Chapter Six

Growth of Loudness Assessment in Children Using Cross-Modality Matching (CMM)

Yula C. Serpanos and Judith S. Gravel

Introduction

Loudness judgments play an important role in the selection and fitting of the electroacoustic characteristics of hearing aids such as the maximum output or the compression ratio (Fabry and Schum 1994). To aid in this process, subjective judgments of loudness are often obtained to define regions of comfort or discomfort (i.e., most comfortable loudness level [MCL]; loudness discomfort level [LDL]). This procedure is frequently used in the clinical setting. Another method is to obtain loudness judgments over a range of stimulus levels, providing information on how the listener perceives the growth of loudness. The plotted values of stimulus level by loudness magnitude are referred to as loudness growth functions.

The recent popularity of non-linear hearing aid circuits as found in digital or wide-dynamic range compression (WDRC) instruments has necessitated new fitting strategies that could incorporate information about loudness over the range of intensities modified by the amplification circuitry (Kruger and Kruger 1994). A common approach to the fitting of non-linear circuits involves the concept of normalization of loudness growth, where hearing aid characteristics would be adjusted for the individual listener with hearing loss in order to normalize his/her perception of loudness (Dillon 2001). For example, insertion gain would be calculated for each input level by the amount needed to restore normal loudness for the individual hearing aid user.

Address correspondence to: Yula C. Serpanos, Ph.D., Associate Professor/Chair, Department of Communication Sciences and Disorders, Adelphi University, Hy Weinberg Center, Cambridge Avenue, Garden City, NY 11530, USA

Methods of Loudness Scaling

There are several psychoacoustic methods for a listener to scale the perceived magnitude of loudness at discrete stimulus levels. These include magnitude estimation, magnitude production, categorical scaling and cross-modality matching (Stevens 1975). In the procedure of magnitude estimation, the listener uses numbers to scale perceived loudness magnitude. Magnitude production is the inverse of the estimation method, in which the listener produces a loudness level to match the magnitude of a given number, usually by adjusting the stimulus attenuator. The method of categorical scaling incorporates a bounded range of number (e.g., 1–100), word (e.g., soft–loud) or picture (e.g., happy face–sad face) categories to which a listener matches loudness magnitude. Cross-modality matching (CMM) involves the substitution of another sensory modality, such as vision, to judge loudness magnitude.

Currently with adult listeners, categorical scaling is the most popular clinical method of loudness growth assessment for the purpose of individually modifying a hearing aid's electroacoustic characteristics (Dillon 2001). The individual is instructed to choose one item from a restricted range of items to match the perception of loudness. While word descriptors are used in several current clinical fitting paradigms (e.g., Contour Test [Cox, Alexander, Taylor and Gray 1997]; Loudness Growth in ½ Octave Bands [LGOB; Allen, Hall and Jeng 1990]), number and picture categories have also been used by clinical researchers (e.g., Geller and Margolis 1984; Ellis and Wynne 1999).

These methods of categorical scaling for assessing loudness growth, however, have limitations when used with a pediatric population. For example, the use of a continuum of numbers to reflect stimulus magnitude is difficult for children younger than eight years of age (Teghtsoonian 1980; Zwislocki and Goodman 1980). In addition, word descriptors may be problematic for very young children, or those with limited language abilities. Even pictoral representations of word descriptors may not improve the task. A recent study that used line drawings of faces with various expressions representing the word descriptors for loudness used in the LGOB task showed poor reliability in children with normal hearing, 7 to 12 years of age (Ellis and Wynne 1999).

Certainly, for very young children (perhaps younger than 4 years of age) clinicians will initially need to rely on prescriptive methods (e.g. Desired Sensation Level [DSL; Seewald 1992]) that use hearing thresholds to estimate maximum output targets rather than relying on subjective loudness judgments. However, when the child is capable, individual assessment of loudness growth may be useful in individually tailoring hearing aid characteristics to the child's own perception of loudness. Therefore, a clinically efficient, reliable and valid procedure for assessing loudness growth could have a useful place in the hearing aid selection and fitting process used with young children.

CMM Between Line Length and Loudness: Studies with Children

Recently, the cross-modality matching (CMM) procedure that employs matches between the visual of line length and auditory percept of loudness has shown promise as a reliable, valid method of loudness growth assessment in adults with normal or impaired hearing (Hellman and Meiselman 1988, 1990, 1993; Hellman 1999). There is also some evidence that the CMM procedure may be used with children with normal hearing (Teghtsoonian 1980; Collins and Gescheider 1989). Results from the studies with children suggest that children as young as 4 years of age are able to provide reliable matches of auditory loudness to visual length, similar to adults.

