Assessing Growth of Loudness in Children by Cross-Modality Matching

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Abstract

This study examined the clinical feasibility, validity, and reliability of loudness growth assessment using cross-modality matching (CMM) between line length and loudness in 16 children 4 to 12 years old with normal hearing or bilateral sensorineural hearing losses ranging from moderate to severe in degree. Eight adult listeners with normal hearing were used as a comparison group. Loudness growth functions and real-ear measures were obtained for 500-Hz and 2000-Hz narrowband noise stimuli for each individual. No significant differences were found between the loudness slope values for the adults and children with normal hearing. Loudness growth functions of the children with sensorineural hearing loss were significantly steeper (larger) than the slopes obtained from children with normal hearing. The numeric slope value of the loudness growth function became larger and more variable as children's hearing threshold increased and differed for children with similar thresholds. The loudness functions obtained for retested participants at two different test sessions were highly correlated. Real-ear measurements revealed that for equivalent input stimulus levels, significantly higher stimulus levels were present in the ear canals of children versus adults. Although adults and children with normal hearing had similar overall rates of loudness growth, discrete points along the loudness growth function were judged to be louder by the children. This preliminary study suggests that measures of loudness growth using CMM between line length and loudness are feasible, valid, and reliable in children with normal hearing or sensorineural hearing loss. The individual variability noted in slope values for children with hearing loss attests to the importance of subjective assessments of loudness. The protocol used in this study may have potential as a clinical tool for selecting and fitting amplification technology for children with hearing loss as young as 6 years.

Key Words: Children, cross-modality matching, loudness, loudness growth functions, sensorineural hearing loss

Abbreviations: CMM = cross-modality matching, HI = hearing impairment, LDL = loudness discomfort level, MCL = most comfortable loudness, NBN = narrowband noise, NH = normal hearing

The timely fitting of appropriate amplification technology to infants and young children with sensorineural hearing loss is essential for the development of aural/oral communication (Pediatric Working Group, 1996). The goal of hearing aid fitting is to ensure audi-
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devices used by children. Such prescriptive methods, at least initially, eliminate the need for subjective judgments of loudness in the hearing aid fitting process as amplification targets are based on frequency-specific thresholds. However, as the child ages, more individualized measures of loudness growth could be beneficial toward optimizing the hearing aid fitting (Scewald, 1991).

Listeners with sensorineural hearing loss frequently experience a reduced dynamic range (threshold to discomfort) that is often limiting when these individuals listen to the amplified speech signal (Venema, 1998). However, conventional clinical procedures used for assessing the dynamic range of hearing in adults with normal hearing and sensorineural hearing loss may be inadequate for that purpose (Stevens, 1959; Thalmann, 1965; Geller and Margolis, 1984; Hellman and Meiselman, 1990). Most comfortable level (MCL) and loudness discomfort level (LDL) judgments for speech and/or tonal stimuli (Humes and Halling, 1994) are dependent on the specific instructions provided to the listener (Dillon, 1995), the spectra of any broadband stimuli used (Skinner, 1988), and the duration of test signals (Garnier et al, 1999). In addition, Fillion and Margolis (1992) reported a poor agreement between LDLs measured clinically and real-life judgments of loudness discomfort. Importantly, measures of MCL and LDL do not provide an index of the perception of loudness over the individual’s entire dynamic range of hearing. Asking young children with congenital hearing loss, often with limited language abilities and little or no experience with amplified sound, to judge stimuli as most comfortable or uncomfortable for long-term listening can be problematic. Some investigators have shown that LDLs are difficult to obtain reliably in children with normal hearing for developmental ages below 5 to 7 years (MacPherson et al, 1991).

Rather than the limited clinical determinations of MCL and LDL, the psychophysical procedures of magnitude estimation, magnitude production, categorical scaling, and cross-modality matching (CMM) have been used to estimate loudness across the listening range in adults with sensorineural hearing loss (Geller and Margolis, 1984; Margolis, 1983; Hellman and Meiselman, 1988).

Magnitude estimation involves the individual assignment of a number to a given stimulus level, whereas magnitude production is the inverse. These procedures reflect a listener’s perception of the loudness of any given signal. However, children younger than 8 years of age may have difficulty using the numeric ratio properties inherent in this scaling method (Teghtsoonian, 1980; Zwislocki and Goodman, 1980).

Categorical scaling involves assigning a bounded range of categories (typically numbers) to a range of stimulus levels. This psychophysical procedure has been used to estimate loudness in young children. Kawell et al (1988) used pictorial representations of five loudness categories (i.e., “too soft,” “just right,” “a little bit loud,” “too loud,” “hurts”) to obtain a reliable LDL judgment in 7- to 14-year-old children with sensorineural hearing loss. However, Ellis and Wynne (1999) found that the categorical scaling procedure of loudness growth in 1/6-octave bands (LGOB) was unreliable for measuring loudness growth functions in 7- to 12-year-old children with sensorineural hearing loss even when pictorial representations were added to the written descriptors (i.e., “a little bit loud,” “a little bit soft,” “just right”).

