratory consider a number of modifications and elaborations to both the DSL Method and the DSL[i/o] algorithm. First, children with hearing loss are being identified at birth and amplification is being provided to infants by 6 months of age (Joint Committee on Infant Hearing, 2000; American Academy of Audiology, 2003). These infants will wear their hearing instruments at settings determined by clinicians for at least the first few years of life increasing the importance of continued research and development on an objective, evidence-based procedure like the DSL Method for hearing instrument fitting. Secondly, improvements in auditory brainstem response (ABR) testing procedures, and significant advances in hearing instrument technology make continued development both desirable and necessary. In addition, since the release of the computer-assisted

implementation of DSL v4.1 in 1997 anecdotal reports from clinicians, research studies in our laboratory and published studies indicated some modifications could be applied to the algorithm for more appropriate adult application (e.g., Moore, Alcántara, and Marriage, 2001). Finally, clinicians still desire access to generic prescriptive algorithms relative to manufacturer-specific proprietary fitting algorithms, especially for their pediatric clients. This is understandable in light of recent published studies which have shown that adult clients with similar hearing losses might be fitted with substantially different amplification characteristics depending on the hearing instrument proprietary fitting method chosen (Smeds and Leijon, 2001; Keidser, Brew and Peck, 2003; Killion, 2004). Given all these considerations, work was initiated in the late 1990s on a new version of the DSL Method (DSL v5) which includes the DSL multi-stage input/output algorithm, referred to as DSL m[i/o].

## The Role of Clinical Protocols

Although modifications to the DSL algorithm continue to be made into the 21st century, it is clear to us that electroacoustic selection cannot be isolated from the manner in which audiometric assessment data are collected or from the verification procedures that will be applied at the time of fitting. DSL is more than just an algorithm for electroacoustic selection, it is a method consisting of sequential stages in a well-integrated hearing instrument fitting process. As illustrated in Figure 3, the emphasis of our work has been on audiometric assessment, hearing instrument selection, and verification of aided auditory performance (Seewald, 1995; Seewald, Moodie, Sinclair and

**Figure 3**  
The DSL Method recommended hearing aid fitting process. At each stage of the process the changes implemented in DSL v5 are shown.



Cornelisse, 1995). Our current research program includes the continued development of not only the DSL m[i/o] algorithm, but research and development of clinical procedures and protocols to assist with appropriate pediatric assessment, verification and validation procedures that can be implemented in routine clinical practice (Seewald et al., 1993; Moodie, Seewald and Sinclair, 1994; Seewald, 1995; Bagatto, 2001).

Information regarding the revisions and modifications made for DSL v5 are provided in Figure 3 for each stage of the hearing instrument fitting process. These revisions/modifications will be discussed in the subsequent sections.

## **DSL v5: Assessment Considerations**

### **Compatibility with ABR assessment**

Audiologists working with Early Hearing Detection and Intervention (EHDI) programs are assessing the hearing abilities of very young infants using electrophysiologic procedures (American Speech Language and Hearing Association, 2004; Joint Committee on Infant Hearing, 2000). The ABR measurement has been shown to be feasible for estimating hearing thresholds in young infants (Stapells, 2000a; 2000b; American Speech Language and Hearing Association, 2004; Joint Committee on Infant Hearing, 2000). While much research has focused on the development of frequency-specific (FS) ABR procedures for threshold estimation in infants, little work has been done to investigate how ABR data are to be applied in hearing aid prescriptive software. In DSL v5, clinicians may enter threshold data referenced to normalized HL (nHL) or estimated HL (eHL). The interested reader is

directed to Bagatto et al. (2005) for a detailed description of nHL and eHL-referenced electrophysiologic data. Many studies have shown that ABR threshold estimates are higher than behavioral thresholds. For this reason, a correction must be applied to the ABR threshold estimation to better predict the behavioral threshold that will be used for calculating the hearing aid prescription. It is important for the clinician to know if their ABR equipment has behavioral corrections imbedded in it or not. If the correction has not been imbedded in the system, a correction needs to be applied to the nHL value to provide a better estimate of behavioural thresholds. In this case, frequency-specific threshold estimates are entered in nHL, and corrections will be applied within the DSL software to convert the nHL data to eHL. These corrections can either be default values that are stored within the software, or the clinician can enter their own custom nHL to eHL correction values. The default values are appropriate for use with FS-ABR procedures that comply with the calibration and stimulus parameters outlined in Bagatto et al. (2005) and shown in Table 1. If the threshold estimates have already been corrected to an eHL reference by the clinician or if the ABR system has the corrections imbedded in it, no additional correction is required and is therefore not applied. Clinicians with these situations should choose ABR (eHL) and enter the data. Clinicians who assess the hearing of infants using ASSR procedures are cautioned to ensure that the ASSR system is applying an nHL to eHL correction that is valid for use with infants who have hearing loss (Stapells, Herdman, Small, Dimitrijevic and Hatton, 2005). In this case, data may be entered directly into DSL v5 by using the eHL reference.