Serpanos and Gravel (2000) used a modified CMM procedure to study loudness growth in a pediatric population of 16 children, 4–12 years of age, with normal hearing or sensorineural hearing loss. The visual stimuli were eight line lengths ranging from 0.52 to 65 cm (a ratio of 125:1), in accordance with those utilized in prior CMM studies (e.g. Hellman and Meiselman 1988, 1990, 1993). In order to make the visual stimuli more appealing to a pediatric population, a graphic (a circular smiling face), was affixed to the left side of each line length (the visual becoming a schematic of a 'caterpillar'). The graphic was identical in size and location on each line length, so that the only variable of change in the visual stimulus was length. A graphic depicting one of each of the eight line lengths was placed onto a separate 21.5 cm x 28 cm card.

The acoustic stimuli were narrow bands of noise centered at 500 Hz and 2000 Hz, generated by a clinical audiometer and presented monaurally via an EAR-3A foam tip to the designated test ear. Each signal was randomly presented at one of eight levels. The stimulus level ranged in 10 dB increments from 20 to 90 dB HL for the listeners with normal hearing. The levels of signal presentation for the listeners with hearing loss were determined for each participant by dividing the individually-determined audiometric range (between threshold and LDL) by eight (resulting in eight equal dB-intervals).

Loudness growth functions were defined separately for the 500 Hz and 2000 Hz narrow band noise signals. For each of these stimuli, two loudness tasks, length to loudness (task 1) and loudness to length (task 2) were evaluated, yielding separate loudness growth functions for each listener. In the first task, the child was asked to match the length of one of the graphics to equal the perceived loudness of the presented signal. In the second task (the inverse of the first), the child was instructed to adjust the audiometer attenuator in order to make the loudness of the sound subjectively equal to the length of one of the eight graphics presented by the examiner. Both tasks are necessary in order to prevent a response bias termed a *"regression effect"* which may occur if either task is used in isolation (Stevens 1975). A geometric mean was taken of the two loudness functions so that one loudness function was calculated for each stimulus. The geometrically averaged loudness function is considered to most accurately represent the "true" loudness growth function of the individual. Figure 1 depicts hypothetical loudness growth curves for each of the tasks (length to loudness and loudness to length) and an approximation of the derived geometric mean.

The results of the Serpanos and Gravel (2000) study suggested that the modified CMM task was a clinically feasible, reliable and valid method for loudness growth assessment in children with normal or

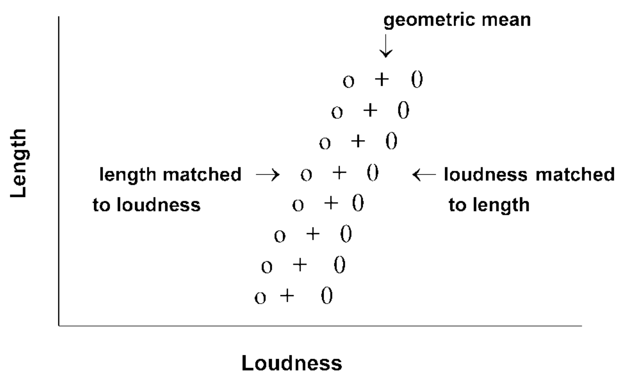

Figure 1. Hypothetical example of the method used to derive the geometric mean of loudness growth.

impaired hearing 4 to 12 years of age. The children seemed to enjoy the task, and the method was easily administered using a standard clinical audiometer and picture cards. The primary disadvantage related to clinical efficiency of the task was that the time to complete the task was lengthy, in that it took 20 minutes to complete one frequency for each ear.

Re-test data were also obtained on a subset of adults and children with normal hearing and sensorineural loss (n = 12) within one month of original testing. Significant correlations ($r = \geq .90$, $p < .01$) were obtained on test-re-test data for both 500 Hz and 2000 Hz stimuli for each group, suggesting that the CMM task is reliable. The validity of the CMM task was also established. The loudness growth functions of children with normal hearing showed no significant differences from those of adults, a finding in good accord with previous research (Teghtsoonian 1980; Collins and Gescheider 1989). In addition, children with sensorineural hearing loss displayed steeper loudness growth functions as compared to their peers with normal hearing, consistent with previous findings on adult listeners with sensorineural hearing loss (Hellman and Meiselman 1988, 1990, 1993).