Stevens (1959) suggested that a sensory modality that functions normally (e.g., the visual modality) could be used as a substitute for the impaired ear for loudness comparison measures in listeners with bilateral sensorineural hearing loss. This psychophysical procedure is known as CMM. Hellman (1999) and Hellman and Meiselman (1988, 1990, 1993) have reported on the clinical utility, validity, reliability, and precision of CMM of loudness and line length. They found CMM could be used for the assessment of loudness growth in adult listeners with normal hearing and varying degrees of sensorineural hearing loss. Importantly, Teghtsoonian (1980) and Collins and Gescheider (1989) examined CMM between loudness and line length and found the technique to be reliable in children as young as 4 years of age. However, the investigators’ sample was limited to young listeners with normal hearing.

Unfortunately, although clinical physiologic and electrophysiologic measurements such as acoustic reflex thresholds for tones and noise bands (Kiessling, 1987; Northern and Abbot-Gabbard, 1994) and auditory brainstem response latency-intensity functions and amplitude measures (Mahoney, 1985; Seitz and Kisiel, 1995; Serpanos et al, 1997) would be useful indexes of loudness growth in children, work with adults has yielded mixed results.

This report represents a preliminary study of a technique for assessing loudness growth in the pediatric population using the psychophysical
method of CMM. Sixteen children ranging in age from 4 to 12 years were asked to match line length and loudness. Eight children with normal hearing and eight children with sensorineural hearing loss ranging from moderate to severe in degree were participants in this investigation. This initial study of the validity and reliability of the CMM procedure also provides data on the effect of age, real-ear stimulus level, stimulus frequency, and degree of hearing loss on children's perception of loudness. Our long-term goal is to develop a procedure that will provide the clinician with valuable information for individualizing and refining the selection and fitting of today's amplification technology to the young child with sensorineural hearing loss.

**METHOD**

**Participants**

Sixteen children participated in this investigation. Eight (three females, five males) of the children had normal hearing (NH) and eight (six females, two males) had varying degrees of sensorineural hearing impairment (HI). Children fell into two general age groups: younger (4–7 years; n = 8) and older (8–12 years; n = 8).

Two (NH) of the children were 4 years, two (HI) were 6 years, four (two HI, two NH) were 7 years, three (two HI, one NH) were 8 years, two (NH) were 9 years, two (one HI, one NH) were 10 years, and one (HI) was 12 years of age. The children all had normal or corrected normal vision and no prior experience with loudness growth tasks.

Pure-tone audiometry (GSI-16, Grason-Stadler, Inc.), acoustic immittance measures (tympanometry and acoustic reflex thresholds) (GSI-33 Middle Ear Analyzer, Grason-Stadler, Inc.), and speech audiometry were completed on each participant regardless of the availability of previous audiometric evaluations in order to verify hearing status. NH was defined as pure-tone thresholds less than or equal to 20 dB HL at octave frequencies from 250 to 8000 Hz in the test ear. Sensorineural hearing loss was defined as pure-tone thresholds greater than or equal to 25 dB HL in the same frequency range with no air–bone gap exceeding 10 dB at more than one audiometric frequency. All measures were obtained in a double-walled sound-treated test booth at each study location.

The hearing losses of all eight children were bilateral and ranged from moderate to severe in degree based on the three-frequency (500, 1000, and 2000 Hz) pure-tone average (range: 47–78 dB HL). The audiometric configurations for seven of the eight children were symmetric. The better ear of the one participant with asymmetric hearing loss served as the test ear. Case history information revealed that hearing losses were thought to be congenital for four of the eight children. Meningitis, high fever, and premature birth were cited as the probable etiology of the sensorineural hearing loss for the remaining children. All children with hearing loss were aided binaurally with behind-the-ear hearing instruments with duration of amplification use ranging from 1.5 to 8 years. Audiometric and demographic data for each young listener with hearing loss are found in Table 1.

Eight adults with NH were also participants in this study. Adults met the same criteria for NH as detailed above for the children in the same hearing status category. Data from the adults were obtained using the identical test procedures as were used with the children.