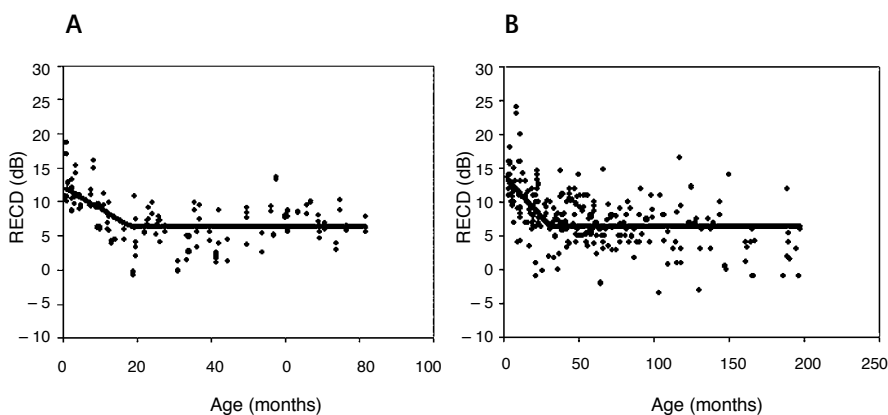
**Table 1**

Stimulus and recording parameters used to obtain frequency-specific ABR threshold estimations in a recent study comparing ABR thresholds to behavioural thresholds in RESPL.

Stimulus calibration (ER-3A)	500 Hz: 22 dB ppeSPL 1000 Hz: 25 dB ppeSPL 2000 Hz: 20 dB ppeSPL 4000 Hz: 26 dB ppeSPL
Filters	High pass: 30 Hz Low pass: 1500 Hz 6 or 12 dB/octave Analog
Stimuli	2-1-2 cycle, linearly gated tones
Window length	25 msec
Polarity	Alternating
Rate	37-41 sweeps/sec
Artifact reject	Trials exceeding 25 $\mu$ V or $\pm 2$ SD of quietest EEG signal, whichever is smaller
Average	2000 sweeps per average At least 2 averages

**Figure 4**

Real-ear-to-coupler differences (RECD) (in dB) measured with (A) foam/immittance tips and (B) earmolds as a function of age at 3000 Hz. The sloping line indicates the linear regression represented by the prediction equation. The horizontal line represents the mean RECD values for a particular age group. (from Bagatto et al., 2005. *Reprinted with permission*).



### Age-appropriate real-ear-to-coupler difference (RECD) values

The RECD is a clinically useful measurement, and may be feasibly and reliably obtained in the pediatric and adult populations in the majority of cases (Sinclair et al., 1996; Tharpe, Sladen, Huta and McKinley, 2001; Munro and Davis, 2003). The DSL method has always provided age-appropriate average RECD values in software implementations for cases where clinicians have not been able to directly obtain the measurement (Seewald et al., 1997; Seewald et al., 1993). For DSL v5 the age-appropriate average RECD values have been updated to include: (1) frequency-specific predictions by age for eartip coupling; and (2) frequency-specific predictions by age for earmold coupling (Bagatto et al, 2005; Bagatto, Scollie, Seewald, Moodie and Hoover, 2002). The 95% confidence intervals for predictions of RECDs for eartip coupling and earmold RECD predictions were examined to determine the accuracy of prediction (Bagatto et al., 2005). Depending on the frequency of interest, an eartip RECD can be predicted to fall within a range of  $\pm 5.6$  dB (at 500 Hz) at best and  $\pm 10.9$  dB (at 6000 Hz) at worst for children 24 months of age and younger. Predictions of earmold RECDs can span a range of accuracy from  $\pm 6.7$  dB (at 2000 Hz) to  $\pm 12.4$  dB (6000 Hz) for children 36 months of age and younger. Figure 4 illustrates the measured RECD values in dB as a function of age for one frequency for both coupling procedures. Although more desirable than using adult-based RECD average values when fitting amplification to infant and young children, these results indicate that age-appropriate predictions should not replace a more precise individualized RECD measurement.