Variability of Loudness Growth Functions Among Individual Listeners

Though similar mean loudness growth functions are obtained across groups of individuals with normal hearing, there is individual variability among listeners, typically within two standard deviations about the mean function (e.g., Serpanos and Gravel 2000; Serpanos, O'Malley and Gravel 1998). In sensorineural hearing loss, the loudness growth function steepens with increasing (poorer) hearing threshold. Individual variability exists in loudness functions among listeners with identical hearing thresholds. Serpanos and Gravel (2000) for example, noted slope values that varied from 1.48 to 2.21 in four children with identical hearing thresholds (65 dB HL) at 2000 Hz. In addition, loudness growth functions may vary with threshold across different frequency regions within the same individual. The individual variability and steepening loudness growth with threshold elevation suggests that it is important to assess loudness growth individually for listeners with sensorineural hearing loss (Hellman 1999).

Loudness Growth and Real Ear Measures – Implications in Children

Serpanos and Gravel (2000) examined loudness growth judgments for equivalent input stimulus levels in 8 adults and 8 children, 4 to 12 years, with normal hearing. Real ear values for 500 Hz and 2000 Hz narrow band stimuli were 3 to 4 dB SPL higher in children's ear canals than adults. When the loudness growth functions were re-plotted by real-ear sound pressure level, it was noted that at similar magnitude (line length), children with normal hearing perceived discrete stimulus levels as less loud than did adults. However, the slope values of the loudness functions showed no significant differences between adults and children with normal hearing, suggesting that the rate of loudness growth is similar for these individuals.

Loudness growth data at equivalent stimulus levels suggest that the perception of loudness is different between groups of children and adults with normal hearing. That is, children may perceive sounds of similar level as less loud than adults. While further study is necessary in adults and children with similar degrees of sensorineural hearing loss, confirmation of this finding may have significant implications in the hearing aid fitting process of young children. Said differently, it would be valuable to know whether children with congenital or early-onset hearing loss perceive loudness similar to adults with acquired hearing loss of similar degree. If the perception of loudness is different between children and adults with similar degrees of sensorineural hearing losses but vastly different auditory experiences, then this might impact the setting of maximum output levels in hearing aids.

Computer-Controlled CMM: A Current Investigation

Clinical Efficiency

In a current investigation, we are studying the clinical efficiency of the pediatric CMM task when a computer controls the derivation of the loudness growth functions. The purpose of the computer-controlled CMM task is to standardize the derivation of the loudness functions through generation, specification and presentation of test stimuli. In the current study, we are also interested in probing the youngest age (the lower limit) at which the CMM task can be used for estimating loudness growth. In data obtained thus far, twenty children with normal hearing and ranging in age from 3 to 9 years, and six adult listeners with normal hearing have been studied. The acoustic stimuli were computer-generated ½-octave bands of noise centered at 2000 Hz. In the version of the software that has been used to date, levels or stimuli were randomly selected and generated by the computer. The graphic line lengths were presented manually.

Loudness growth functions were constructed by calculating the geometric mean of stimulus level by graphic length. Slope values for each individual intensity function were derived by linear regression analysis (length [y] by stimulus level in dB HL [x]). The mean group slope values and standard deviations (table 1) were similar for adults and children, and were consistent with previous findings (Serpanos and Gravel 2000). Figures 2 and 3 display the loudness growth functions for children 4 to 6 years and 7 to 9 years of age, respectively.

Although not completed, the current computer version of the CMM task was found to be more time efficient than the manual method that was used previously. The task time was reduced over that of the manual version to about 10 minutes per frequency per ear. Given the limited data available thus far, it appears that 4 years may be the lower age limit for success with the CMM task. None of the three participants aged 3 years were able to reliably complete the CMM task. However, the instruction set and procedure may need significant modification for this age