<table>
<thead>
<tr>
<th>Subject # (Yr)</th>
<th>Test Ear</th>
<th>Gender</th>
<th>Etiology</th>
<th>Years Aided</th>
<th>Three-Frequency PTA (dB HL)</th>
<th>Test Ear Thresholds (dB HL) by Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>1 HI</td>
<td>7 R F</td>
<td>Meningitis</td>
<td>5</td>
<td>53</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>2 HI</td>
<td>6 R F</td>
<td>? congenital</td>
<td>4</td>
<td>53</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>3 HI</td>
<td>7 R F</td>
<td>? congenital</td>
<td>4</td>
<td>68</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>4 HI</td>
<td>6 R M</td>
<td>? congenital</td>
<td>3</td>
<td>62</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>5 HI</td>
<td>8 R F</td>
<td>? congenital</td>
<td>6</td>
<td>65</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>6 HI</td>
<td>12 L F</td>
<td>Premature</td>
<td>7</td>
<td>78</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>7 HI</td>
<td>10 R F</td>
<td>Premature</td>
<td>8</td>
<td>47</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>8 HI</td>
<td>8 R M</td>
<td>High fever</td>
<td>1.5</td>
<td>55</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Mean</td>
<td>8</td>
<td></td>
<td></td>
<td>5</td>
<td>60</td>
<td>39</td>
</tr>
<tr>
<td>SD</td>
<td>2.07</td>
<td></td>
<td></td>
<td>2.14</td>
<td>10.06</td>
<td>13.21</td>
</tr>
</tbody>
</table>

PTA = pure-tone average of 500, 1000, and 2000 Hz.
The loudness growth functions obtained from the adults served as a comparison for the loudness growth functions obtained from the children with normal hearing.

Children were paid participants and were recruited from the clinic population at the Hy Weinberg Center for Communication Disorders at Adelphi University, Garden City, NY and the Clinical Research Center for Communicative Disorders at the Rose F. Kennedy Center, Albert Einstein College of Medicine, Bronx, NY. Adults were unpaid volunteers and were all tested at Adelphi University. Both the Human Subjects Research Committee (Adelphi) and the Committee on Clinical Investigations (Albert Einstein) approved the study. Parents provided signed informed consent for their children's participation in the study; children over the age of 7 years who agreed to participate also signed child assent forms. Adult participants also provided written informed consent.

Stimuli

The acoustic stimuli consisted of 1/3-octave noise bands (narrow-band noise; NBN) centered at 500 and 2000 Hz (ANSI, 1996). The stimuli were generated, amplified, and attenuated by a clinical audiometer (GSI-16). The duration of each stimulus presentation, controlled manually, was approximately 4 sec. When necessary, the duration of the stimulus was extended in order for the listener to complete the response task.

The visual stimuli were eight separate 8" × 11" cards each depicting a single graphic of varying length. The graphic depiction of line length (with a face of a smiling caterpillar affixed to the left end of the line) was cartoon-like and intended to be fun for young children to view. The body lengths of the smiling caterpillars were 0.52, 1.04, 2.08, 5.2, 10.4, 20.8, 41.6, and 65 cm (a ratio of 125:1), in accord with the line lengths used in recent CMM studies with adults (e.g., Hellman and Meiselman, 1988, 1990, 1993; Hellman, 1999; Serpanos et al, 1998). The width of each line and size of the affixed graphic (the "face" of the caterpillar) was identical for each line length. When needed for the CMM tasks (see below), the cards could be attached to a large poster board via Velcro strips.

Procedures

Thresholds and discomfort levels for the auditory stimuli were obtained from each individual prior to loudness growth assessment. The stimuli were presented monaurally to the listener's test ear through an insert earphone (EAR-3A, 50 ohm) coupled to a conventional foam eartip. Thresholds for the two NBN stimuli were obtained using an adaptive method of limits (ASHA, 1978). In addition, a threshold of loudness discomfort for each NBN was measured in order to prevent the use of stimulus levels that would be intolerably loud for the listener. For children and adults with normal hearing, the individual was asked to indicate whether the highest stimulus level to be used during the loudness growth task (i.e., 90 dB HL) was tolerable. If the participant reported discomfort, tolerance for the next lowest stimulus level was assessed.

A more systematic approach was used to measure the LDL for the children with hearing loss, as this level determined the child's dynamic range, which was used to calculate the step size of the stimulus level presentation (described below). The discomfort level was determined by asking the child to listen to an ascending series (1-dB step size) of stimulus levels and to indicate the level that was "very, very loud." With the young children, the examiner's verbal instruction was also accompanied by a facial expression of discomfort. The stimulus level identified as uncomfortable served as the loudness limit for the test conditions at that frequency.

The loudness growth function was defined separately for 500 and 2000 Hz over a range of stimulus levels for each individual. The technique for each task was demonstrated by the examiner and informally assessed with each child in order to ensure familiarity with the procedure prior to testing. Typically, the loudness growth tasks were completed in a single 30-minute session. Children were offered breaks as needed.

The procedure for the CMM loudness growth tasks, described below, includes two methods. In the first task, length is matched to loudness. The second task is the reverse of the first: loudness is matched to length. Both procedures are necessary in order to counterbalance a psychophysical bias known as the regression effect, in which there is a tendency for the listener to restrict the range of the variable (e.g., stimulus level) to be adjusted. For example, a smaller loudness exponent (slope) will be obtained when length is matched to loudness than when loudness is matched to length. To eliminate the regression effect, a geometric average of the two exponents is calculated. This value represents
the actual loudness exponent (Stevens, 1975). Therefore, two separate loudness functions were obtained for each individual for each test frequency and the values geometrically averaged to provide the actual loudness growth function at that frequency.