### Description of a modified RECD measurement procedure for use with infants

Procedures for measuring the RECD in the pediatric population have been published (Moodie et al, 1994). Other publications have provided recommended probe-tube insertion depth guidelines (Tharpe et al., 2001). The typical RECD measurement method described in most studies involves inserting the probe-tube and tip separately. This may not be practical in the infant population due to very small ear canals and the position of the infant during the measurement. Bagatto, Seewald, Scollie and Tharpe (2006) described details and study results for a new technique for obtaining accurate RECD measurements on an infant's ear. Briefly, the strategy involved simultaneous insertion of the probe-tube and the tip into the ear canal (see Figure 5). Study results indicated that extending the probe-tube approximately two to four millimeters (mm) beyond the tip resulted in appropriate insertion depth, as well as reliable and valid RECD values for infants between the ages of two to six months. A suitable insertion depth for the probe-tube was determined to be approximately 11mm from the entrance to the ear canal.

### DSL v5: Selection and Fitting Considerations

#### The DSL multistage input/output algorithm: DSL m[i/o]

A detailed description of the development of the DSL m[i/o] algorithm is provided in Scollie et al., 2005. A brief summary of some, but not all, important modifications, is provided here. Revisions to the DSL[i/o] algorithm were determined to be necessary for at least two reasons: (1) to implement evidence-based revisions, additions, or corrections to the approach described as the DSL[i/o] algorithm (Cornelisse et al., 1995; Seewald, Ramji, Sinclair, Moodie, and Jamieson, 1993a) and (2) to modify the scope of the algorithm to support specific hypothesis testing in pediatric hearing instrument research.

Figure 5

Probe tube coupled to ER-10 3.5 mm otoacoustic emission tip using plastic film (from Bagatto et al., 2006. Reprinted with permission).



Specific objectives for DSL version 5 include:

1. Avoidance of loudness discomfort during hearing instrument use;
2. Hearing instrument prescription that ensures audibility of important acoustic cues in conversational speech as much as possible;
3. Support for hearing instrument fitting in early hearing detection and intervention programs;
4. Prescription of hearing instrument compression that is appropriate for the degree and configuration of the hearing loss, but that attempt to make a wide range of speech inputs available to the listener;
5. Adaptation for the different listening needs of listeners with congenital versus acquired hearing loss;
6. Accommodation for the different listening requirements within quiet and noisy listening environments.

#### DSL m[i/o]target generation

In DSL v5, we use the DSL[i/o] algorithm (DSL v4.1) as a starting point, but modify it to apply WDRC to a smaller input range. The inputs selected for the WDRC range are intended to cover some or all of the conversational speech range. Low-level inputs are less likely to be included in the compression stage as hearing levels increase.

The DSL multistage input/output  $m[i/o]$  algorithm includes four stages of processing: (1) expansion; (2) linear gain; (3) compression; and (4) output limiting. These  $m[i/o]$  stages reflect conventional signal processing for amplitude control in current digital hearing instruments. The final result is a series of target input/output functions that prescribe how a multi-channel, multistage device should respond to speech inputs across vocal effort levels.

#### **The output limiting stage**

Version 5 of DSL provides three variables that facilitate definition of output limiting: (a) the user's upper limits of comfort (ULC) defined with narrowband inputs, which should not be exceeded by any aided narrowband signal; (b) targets for 90 dB SPL narrowband inputs – these targets may be slightly below the upper limits of comfort if the hearing instrument is not fully saturated by a 90 dB input; (c) the broadband output limiting thresholds (BOLT) per frequency, which defined the maximum one-third octave band levels for broadband sounds. These targets may be used for slightly different purposes, depending upon the test signals at hand, and/or the user's knowledge of the signal processing characteristics of the hearing instrument to be tested. Each of these target types will be discussed in more detail in the section below.

#### **Narrowband output limiting targets**

DSL v5 provides narrowband predictions of the listener's upper limit of comfort (ULC), which may be replaced by individually measured ULCs. In either case, the fitting goal is that aided levels of high-level pure tones, warbled pure tones or speech peaks should not exceed the ULC. The predicted ULCs are limited to a maximum of 140 dB SPL in the ear canal. Narrowband targets for 90 dB SPL inputs can be generated in DSL v5. These targets may be slightly below the upper

limits of comfort if the hearing instrument is not fully saturated by a 90 dB narrowband input. When verifying fit to targets using a narrowband signal, clinicians can choose to either match the 90 dB target, or to ensure that the maximum output does not exceed the ULC.

#### **Broadband output limiting targets**

DSL v5 incorporates a variable that prescribes a limiting stage for the one-third octave band levels of speech signals. This broadband output limiting threshold (BOLT) corresponds with a hearing instrument fitting that places the peaks of speech 13 dB below the upper limit of comfort. A detailed description of the rationale for BOLT is provided in Scollie et al., 2005. Clinical verification of fit to BOLT targets may not always be possible, depending upon the test signals and analyses that are currently available. This is not likely a problem if the narrowband limiting has been fitted appropriately (see above). However, the BOLT targets may be helpful in defining initial settings of programmable hearing instruments that include limiting controls for broadband stimuli – this type of setting may occur "behind the scenes" within hearing instrument programming software.