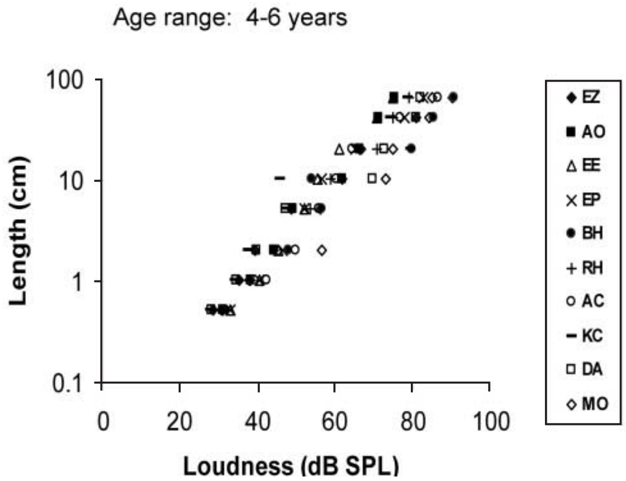

Figure 2. Individual Loudness Functions for ten children in the age group: 4–6 years. The functions are plotted according to Length (cm) and Loudness (dB SPL). See text for explanation of the cross-modality measure.

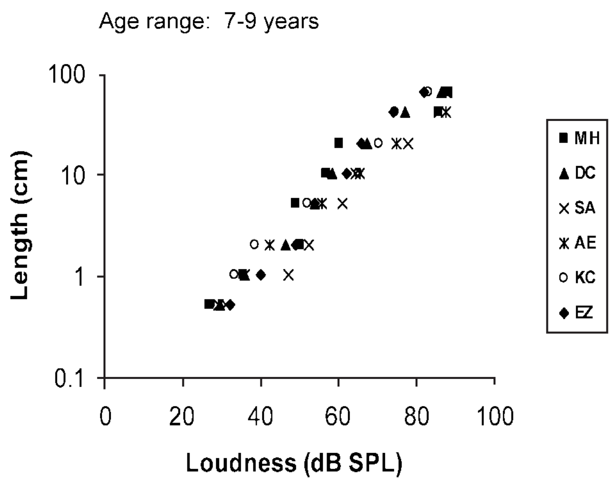

Figure 3. Loudness Functions for six children in the age range of 7–9 years. The functions are plotted according to Length (cm) and Loudness (dB SPL). See text for explanation of the cross-modality measure.

Table 1. Loudness Slopes: Group Averages

4–6 yrs. n = 11	0.80 (SD = .13)
7–9 yrs. n = 6	0.77 (SD = .08)
Adults n = 6	0.77 (SD = .10)

group, and larger numbers of participants in the 3-year age range would be necessary before a definitive conclusion on the lower age limit for reliable use of the CMM can be determined.

Reliability Measures

Reliability has been assessed by test-retest measures within the same session and approximately one week later. Within the same day of testing, the CMM task was repeated three times (with breaks as needed) for children 4 to 9 years (n = 17) and adults (n = 6) with normal hearing. Two-sample t-tests revealed no significant differences when the loudness functions from run 1 were compared to those of run 2 and run 3 (table 2).

Table 2. Test-retest reliability: within same day of testing

	run 1 vs. 2	run 1 vs. 3
4–6 yrs n = 11	t = 0.35; p = .73	t = –0.36; p = .72
7–9 yrs n = 6	t = –0.08; p = .94	t = 0.09; p = .93
Adults n = 6	t = –0.11; p = .91	t = –0.16; p = .87

A subset of the participants were re-tested within one week of testing (children, n = 7; adults, n = 4). Two-sample t-tests revealed no significant differences when the loudness functions from week 1 were compared to week 2 (4–6 yrs: t = –0.15, p = .88, n = 4; 7–9 yrs: t = –0.17, p = .87, n = 3; adults: t = –0.16, p = .87, n = 4). In terms of clinical importance, the geometric means of loudness were within 5 to 10 dB from week 1 to week 2 across all points of the loudness function for 10 of the 11 participants (tables 3 and 4). Figure 4 displays a sample of the test-retest data from week 1 to week 2; note that differences for three of the four 4 to 6 year-old participants are within 10 dB.

One 4 year-old subject, KC, showed greater than 10 dB differences between the loudness growth functions obtained on week 1 to week 2 (figure 5; see table 4b). In a retrospective assessment, it was noted that the correlation coefficients measured for each loudness growth function were lower for KC than those measured for the other participants. Specifically, loudness function correlations of 0.85 and 0.78 were measured for weeks 1 and 2, respectively, while the correlations for all other participants were greater than 0.90. In addition, a possible behavioral indication of poor reliability was that KC required frequent refocusing to the task. Though further study on the issue of reliability is necessary, it is possible that the

Table 3. Loudness function dB SPL differences for week 1 vs. week 2: Adults.