CMM: Length to Loudness

For this task, each listener was required to assign the length of one of the graphics to represent the perceived loudness of each stimulus (NBN at 500 or 2000 Hz) level. The eight graphic cards were arranged in ascending length order in four rows on the poster board. The listener was taught by verbal instruction or demonstration to touch the graphic that was as long as the sound was loud. Each stimulus was presented at eight different levels chosen according to the hearing status of the test ear (see below).

For participants with NH, stimulus levels ranged from 20 to 90 dB HL and were presented in 10-dB increments. Stimulus levels for each test frequency were individually determined for the children with hearing loss by dividing the listener's dynamic range (discomfort level in dB HL minus the threshold of audibility in dB HL) by eight. This value was the fixed step size and was used to determine the actual dB HL of the stimulus for each listener beginning with the individual's threshold and increasing through seven additional stimulus levels (each one step size more intense than the previous).

The examiner controlled the presentations of the auditory stimuli. The 500-Hz NBN stimuli were presented to the listener's test ear at each of the eight levels in a randomized order. At least two separate trials were presented but could be presented as many times as needed until each graphic was matched to the same stimulus level twice. The replicated perceived length was then recorded for each level. The same procedure was then used for the 2000-Hz condition.

CMM: Loudness to Length

For this CMM task, the stimulus was adjusted to be as loud as the listener perceives the graphic was long. By means of verbal instruction or graphic demonstration, the listener was taught to adjust the attenuator of the audiometer to make the loudness of the auditory stimuli subjectively equal to the length of one of the eight graphics presented by the examiner. The listener was not able to see the numeric values of the attenuator display. The attenuator step size was set to 1 dB; a range of adjustment was permitted between -10 and 110 dB HL. The examiner showed the listener one of the eight graphic cards in randomized order. Again, at least two separate test runs were presented; each run included all eight graphic stimuli. The matched stimulus level was recorded, and the dB average of the perceived loudness was computed for each length. Therefore, eight level estimates were obtained for each individual for each graphic stimulus.

Test–retest reliability of the CMM technique was completed on half of the participants in each of the three (HI children, NH children, adults) groups. The 12 participants were retested with the CMM procedure on another day, generally within 4 to 6 weeks after the original test session.

Real-Ear Measurements

Real-ear measurements (RM500, Audioscan, Inc.) of each acoustic test stimulus were obtained in the test ear of each listener in order to examine loudness growth judgments for equivalent input stimulus levels. For the children with sensorineural hearing loss, the probe microphone tube was inserted into the ear canal at a depth of 5 mm past the medial tip of the individual's own earmold (Tecca, 1990). For the adults and children with NH, the probe microphone tubing was placed 5 mm past the medial end of the foam tip. For the measurements of real-ear sound pressure levels, the 500- and 2000-Hz NBN stimuli were presented at 70 dB HL (GSI-16) to all participants via the foam tip of the insert earphone. Real-ear measurements of the test stimuli in dB SPL were recorded and printed.

RESULTS

Threshold and Discomfort Measures

For the children with NH, mean thresholds for the 500- and 2000-Hz NBN stimuli were less than 10 dB HL (range: -5–15 dB HL) (Table 2). All of the children with NH were able to tolerate the highest stimulus level (90 dB HL) used for the loudness growth task.

The children with sensorineural hearing loss had average hearing threshold levels of 49 dB HL (range: 30–60 dB HL) for 500 Hz and 61 dB HL (range: 45–85 dB HL) for 2000 Hz (Table 3). Levels of discomfort to both stimuli
Table 2  Individual Measured Loudness Slopes for Children with Normal Hearing (NH)

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Age (Yr)</th>
<th>Threshold (dB HL)</th>
<th>500 Hz</th>
<th>2000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured Loudness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 NH</td>
<td>7</td>
<td>-5</td>
<td>0.77</td>
<td>0.96</td>
</tr>
<tr>
<td>2 NH</td>
<td>4</td>
<td>5</td>
<td>0.63</td>
<td>0.99</td>
</tr>
<tr>
<td>3 NH</td>
<td>4</td>
<td>10</td>
<td>0.75</td>
<td>0.98</td>
</tr>
<tr>
<td>4 NH</td>
<td>7</td>
<td>10</td>
<td>0.77</td>
<td>1.00</td>
</tr>
<tr>
<td>5 NH</td>
<td>10</td>
<td>0</td>
<td>0.77</td>
<td>0.99</td>
</tr>
<tr>
<td>6 NH</td>
<td>9</td>
<td>0</td>
<td>0.72</td>
<td>0.97</td>
</tr>
<tr>
<td>7 NH</td>
<td>8</td>
<td>10</td>
<td>0.74</td>
<td>0.96</td>
</tr>
<tr>
<td>8 NH</td>
<td>9</td>
<td>15</td>
<td>0.77</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean</td>
<td>7.25</td>
<td>5.63</td>
<td>0.74</td>
<td>0.98</td>
</tr>
<tr>
<td>SD</td>
<td>2.25</td>
<td>6.78</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

ranged from 85 to 100 dB HL for the children with sensorineural hearing loss (see Table 3). Interestingly, results obtained during the CMM loudness to length task, however, revealed that the LDL measurements were invalid in the majority of young children. Test stimulus levels adjusted by children with hearing loss to equal the perceived level of the longest line length exceeded the children’s initial LDLs by 3 to 14 dB in five (63%) of eight cases.