#### **Compression**

In DSL v5 we prescribe compression processing to meet the goals of providing audibility and comfortable loudness of important speech cues, given the gain limits of hearing instruments and the limited dynamic range of the individual hearing instrument user. This differs from the loudness normalization approach in previous versions of the DSL algorithm.

#### **Prescription of the WDRC compression threshold (CT)**

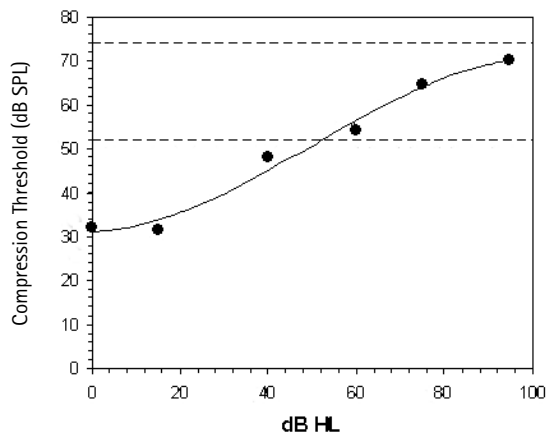
The DSL  $m[i/o]$  algorithm prescribes a variable CT based on hearing levels that attempts to

maintain the compression stage across as broad a speech input range as possible. The intention is to support low-level speech recognition whenever possible (Jenstad et al., 1999; 2000). For more severe-to-profound hearing losses this fitting goal is modified to use WDRC as a means for controlling loudness of high-level speech. Experimental validation of this hypothesis-driven aspect of DSL v5 is necessary. Therefore, in hearing instrument manufacturers software-based implementation of DSL v5, more ambitious goals for WDRC can be incorporated by using custom CTs if the higher gains can be achieved without feedback. Figure 6 illustrates the relationship between hearing threshold levels (dB HL), the proposed input levels (dB SPL in the sound field) and the prescribed WDRC threshold from the DSLm[i/o] algorithm.

### Hearing instrument prescriptions for multi-channel compression

DSLm[i/o] target calculations can be tailored to correspond to the channel structure of multi-channel hearing instruments (Scollie et al., 2005). The one-third octave band frequencies are grouped into defined channel families using the crossover frequencies of the hearing instrument. The multistage input/output algorithm is then re-computed per channel, resulting in a single compression ratio target per channel. The gains within the compression region of the revised input/output target plots are also adjusted in an effort to preserve the frequency response for mid-level signals. A slight frequency re-shaping may occur to prevent hearing instruments with different channel structures from providing a different frequency response for mid-level speech signals. Targets at moderate input levels show very little effect of channelization, while targets for very high and very low inputs show a somewhat greater effect.

**Figure 6**  
Relation between hearing threshold levels (dB HL) and proposed input levels (dB SPL in the sound field) for the wide-dynamic-range compression (WDRC) threshold. The solid line is a third-order polynomial fit to a set of hypothesized compression threshold values (•). Dashed lines indicate the range of speech inputs considered by DSL v5 (i.e., 52 and 74 dB SPL), for reference. (from Scollie et al., 2005. Reprinted with permission).

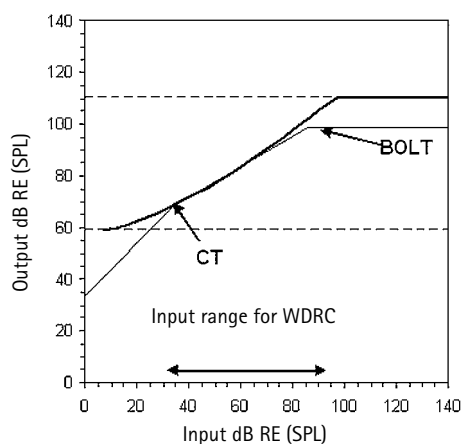


### Gain prescription within the WDRC stage

To prescribe gain within the WDRC stage consideration must be given to the desired range of input levels considered appropriate for amplification; the individual's residual auditory area; and the technology to be fitted. Unlike the DSL[i/o] algorithm, the DSL m[i/o] algorithm restricts the input range over which the compressive algorithm is applied from approximately 30 dB SPL to 70 dB SPL (re: FF as a function of hearing loss). A target for 60 dB SPL speech input is calculated for all one-third octave band frequencies. The WDRC stage is then defined as the straight line with a slope that equals the compression ratio target that passes through this calculated DSL m[i/o] target. For hearing losses exceeding approximately 70 dB HL a higher CT is used by the DSL m[i/o] algorithm to derive the target for 60 dB SPL speech input. Some hearing instrument manufacturers or clinicians may choose to use a lower CT (i.e., more gain for low level