RC	WL	CG	ME	Mean dB Difference
0	0	1	0	0
0	0	2	2	1
–4	–4	–2	–8	–5
7	7	2	–6	3
5	5	1	–6	1
–1	–1	6	–9	–1
6	6	2	–6	2
6	6	–9	–3	0

Table 4. Loudness function dB SPL differences for week 1 vs. week 2:

a. 7–9 yrs

MH	DC	KC	Mean dB Difference
2	0	–4	–1
2	0	–5	–1
5	1	–6	0
4	3	–7	0
0	–4	5	0
-2	1	–4	–1
4	–2	–5	–1
5	–5	–9	–3

b. *4–6 yrs*

EZ	RH	AC	KC	Mean dB Difference
0	–2	–1	1	–1
0	–2	3	–5	–1
–2	–2	3	–1	–1
0	4	4	4	3
–5	–3	0	–8	–4
–5	0	–1	21*	4
1	–1	4	–12*	–2
–3	–2	2	–12*	–4

* dB difference exceeds 10 dB

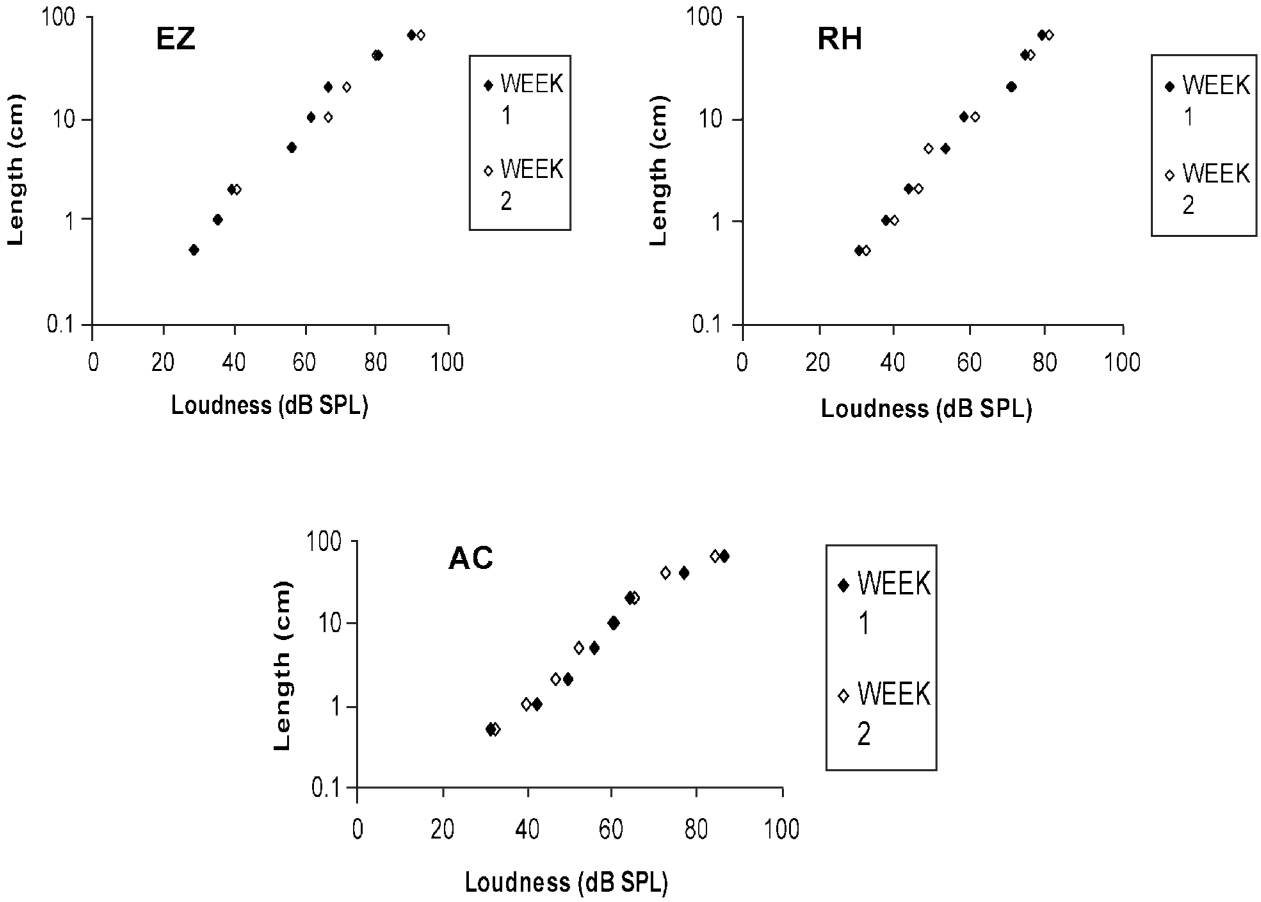

Figure 4. Week 1 to Week 2 Re-test data for three individual children with normal hearing in the 4–6 year age range.