**Measured Loudness Slopes**

All children, regardless of their hearing status, were able to perform the CMM tasks. One 4 year old with NH was replaced during the study as he refused to continue with testing. This was not, however, a consequence of his inability to do the required matching tasks.

The measured loudness function was constructed for each individual by calculating the geometric mean of the two stimulus levels (obtained from both loudness tasks) matched to each graphic length. Next, linear regression analysis (length [y] by stimulus level in dB HL [x]) was performed on each individual intensity function in order to obtain the power function exponents (slope values).

**Participants with Normal Hearing**

The individual slope values were averaged to provide group slope values. For the children with NH, the group mean measured loudness slope was 0.74 (SD = .05) for 500 Hz and 0.75 (SD = .06) for the 2000-Hz NBN stimulus. The individual correlations (r) of the measured loudness functions for both stimuli ranged from 0.96 to 1.0. Table 2 provides the individual and group measured loudness slope values for the children with NH.

For the adults with NH, the group mean measured loudness slope was 0.69 (SD = 0.08) for the 500-Hz and 0.70 (SD = 0.06) for the

Table 3  Individual Measured Loudness Slopes for Children with Sensorineural Hearing Impairment

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Age (Yr)</th>
<th>Threshold (dB HL)</th>
<th>500 Hz</th>
<th>2000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured Loudness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 HI</td>
<td>7</td>
<td>60</td>
<td>1.73</td>
<td>0.99</td>
</tr>
<tr>
<td>2 HI</td>
<td>6</td>
<td>55</td>
<td>1.60</td>
<td>0.95</td>
</tr>
<tr>
<td>3 HI</td>
<td>7</td>
<td>55</td>
<td>1.65</td>
<td>0.98</td>
</tr>
<tr>
<td>4 HI</td>
<td>6</td>
<td>55</td>
<td>1.45</td>
<td>0.94</td>
</tr>
<tr>
<td>5 HI</td>
<td>8</td>
<td>55</td>
<td>1.31</td>
<td>0.99</td>
</tr>
<tr>
<td>6 HI</td>
<td>12</td>
<td>45</td>
<td>1.43</td>
<td>1.00</td>
</tr>
<tr>
<td>7 HI</td>
<td>10</td>
<td>35</td>
<td>1.17</td>
<td>0.99</td>
</tr>
<tr>
<td>8 HI</td>
<td>8</td>
<td>30</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>Mean</td>
<td>8.00</td>
<td>48.75</td>
<td>1.41</td>
<td>0.98</td>
</tr>
<tr>
<td>SD</td>
<td>2.07</td>
<td>10.94</td>
<td>0.26</td>
<td>0.02</td>
</tr>
</tbody>
</table>
2000-Hz NBN stimulus. Similar to the children, the individual correlations (r) of the measured loudness functions at both frequencies for adults ranged from 0.96 to 1.0. The high correlations found for the measured loudness functions in both adults and children with NH suggest that the data from both groups are well described by linear analysis.

Figures 1A and 1B show the individual measured loudness functions for the younger (filled symbols) and older (open symbols) children with NH plotted with the mean measured loudness function obtained for adults (± 2 SD) for the 500- (see Fig. 1A) and 2000-Hz (see Fig. 1B) test stimuli, respectively. A two-sample t-test assuming equal variances was conducted in order to determine whether there was any difference in the slopes of the measured loudness functions between the adults (x) and children (y) with NH. No significant differences were found in the slope values between the groups for either the 500- (t = 1.50, df = 14, p = .16) or 2000-Hz (t = 1.70, df = 14, p = .11) narrowband stimuli.

A linear regression analysis revealed a significant relationship between the measured loudness functions at 500 (x) and 2000 Hz (y) for the adults (r = .98, p < .01) and children (r = .98, p < .01) with NH.

Children with Hearing Loss

Individual slope values for the children with hearing loss are provided in Table 3. Thresholds ranged from 30 to 85 dB HL with corresponding slope values increasing from 0.96 to 3.1 as a function of hearing level. Individual correlations of the functions ranged from 0.94 to 1.0. As in the group of children with normal hearing, the high correlations found for the measured loudness functions suggest that the data are well described by linear regression analysis.