**Figure 7**

Comparison of DSL[i/o] and DSL m[i/o] target input/output functions, shown as thick and thin lines respectively. The dashed lines mark the detection thresholds and upper limits of comfort. The input range for WDRC is also indicated. BOLT = broadband output limiting threshold; CT = compression threshold; WDRC = wide-dynamic-range compression. (from Scollie et al., 2005. *Reprinted with permission*).



inputs) than recommended if the higher gains can be achieved without feedback. The WDRC stage begins at the calculated WDRC CT and ends where it meets the broadband output limiting stage. Figure 7 provides a target input/output function derived using the DSL m[i/o] algorithm compared to the target input/output function derived using the DSL[i/o] algorithm.

#### **Gain prescription within the expansion stage and linear stage**

The DSL m[i/o] algorithm calculates a default expansion threshold (ET) that is approximately 10 dB below the level of soft speech. It is assumed that input signals below this level are likely background noise and negative or no gain is desirable. The linear stage of the DSL m[i/o] algorithm spans the input range between the ET and the WDRC CT.

#### **DSLm[i/o] algorithm effective compression ratio**

The effective compression ratio calculated within the DSL m[i/o] algorithm is intended to functionally describe the amount of longterm

compression of soft to loud speech inputs encountered by the listener. It is not intended to be an electroacoustic descriptor for verification, nor is it intended to be interpreted in the way that traditional compression ratios are.

### **DSL m[i/o] Algorithm Considerations for Individual Fittings**

#### **Should the DSL algorithm generate different prescriptive targets for children and adults?**

Published results of using DSL[i/o] with adults have been somewhat mixed, with some studies showing positive and acceptable results (Humes, 1999; Hornsby and Ricketts, 2003; Scollie et al., 2005), and others showing good speech recognition but higher ratings of loudness with higher level inputs and/or frequencies than those considered ideal (Lindley and Palmer, 1997; Alcántara, Moore and Marriage, 2004; Smeds, 2004).

Clinical trials that have compared DSL[i/o] with alternative fitting procedures have generally shown that less gain than prescribed by DSL is preferred by adults, either from a lower-gain prescription such as CAMFIT (Moore, Alcántara and Marriage, 2001) or from a patient-driven procedure that customizes gains to preference (Lindley and Palmer, 1997).

Currently there are differing opinions regarding the electroacoustic requirements for hearing aid performance for adults versus children. Some researchers believe that prescriptive procedures developed for adults can be used with young children (Ching, Dillon and Byrne, 2001). Others believe that infants and young children require different prescriptive procedures (e.g., Stelmachowicz, 1991; 2000; Seewald, 1995). Snik and Hombergen (1993) measured the preferred insertion gain for 40 adults and 60 children.

Figure 8 displays the preferred insertion gain as a function of the pure-tone average for the adults and children in this study. The results showed that overall the mean use insertion gain was 7 dB less for the adults relative to that used by the children.

#### Adult/child preferred listening levels

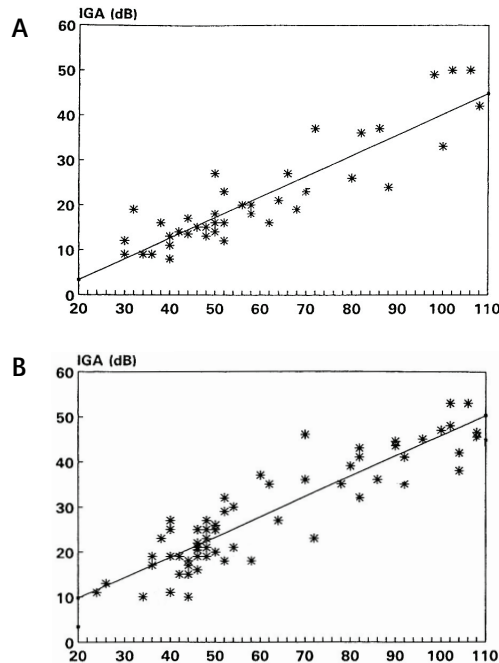
A recent study by Laurnagaray and Seewald (see Scollie et al., 2005) included 24 children who were full-time hearing aid wearers, 24 adults who were experienced hearing aid users, and 24 adults who were new hearing aid users. The hearing aids were fit to the DSL v4.1 prescription and new users were provided with a 15 to 20 day trial period. The objective of the study was to determine whether the preferred listening level (PLL) differed between adults and children who use hearing instruments, and whether adult PLLs differ between new and experienced adult users. A second purpose was to compare measured PLLs to the DSL v4.1 recommended listening level (RLL). As illustrated in Figure 9, analysis results indicated that all three of the groups differed from one another regarding their agreement between PLL and RLL.