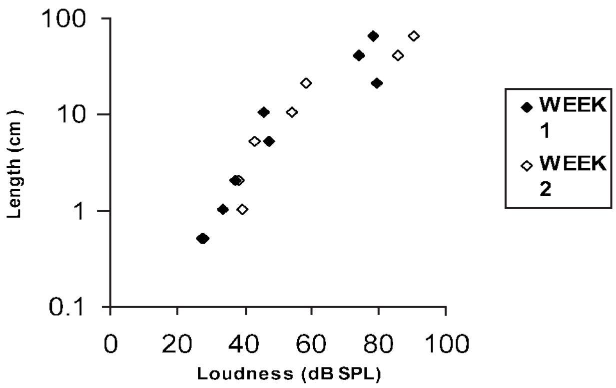

Figure 5. Individual loudness growth functions displayed for one participant in Week 1 to Week 2. Re-test data: KC 4 yrs.

correlation coefficient may be the index of reliability for the CMM task.

Summary and Conclusions

Loudness growth measures are used in current adult hearing aid fitting paradigms, however, clinically reliable methods of loudness growth are not currently available for use in young children. While many hearing aid fitting paradigms estimate loudness perception, the individual variability that exists among behavioral assessments of loudness within similar hearing range suggests that loudness should be measured directly when possible.

Serpanos and Gravel (2000) suggested that a pediatric modification of a cross-modality matching task using matches of line length (modified with a graphic) to loudness could be used as a clinical method for loudness growth assessment in children.

A recent study on loudness growth measures using a computer version of cross-modality matching between loudness and line length (Serpanos and Gravel, current investigation) thus far, suggests that the CMM task appears to be a valid and reliable method for assessing loudness growth in children as young as age 4 years. While none of the 3-year old participants in the current investigation were able to complete the task, modification of the test procedure as it is currently used with children was not attempted. Our current work includes changes in the instructional set (see Appendix A and B) and procedures so that the feasibility of completing an individual loudness growth assessment can be adequately addressed in pre-school children and the lowest age for which the CMM task is feasible can be determined. It will be necessary to examine 3-year olds as a group and then examine specific age in months and language age to determine whether these variables may contribute to a successful outcome. In addition, an important consideration of loudness growth assessment is to determine an index of reliability during the procedure so that the audiologist could determine whether or not the information obtained within a test session represented a reasonable estimate of the child's actual perception of loudness. Our studies of the CMM procedure thus far suggests that an index of reliability may be the correlation coefficient of loudness growth functions which can be readily determined when using computer software specifically developed for CMM assessment.

Our studies on CMM will also examine optimal test signals for use in hearing aid prescriptive procedures. Given that young children have a limited attention span, it would be useful to derive loudness growth estimates at the most useful frequencies for comfort and use of the hearing aid. Finally, many more children with normal hearing and sensorineural hearing loss need to be evaluated, so that the database on the perception of loudness growth is available to clinicians and hearing scientists alike. Many questions regarding the influence of auditory deprivation and early experience with amplified sound remain to be addressed. Ultimately, even if the determination of individual estimates of loudness growth were demonstrated to be useful for individualizing the fitting of amplification, the practical feasibility and efficiency of the CMM procedure in the clinical setting may determine its role in the hearing aid fitting process.

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Appendix

Instructions for Task 1: Length to Loudness

"You are going to hear some sounds that will be big and small.
My friend Katy the caterpillar likes to copy the sounds.
When the sound is big, Katy makes herself big.
When the sound is small, Katy makes herself small.
Sometimes she will be in the middle.
When you hear the sound, point to one of the pictures and show me what Katy looks like.
You can use any of the pictures.
Let's start."

Instructions for Task 2: Loudness to Length

"Now I will show you a picture of Katy the caterpillar.
You make the sound as big when Katy is big.
Make the sound small when Katy is small.
I'll help you do it. See . . .
In some pictures Katy is big.
In some pictures, Katy is small.
Sometimes Katy is in the middle.
See how that works?
Now you do it.
Let's start."

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