Electrophysiological Correlates of Loudness using Auditory Steady State Responses

Prathibha K.K.[1] & Rajalakshmi K.[2]

Abstract

The present study investigated the usefulness of Auditory Steady State Response (ASSR) in predicting the loudness growth function in normal hearing children. Objective loudness growth function can be used as a supplementary measure in hearing aid fitting especially in the pediatric populations who have difficulty in reporting such measures of loudness growth. To assess the same, the amplitude intensity function of the multiple steady state response (77 Hz-105 Hz) was compared with two standardized subjective loudness growth procedures: the Cross Modality Matching (CMM) and the Cox contour loudness test in twenty normal hearing children at 500 Hz, 1 kHz, 2 kHz and 4 kHz. Results showed that the two standardized methods were able to adequately predict the loudness growth function and had similar exponents of 0.49 and 0.43. No significant difference in the perception of loudness across the frequencies was noticed using the subjective loudness procedures. In ASSR recordings, the amplitude measures were highly variable. On fitting a non linear power function to the amplitude measure and the perceived loudness measure obtained from the two subjective loudness growth tests separately, a overall modest correlation was observed at all frequencies. Correlation coefficients between ASSR amplitude growth and Cross Modality Matching were, r = 0.35, 0.58, 0.35 and 0.54 at 500 Hz, 1 kHz, 2 kHz and 4 kHz respectively. Similarly, with the Cox contour test, correlation coefficient were, r = 0.37, 0.58, 0.30 and 0.29 at 500 Hz, 1 kHz, 2 kHz and 4 kHz respectively. Additionally, exponents obtained from each frequency were not similar. The ASSR amplitude growth in the present study only proved to be a modest predictor of the loudness growth function. Variability in the ASSR amplitude, structures involved in both the tasks, for example ASSR being generated from brain stem as opposed to the whole auditory system being involved in both subjective loudness tests, probably could lead to a relatively modest correlation. Also, different parameters used in assessing these two tests should be taken into consideration. The findings of the present study suggest that ASSR should be used with caution in predicting the loudness growth function and such a relationship of the ASSR and loudness growth function in the hearing impaired population must be established before using the tool for clinical purposes.

Key words: *Loudness, ASSR, modality matching.*

Loudness corresponds to the subjective impression of the magnitude of a sound (Moore, 2007). It is defined by ANSI, 1994 as that attribute of auditory sensation in terms of which sounds can be ordered on a scale extending from quiet to loud. Because of its subjective nature, it is very difficult to measure loudness in a quantitative way.

As restoration of the normal loudness growth functions is the goal of hearing aid fitting (Hellman, 1999) incorporating an objective measurement of loudness in the process of hearing aid fitting can be very advantageous. Though a number of subjective tests can be used, asking children with congenital hearing loss, who often have limited language abilities and no or little amplified sound to judge stimuli as 'most comfortable" or "uncomfortable for long term listening" can be problematic. Results can be misleading in such tests, and hence in such cases an electrophysiological measure of loudness growth could assist audiologists in estimating discomfort levels (Thornton, Farrell, & McSporran 1989; Zenker Fernandez, & Barajas, 2005) and in the determination of hearing-aid features (Zenker, de Prat, & Zabala, 2008). Objective loudness growth functions in adults using the ASSR have been measured (Zenker, de Prat, & Zabala, 2008, Menard, Vachon, Collet, & Thai-Van, 2008) and it has shown to predict the loudness growth function accurately. However, there is a dearth of literature where such studies with the children are considered who are more difficult to test using a behavioural measure. Thus the present study was taken up to measure the loudness growth function in children objectively using ASSR. Also, it is important to study how the growth of loudness predicted through ASSR amplitude growth actually relates to the growth of loudness predicted using subjective tests. An objective response needs to be validated with subjective responses in controlled conditions before being used for clinical purposes with confidence. Hence in the present study, attempts have been made to study the correlation between the loudness growth function predicted with ASSR and with that of two subjective loudness growth measures, the Cross Modality Matching (CMM) and the Cox contour loudness test.

[1] e-mail: prathibasingh@gmail.com, [2] Reader in Audiology, AIISH; email: veenasrijaya@gmail.com.

Method

Participants: Twenty children, with normal hearing as assessed through audiological tests participated in the study. Equal number of males and females in the age range of 8 – 12 years, with a mean age of 10 years 10 months were considered.

Procedure: The data were collected in two phases. **Phase I** included establishing behavioral loudness growth function using two behavioural measures; Cross modality matching (CMM) & Cox contour loudness test. The order of these tests was varied randomly across subjects to avoid any order effects. **Phase II** included establishing objective loudness growth function using ASSR.