Children had a mean PLL that was approximately 2 dB below the DSL target (RLL). Experienced adults had a mean PLL 9 dB below the DSL target. New adult hearing instrument users had the lowest PLLs, which were 11 dB below target on average. In summary, there was an approximate difference of 8 dB in PLL between the adults and children in this study, and adults who were new hearing aid users preferred a slightly lower listening level than adult experienced hearing aid users. This finding is similar to the 7 dB adult/child difference measured by Snik and Hombergen (1993).

These study results indicate that the DSL[i/o] prescriptive algorithm likely overestimates preferred listening levels for adult hearing instrument users, with the greatest overestimation observed for inexperienced adults. These findings may not generalize to

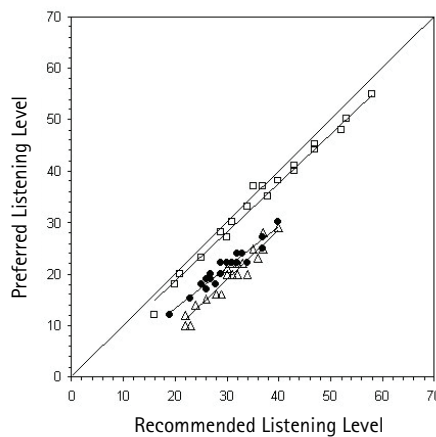
**Figure 8**

The preferred insertion gain as a function of the pure-tone average for the adults (A) and children (B) in this study (from Snik and Hombergen, 1993).



**Figure 9**

Recommended versus preferred listening levels (measured in 2cc coupler gain at 2000 Hz) for three groups of subjects: children ( $\square$ ), new adult hearing aid users ( $\Delta$ ), and experienced adult hearing aid users ( $\bullet$ ). Regression lines are shown for each subject group, along with a diagonal line at target listening levels. (from Scollie et al., 2005. *Reprinted with permission*).



adults with severe-to-profound hearing loss as they have not been included in these studies. Nonetheless, the results make clear the concept that adults and children with hearing loss have distinctly different preferences for listening level. The results also agree with earlier studies of adult/child differences in listening level requirements for speech recognition performance (see above). In considering modifications to the DSL[i/o] algorithm it was decided that a comprehensive prescriptive approach would need to consider that adults and children not only require, but also prefer, different listening levels, perhaps by generating different prescriptions based on client age.

#### **Determining an acceptable range for amplified speech for adult hearing aid wearers**

A study was undertaken in an effort to better understand the acceptable range for amplified conversational speech for adults (Jenstad et al., under review). The purpose of the study was two-fold; first, to define the range of optimal hearing aid settings in both high and low frequencies using subjective ratings of loudness and quality and objective measures of speech intelligibility, and secondly, to determine if the DSL[i/o] 4.1 gain-by-frequency response falls within the optimal range for adult listeners. Measures of loudness, quality and speech intelligibility were obtained for 23 adult listeners with mild to moderately-severe sensorineural hearing loss, across a range of high and low-frequency responses. Consistent with the findings of other researchers (e.g., Dirks, Ahlstrom and Noffsinger, 1993), this study found that there was an approximately 10 dB range for these adult listeners that could be considered optimal hearing aid settings when both speech intelligibility and loudness criteria were considered together. Relative to the DSL[i/o] v4.1 prescription generated for each adult, results indicated that in the low frequencies the optimal range for hearing aid

settings spanned from 2 dB above the DSL[i/o] target to 7 dB below the DSL target. In the high frequencies the optimal range of settings spanned from 3.2 dB below the DSL[i/o] target to 13.2 dB below target.

#### **Modifications made in the DSL v5 algorithm for adult hearing aid wearers**

The DSL[i/o] algorithm described by Cornelisse et al., 1995, and used in the DSL Method: v4.1 attempted to define the ideal amplified output for a range of input levels. The DSL[i/o] algorithm used nonlinear scaling so that input levels corresponding to the acoustic dynamic range of the normal loudness function were mapped onto the auditory area of the loudness function associated with hearing impairment, while maintaining the normal loudness relationship per frequency (Cornelisse et al., 1995). The DSL[i/o] algorithm comprised a very broad compression phase beginning at 0 dB HL. We hypothesize that the resultant gain for low-to moderate speech input levels using this approach may contribute to higher loudness levels than preferred or necessary for adult hearing aid wearers.