Figures 2A and 2B show the individual measured loudness functions for the children with hearing loss plotted on graphs depicting the mean (± 2 SD) measured loudness function obtained for the group of children with NH for the 500- and 2000-Hz stimuli, respectively. Individual data are shown for the general categories of younger (filled symbols) and older (open symbols) children.

Two-sample t-tests (assuming equal variances) were completed to determine whether there were significant differences between the measured loudness growth function slope values for the children with hearing loss versus those of their peers with NH. As was expected, significant differences were found for the 500- (t = -7.23, df = 14, p < .0001) and 2000-Hz (t = -5.68, df = 14, p < .0001) stimuli. Similarly, significant slope differences were found between the children with hearing loss and the adults with NH for both signals (500 Hz: t = -7.55, df = 14, p < .0001; 2000 Hz: t = -5.94, df = 14, p = .0001).
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A 100

E

L

m

J

500- (NH children: r = .90, p < .01; HI children: r = .96, p < .01; adults: r = .98, p < .01) and 2000-Hz (NH children: r = .96, p < .01; HI children: r = .97, p < .01; adults: r = .99, p < .01) NBN stimuli.

Real-Ear Measurements

The results the real-ear measures to the auditory stimuli were analyzed by listener age. For the 500-Hz NBN, mean sound pressure levels were 82.5 dB for the younger children (4–7 years), 81.8 dB for the older children (8–12 years), and 78.9 dB for the adults. For 2000 Hz, mean real-ear values were 86.3 dB SPL for the younger children, 85.8 dB SPL for the older children, and 82.4 dB SPL for the adults. The variability of the measures ranged from 1.0 to 3.1 dB SPL.

Statistical analysis was performed using two-sample t-tests (assuming equal variances) between the real-ear values for the two age groups of children and between the adults and children. Significant differences were obtained between the real-ear values for adults and children aged 4 to 7 years for the 500- (t = 3.22, df = 14, p = .01) and 2000-Hz stimuli (t = 2.63, df = 14, p = .02). Similarly, for the adults and 8- to 12-year-old children, measured real-ear SPL values differed for the 500-Hz stimulus (t = 2.56, df = 14, p = .02). However, no significant differences were found between the adults and older children for the 2000-Hz stimulus (t = 2.03, df = 14, p = .06). Neither were there differences between the younger and older children for either stimulus frequency (500 Hz: t = 0.85, df = 14, p = .41; 2000 Hz: t = 1.04, df = 14, p = .32).

DISCUSSION

This study is a preliminary investigation on the usefulness of the CMM procedure for gaining clinically relevant information from children regarding the individual growth of loudness with hearing loss. In addition, the data also provided some interesting insight into potential differences in the growth of loudness in children with NH compared to adults with similar hearing status. The significant relationships found in the test–retest data for all three study groups attest to the reliability of the CMM method regardless of frequency of the stimulus, the listener's age, or hearing status. Moreover, the variability of the CMM measures were similar for adults and children, suggesting that CMM is a valid measure of loudness growth for use in the pediatric population.
Loudness Growth Function for Children and Adults with Normal Hearing

One important question this study addressed is whether the loudness growth function differs for adults and children with normal hearing. Recall that the mean measured slope values of 0.74 (500-Hz NBN) and 0.75 (2000-Hz NBN) obtained from the children with normal hearing were found to be close to the adult values of 0.69 and 0.70 for the respective stimuli. Indeed, statistical analysis revealed no significant differences among the slope values between the measured loudness functions for the adults and for those of children with NH for either test stimulus. A visual inspection of the children's measured loudness functions (see Figs. 1A and 1B) shows that the data points fall within the range of deviation (± 2 SD) around the adult mean measured loudness function that is considered a typical variation of loudness scaling (Hellman and Meiselman, 1993; Hellman, 1999). Moreover, the deviations of the individual measured loudness slope values for the younger and older groups of children with NH were within the range found for the adult group (0.08). That the loudness functions for the adults and children show similar variability suggests that the CMM measure is valid for the examination of loudness growth in children. Children with NH at least as young as 4 years of age were able to perform the loudness scaling task using loudness to length matches as well as did adults. This is consistent with the findings of Teghtsoonian (1980).

The finding of no significant differences between the measured loudness slope values for adults and children with NH for either test stimulus suggests that the rate of loudness growth is the same for listeners with NH, regardless of age. However, real-ear measures obtained with the test stimuli revealed that at similar hearing levels (dB HL), actual sound pressure levels were different between adults and children. Not surprisingly, real-ear differences were found for both the 500- and 2000-Hz NBN stimuli between adults and children in the 4- to 7-year age group and for the 500-Hz stimulus between adults and the 8- to 12-year-old children (higher measured real-ear SPLs for children than adults). Of question is how, if at all, these higher stimulus presentation levels affect the loudness growth function.