Phase 1: Establishing behavioural loudness growth function using two behavioural measures.

Cross modality matching

Acoustic stimuli: Pure tones of frequencies 500 Hz, 1 kHz, 2 kHz, and 4 kHz were used as the acoustic test stimuli. The duration of each of the stimulus presentation was controlled manually.

Visual Stimuli: Eight separate equal sized cards each depicting a single graphic of varying length served as the visual stimuli. The graphic depiction of line length (with a face of a smiling caterpillar affixed to the end of the line) was made cartoon-like and intended to be fun and attractive 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 in accord with the line lengths used in earlier CMM studies like those of Hellman, 1999. Identical width of each line and size of the affixed graphic (the "face" of the caterpillar) was maintained for all the eight visual stimuli.

Procedure: The acoustic stimuli were presented monaurally to the test ear (right ear) of the participant through TDH 39 headphones. Measurement of threshold of loudness discomfort for each frequency was taken so as to prevent the use of stimulus levels that would be intolerably loud for the participant. On report of discomfort from the participant, tolerance for the next lowest stimulus level was assessed. The technique for each task was demonstrated and informally assessed with each child in order to ensure familiarity with the procedure prior to testing. Children were offered breaks if needed and tangible reinforcements were given at the end of the session.

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

CMM: Length to Loudness: For this task, each participant was required to assign the length of one of the graphics to represent the perceived loudness for the stimulus presented. The eight graphic cards were arranged in ascending length order. The listener was taught by verbal instruction or demonstration to touch the graphic that was as long as the sound is loud. Stimulus levels ranged from 20 to 90 dB HL and were presented in 10 dB increments. Two separate trials were presented, in ascending and decreasing order.

CMM: Loudness to Length: For this CMM task, the stimulus was adjusted to be as loud as the participant perceived the graphic length. The participants were 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. Care was taken to see that the participant was unable to see the numeric values of the attenuator display as this would have led to biased results. The attenuator step size was set to 5 dB and a range of adjustment between -10 and 110 dB HL was permitted. The graphic cards were presented in a randomized order to the participants and the matched stimulus level was recorded for every visual stimuli. To obtain the loudness growth function the geometric mean of the two above mentioned tasks were taken.

Cox contour loudness test

The contour test was also employed in this study in order to obtain loudness growth functions. The stimuli were presented through TDH 39 headphones. The tonal stimuli used were 5% warble tones presented at four frequencies, 500 Hz, 1 kHz, 2 kHz, and 4 kHz. The order of frequency presentation was randomized. The stimuli sequencing was ascending and descending in 10 dB steps. Subjects were instructed to provide a verbal judgment of the loudness perceived for every stimulus they heard according to seven categories ranging from very soft to uncomfortably loud.

1 – Very soft

2 – Soft
3 – Comfortable but slightly soft
4 – Comfortable
5 – Comfortable but slightly loud
6 – Loud but okay
7 – Uncomfortably loud.

A run began with a stimulus delivered at 20 dBHL, continued in an ascending fashion with the subject providing a loudness category for each stimulus. Similarly a descending run began with the stimulus being delivered at 90 dBHL and the subject providing a loudness category for each stimulus level. The run terminated when a judgment of uncomfortably loud was given.

If the uncomfortable level was reached before 90 dBHL, the descending trial started with that particular level. Each stimulus was tested using four consecutive runs. After the test, the value for each loudness category was computed as the mean level of responses (in dBHL) obtained from the four runs.

Phase II- Establishing objective loudness growth function using Auditory Steady State potentials. The participants were made to sit comfortably on a reclining chair. They were instructed to relax, close the eyes and sleep if possible, or they were given a choice to watch a cartoon of their favorite choice with sub titles. The audio was muted thereby avoiding any auditory interruption while recording the ASSR.

The site of electrode placement was prepared with skin preparing paste. Disc type silver coated electrodes were placed with conduction gel. The non-inverting electrode (+) was placed on high forehead (Fz), ground electrode was placed on non-test ear mastoid and the inverting electrode (-) was placed on the mastoid of the test ear.It was ensured that for all the electrodes impedance was less than 5 kΩ and inter-electrode impedance was less than 2 kΩ. The ASSRs were recorded using the protocol given in the Table 1.

To predict the loudness growth function through ASSR, the testing was initiated at the 80 dBHL which was below the uncomfortable level reported by all the participants, and the intensity level was decreased by 10 dB for subsequent measures until 40 dBHL.