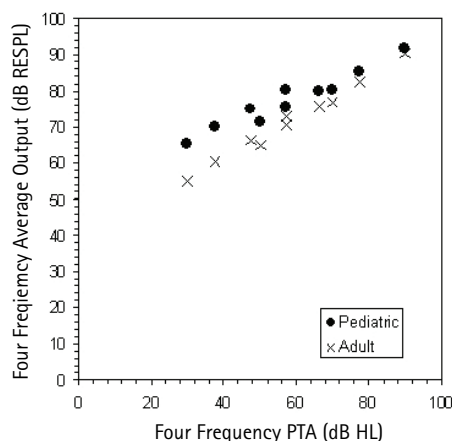
The DSL multistage input/output algorithm (DSL m[i/o]) used in DSL v5, does not use a loudness normalization approach for several reasons. First, current loudness models do not account for the adult-child and developmental differences required for listening reported earlier in this article. Second, loudness normalization attempts to make all sounds audible and normally loud. It is not likely that this is an appropriate goal for low-level background noise, nor is it an attainable goal given the noise floor of most hearing instruments. In developing the DSL m[i/o] algorithm we use compression processing to meet the goals of providing audibility and comfortable loudness of important speech cues, considering the general limits of hearing instruments and the limited dynamic range of the individual

hearing instrument user. As discussed above, the compression stage spans as much of the range of conversational speech across vocal effort levels as possible. As a starting place, the DSL m[i/o] input range was limited to no lower than 20 dB HL for adult listeners with acquired hearing impairment. Compared to the 0 dB HL loudness normalization strategy in DSL[i/o] this provides adults with a lower level of prescribed gain and compression ratio for the entire input-output function. As shown in Figure 10, the differences in prescriptive targets are largest for mild-to-moderate losses. A smaller correction is applied as hearing loss increases which is a desired effect because it maintains audibility of speech for more severe-to-profound hearing losses for adults and children. Further experimental evaluation of this age-related correction is required, however, it appears to be in good agreement with the adult-child differences in preferred gain reported earlier in this chapter.

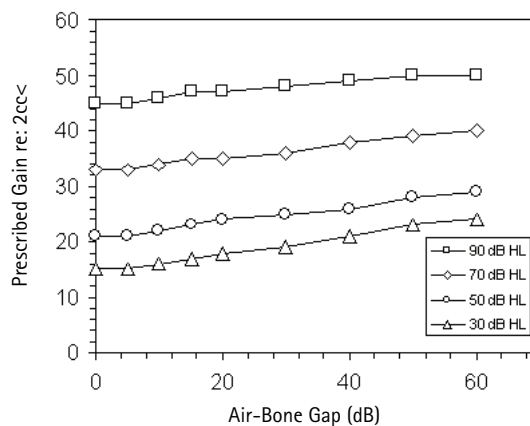
### Hearing instrument prescriptions for conductive hearing loss

Listeners with conductive and/or mixed hearing losses have higher loudness discomfort levels and prefer a higher level of use gain than do listeners with entirely sensory hearing losses (Berger, 1980; Walker, 1997a; Walker, 1997b; Carlin and Browning, 1990; Liu and Chen, 2000). Several strategies for accounting for these effects in hearing instrument prescription have been proposed in the literature (Dillon and Storey, 1998; Walker, 1998; Walker 1997a; Carlin and Browning, 1990). The strategy applied in DSL v5 to correct for conductive hearing loss is to increase the predicted upper limits of comfort (ULC), causing the input/output function to steepen, hence becoming more linear and thereby employing more gain. We have applied several limits to this strategy. First, targets in DSL v5 will not exceed 140 dB SPL in the ear canal, regardless of circuit type or the presence of conductive hearing loss. Second, predictions of the upper

**Figure 10** Average real-ear output target criteria for DSL v5 as a function of four-frequency pure-tone average threshold values (dB HL), for pediatric and adult target types in DSL v5. (from Scollie et al., 2005. Reprinted with permission).



**Figure 11** Effect of applying a conductive correction to the prescribed gains for conversational speech. Prescribed 2cc coupler gains (average gain for 500, 1000, 2000 Hz) for four flat hearing losses are shown, assuming either sensorineural loss or various degrees of conductive overlay within the stated hearing threshold level. (from Scollie et al., 2005. Reprinted with permission).



limit of comfort (ULC) are increased by 25% of the uncorrected air-bone gap, averaged across the frequencies of 500, 1000, 2000, and 4000 Hz, to a maximum of at 60 dB gap. The correction for conductive hearing loss is smaller as hearing level increases (often because the 140 dB limit to LDL is reached). Figure 11 illustrates the effect of applying a conductive correction to the prescribed gains for conversation-level speech inputs.