Figure 3 shows a plot of the mean values for the loudness growth functions of children and adults in real-ear sound pressure level instead of dB HL. Note that the mean loudness growth functions for children are displaced to the right of the mean functions for adults at both 500 and 2000 Hz. This implies that what may actually differ between adults and children with NH is the perception of loudness, even though loudness grows in the same way for both groups. As an example, a comparison of the mean values at one midpoint of the loudness growth function for the 2000-Hz stimulus (i.e., the loudness in dB SPL of the 2000-Hz NBN matched to the 5.2-cm line length) revealed loudness judgments of 45.8 dB HL versus 49.6 dB HL for the adults and children, respectively. When the correction values (HL to real-ear SPL difference: 12.4 dB for adults, 16 dB for children) are added to these HL values (as plotted in Fig. 3), the resultant levels for the same line length were 58.2 dB SPL for the adults and 65.6 dB SPL for children. This implies that at this discrete point along the 2000-Hz NBN loudness growth function, the same test stimulus (line length of 5.2 cm) was perceived to be about 7 dB louder by the children than by the adults. Recall that the plot of the individual loudness growth functions provided for the eight children with NH (see Figs. 1A and 1B) showed that although each individual function fell within the adult range of variability, most are displaced (3–4 dB) toward higher stimulus levels (to the right) compared to the mean adult loudness function. Thus, we conclude that this sample of children with NH judge
sound as louder at the same discrete points along the loudness growth function (primarily at low and mid levels of sound) than do adults with NH.

**Loudness Growth and Children with Hearing Loss**

The individual measured loudness slope values for the children with hearing loss were up to four times larger than those obtained for the groups of children with NH. Although group mean loudness slope values were provided in Table 3, this was not considered an accurate representation as most of the individual threshold values differed among participants by more than 10 dB. In comparison to the variability noted for the mean slope values for NH, this may explain the much larger variability found for the measured loudness slope values at 500 (0.26) and 2000 Hz (0.56) for the children with sensorineural hearing loss. Note than in Table 3, slope values vary by threshold. In general, steeper (larger) slope values were obtained with increasing hearing loss. The range of variability for slope values was 0.26 at 500 Hz to 0.56 at 2000 Hz. This range of variability is higher than the variability observed within the groups of participants (children and adults) with NH. The findings of larger slope values and variability with increasing threshold in children with hearing loss are similar to those reported previously for adult listeners with sensorineural hearing loss (i.e., Hellman, 1999).

The plots of the measured loudness growth functions for the children with hearing loss by stimulus (see Figs. 2A and 2B) verifies the steeper (larger) slopes for each child when contrasted with the normal range of variability for the normal loudness function. Not surprisingly, statistical analysis confirmed that the differences were significant among the measured loudness functions for the older and younger children with hearing loss versus the groups of children or adults with NH. Note, however, that at 500 Hz, one child with hearing loss (8 HI: open diamond symbol) presented with a loudness growth function that was within the normal range for the majority of points of the function. This child presented with the best threshold (30 dB HL) of this group at this frequency. At 2000 Hz, none of the children's functions fell within the normal range, except at the very highest levels. Six of the eight loudness functions for the 500-Hz signal of the children with hearing loss converge toward the normal function at the highest stimulus levels. This finding of normal loudness perception at high stimulus levels (at approximately 30 dB SL above stimulus threshold) has been noted for listeners with sensorineural hearing loss (Moore, 1989).

Figure 4 depicts the loudness growth functions at 2000 Hz for four young children with hearing loss (3, 4, 5, 8 HI). Note that these children all had thresholds of 65 dB HL at 2000 Hz for the NBN stimulus (see Table 3). However, their slope values and loudness growth functions differed markedly. Indeed, the slope values ranged from 1.48 to 2.21. More interesting is that whereas the perception of loudness is similar at low levels, at mid and higher levels the perception of the same length varies widely—indeed, by as much as 11 dB. Thus, even when thresholds are similar for a stimulus, loudness (1) appears to grow differently and (2) is perceived differently at discrete points along the loudness growth function. Consequently, this suggests (at least given the current data) that for children with hearing loss, predictions of individual loudness growth from threshold values may not be accurate.

**Clinical Implications of the Loudness Growth Data**

The individual loudness growth functions, as described by slope value and by graphic display, provide important information about loudness growth for each child with sensorineural

Figure 4 Loudness functions for four children (3 HI [solid line; slope = 2.21], 4 HI [dashed-dot; slope = 1.48], 5 HI [dotted line; slope = 1.96], and 8 HI [dashed line; slope = 1.82]) with the same thresholds (65 dB HL) at 2000 Hz.
hearing loss. First, it is clear that poorer thresholds produced higher numeric slope values and steeper loudness functions. For example, the steepest (3.10) loudness growth function was measured and observed (see Fig. 2B) at 2000 Hz for one child (6 HI; open circle symbol), who also presented with the poorest threshold (85 dB HL) recorded for either stimulus. The lower (45 dB HL) threshold for the 500-Hz stimulus for the same child produced a smaller (1.43) slope value and a flatter loudness growth curve that approximated the normal function at moderate stimulus levels. Thus, loudness growth patterns vary with threshold across various frequency regions within the same individual.

That the loudness function varies with increasing hearing threshold is not surprising. However, that among similar hearing thresholds the slope of loudness is different and, indeed, discrete points along the loudness function are markedly different lends support to the need to assess individual loudness growth in children with sensorineural hearing loss. This concept is supported by Hellman (1999) and Launer (1995).

Initially, during the early years of life (possibly younger than 4 years), clinicians will need to rely on prescriptive procedures that use thresholds to determine output limits for the child's amplification technology. However, as soon as it is possible, obtaining individual loudness growth functions may be very useful in individually tailoring the output characteristics (at low and moderate to moderate-high sound pressure levels) to account for the child's perception of loudness. Reassessment of loudness growth functions may be necessary as the child gains more experience with amplified sound. This was not tested in the present study, but reliability of loudness growth measures in children with maturation and hearing aid experience is a topic in need of investigation.

In addition to the research implications, this study provided practical experience with the CMM method that could be useful clinically. In order to assess the growth of loudness in children with hearing loss for the purpose of refining the output limiting characteristics of their personal amplification, clinicians must have procedures available that are fast, feasible, and, most important, accurate. In this study, the time needed to complete the CMM task averaged approximately 20 minutes for children. Certainly, in a clinical application, two ears and possibly several stimuli would need to be measured, which would add to the test time to the evaluation. CMM also was found feasible in that young children seemed to enjoy and perform the task as if it were a game. Based on our experience in this study, it appears that the CMM task between loudness and line length could be incorporated easily into an existing clinical environment. The only foreseen difficulty for clinical application of CMM may be that the data analysis needed to determine individual loudness functions for several stimuli may be cumbersome. One solution could be that for clinical purposes, only part of the protocol described in the present study would be used. That is, only the task of CMM producing loudness to line length would be used for the measurement of loudness growth functions. This simplified procedure would avoid the need for mathematical computation and also reduce the test time of the procedure. This approach needs to be examined in future investigations.

Perhaps a better solution is to develop a computer-controlled CMM procedure. This would allow the digital generation of test signals, reducing the potential problem of lack of frequency specificity at high sound pressure levels when 1/3-octave bands of noise are generated by a conventional audiometer (Popelka and Mason, 1987). In addition, the computer would control stimulus duration and presentations, providing an alternate method for estimating the length to loudness function (from categorical to continuous). Further, a computerized procedure would allow rapid data analysis and construction of complete loudness growth functions derived from both line to loudness and loudness to length measures.

Finally, a comment concerning the application of the measured loudness growth functions to the fitting of a child's amplification device. Some authors suggest that restoration of the normal loudness growth function is a goal of hearing aid fitting (Geller and Margolis, 1984; Margolis, 1985; Hellman, 1999). Several clinical methods have been suggested as a means of selecting amplification characteristics such as gain and compression through comparisons of loudness growth functions from NH listeners to those obtained from the individual with hearing loss (Geller and Margolis, 1984; Margolis, 1985). For example, in listeners with hearing loss where the rate of loudness is shown to increase more rapidly at higher stimulus levels than in listeners with normal hearing, compression amplification that is level dependent would be recommended. For listeners with sloping configurations of hearing loss, both level- and frequency-dependent compression characteristics...
have been suggested as more appropriate than conventional linear amplification (Hellman, 1999). This could be particularly relevant as young listeners with permanent childhood hearing loss are considered for the wide array of new amplification technologies that are increasingly being fit to adults with acquired sensorineural hearing loss.

CONCLUSIONS

As the loudness growth function for sensorineural hearing loss varies according to the degree of hearing loss, individual assessment of loudness growth appears important. The CMM method was found to be a valid and reliable technique to assess loudness growth in children with sensorineural hearing loss as young as 6 years of age. It appears that the task could be incorporated fairly easily into clinical practice. The method holds promise as a valuable addition to hearing aid selection and evaluation procedures, providing a means to further individualize prescriptive amplification strategies—clearly, the primary procedure for fitting the output of hearing aids to the pediatric population.

In subsequent investigations, we intend to examine larger numbers of children with and without hearing loss in order to understand better the variability associated with the CMM procedure, as well as the age limit at which the technique is applicable. Given that the language demands are minimal and that the task is enjoyable, it is likely that young (between the 3- to 5-year age range) children with sensorineural hearing loss can successfully perform the CMM task. It will also be important in our future studies to compare the growth of loudness in children and adults with similar audiograms to further elucidate any differences in the perception of loudness that may exist between the groups. Equally important clinically is the need to address the effects of degree and configuration of hearing loss, duration of amplification experience, and maturation on children’s perception of loudness.

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