### Hearing instrument venting corrections

Venting corrections are applied in DSL v5 using values reported by Dillon (2001) with some modification to account for the combined effects of sound lost through the vent, and sound coming in through the vent (Hoover, Stelmachowicz and Lewis, 2000). A lower limit of venting reduction is defined, in real ear SPL, as the input test level plus the age-appropriate real ear unaided gain. If the test frequency is below 1000 Hz, the venting reduction is limited to not fall below this unaided level. Venting corrections are only applied in the 2cc transform and will not affect the targets in real ear formats (REAR, REAG, REIG). Manufacturers can use their instrument-specific venting corrections in place of the DSL v5 venting corrections.

### DSL v5: Verification Options

Targets from the DSL m[i/o] algorithm have best clinical utility when displayed on an SPLogram (see Figure 1) and compared with real-ear aided response (REAR) and output limiting targets for narrowband inputs and/or the upper limits of comfort, employing probe-microphone measures of real-ear performance. DSL m[i/o] targets can also be calculated for real-ear aided gain (REAG) and real-ear insertion gain (REIG) reference. If REIG targets are calculated using the DSL m[i/o] algorithm age-appropriate or measured real-ear unaided gain (REUG) values will be used (Bagatto et al., 2005). Targets for 2cc coupler gain can be calculated automatically using

the DSL m[i/o] REAR and RESR values using the following general equation:

$$\text{Real-Ear Targets (in dB SPL re: ear canal)} - \text{RECD} - \text{MLE} - \text{Input speech} = 2\text{cc target gain}$$

Target coupler gain values are advantageous when probe-microphone measurements may not be possible, such as when fitting hearing instruments for infants or young children. Coupler-assisted verification procedures can be clinically useful in predicting real-ear performance using the reverse of the equation above (Moodie et al., 1994). That is,  $2\text{cc target gain} + \text{input speech} + \text{microphone location effect (MLE)} + \text{RECD} = \text{predicted real-ear aided response (in dB SPL re: ear canal)}$ .

Targets from the DSL m[i/o] algorithm are appropriate for comparison with the aided long-term average speech spectrum, measured in one-third octave bands. This type of measurement can be made for soft (50 to 55 dB SPL), conversational (60 to 70 dB SPL), or loud (75-85 dB SPL) speech signals. Speech-based verification signals are strongly recommended for use with targets derived using DSL v5. Targets can be converted for use with speech-weighted noise and pure tone verification signals. The disadvantage of the corrections used in DSL v5 for signals other than speech is that it is less accurate and only useful for input levels between 50 and 70 dB SPL (Bagatto et al., 2005; Scollie and Seewald, 2002).

## Summary

This article describes some of the research and development that has resulted in the most recent version of the DSL Method: DSL m[i/o] v5 for hearing instrument selection and fitting for children and adults. Although modifications to the DSL algorithm continue to be made into the 21st century, the goals and objectives expressed in the initial publications have not changed (Seewald et al., 1985; Seewald et al., 1987; Ross and Seewald, 1988; Seewald and Ross, 1988). Nor has the point of view that the hearing instrument fitting process is a series of well-integrated stages that include audiometric assessment, hearing instrument selection, verification and evaluation of aided auditory performance.

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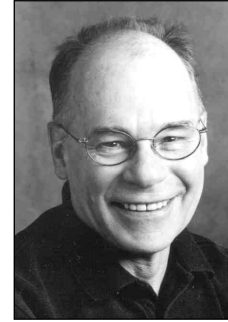
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**Dr. Richard C. Seewald** is a Principal Investigator at the National Centre for Audiology in London, Ontario, Canada and holds the Canada Research Chair in Childhood Hearing. He is also a Professor in the School of Communication Sciences and Disorders, Faculty of Health Sciences, University of Western Ontario. For the past 25 years, Dr. Seewald's work has been focused on issues that pertain to the selection fitting of amplification in infants and young children. He is known internationally for his work in developing the Desired Sensation Level (DSL) Method for pediatric hearing instrument fitting.



**Steve Beaulac** joined the DSL Team in 2000. He is the Lead Programmer for the DSL m[i/o] library and the Systems Specialist for the National Centre for Audiology. He is a graduate of the University of Western Ontario with degrees in Electrical Engineering and Computer Science.



**Dr. Susan Scollie** is Principal Investigator at the National Centre for Audiology and an Assistant Professor at the University of Western Ontario in London, Ontario, Canada. Together with her collaborators, she developed the recently released DSL m[i/o] algorithm for hearing aid fitting. Her current research focuses on the evaluation of novel digital signal processing for high frequency hearing losses, the Speech Intelligibility Index, and sound localization in children with hearing losses.

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