The instrument determined the presence of responses based on "F-ratio" and the amplitude of the response was automatically calculated and displayed. The amplitude values displayed in microvolt were noted across all the intensity levels and across the frequencies tested.
Appropriate sized insert ear tip was used to place the insert earphone of the IHS system into the ear canal to deliver the stimuli. Before the recording could begin the electroencephalographic (EEG) recording was checked for. Recording was not initiated until a stable EEG recording was obtained. In cases where there was high variability with the EEG recordings the participant was instructed to relax and changing the position of the participant to a more relaxed position was done until a stable EEG recording was obtained.

Analysis of the Response: The ASSR gives an automatic detection of response based on the f-statistic technique. The analysis of the response is simultaneously depicted during the process of recording. The following was monitored during the process of recording to look for the responses.

Table 1. Test protocol for ASSR measurement

Test set	Setting
Transducer Type of stimulus Amplitude modulation Frequency modulation	ER 3 A inert receivers Mixed modulation stimuli 100 % 10 %
Stimulus presentation	Multi frequency, monaural
Carrier frequencies	500, 1000, 2000 and 4000 Hz
Modulation frequencies	79 Hz for 500 Hz, 87 Hz for 1 kHz, 95 for 2 kHz and 103 Hz for 4 kHz
Intensity	Varied from 80 to 40 dBHL in 10 dB steps.
Band pass filter	30 – 300 Hz
Amplification gain	100%

1. The analysis window was monitored during the process of testing. Figure 1 is a representation of the analysis window obtained for a 60 dB stimulus from a single participant.

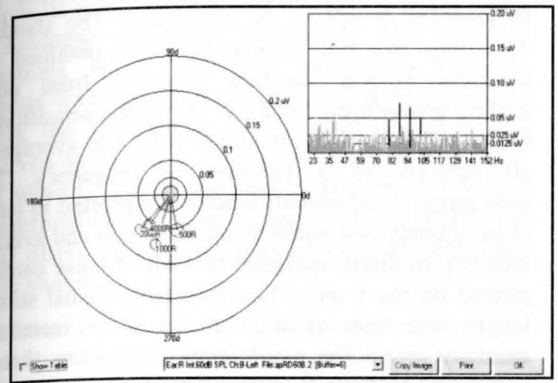

Figure 1. Representative sample from a single participant of the analysis window seen during the recording of ASSR for a 60 dB stimuli.

2. From the above figure it is seen that the response amplitude is depicted both graphically and pictorially. On the top graph the x axis depicts the modulation frequency in Hz and the y axis is the amplitude in micro volts. The red lines at specific modulation frequencies signify the amplitude of the responses from the right ear. The tips of these vertical lines are highlighted in green color indicating the presence of a response. The yellow lines depict the energy level at the side bins and the grey lines are the representation of the noise floor. The vector length in the pictorial representation also indicates the amplitude of the Electroencephalogram (EEG) sample in μV.
3. A tabular representation of the data values is also displayed.
4. Once a response was indicated across all the frequencies and it had stable amplitude for the next consecutive two to three runs the test was terminated. Thus a maximum of 500 samples and a minimum of 250 samples were taken on an average.
5. Thus the test duration was dependent on the number of samples required for obtaining a "yes" response.
6. From the ASSR display, the amplitude of the response was noted at all the tested levels. Later, the intensity-amplitude function was plotted at each frequency for each participant.
7. The obtained data was subjected to appropriate statistical analysis using SPSS (version 17).
8. The analysis window was monitored during the process of testing. Figure 1 is a representation of the analysis window obtained for a 60 dB stimulus from a single participant.

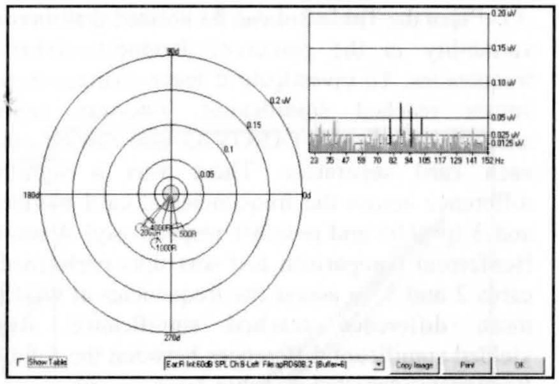

Figure 1. Representative sample from a single participant of the analysis window seen during the recording of ASSR for a 60 dB stimuli.

9. From the above figure it is seen that the response amplitude is depicted both graphically and pictorially. On the top graph the x axis depicts the modulation frequency in Hz and the y axis is the amplitude in micro volts. The red lines at specific modulation frequencies signify the amplitude of the responses from the right ear. The tips of these vertical lines are highlighted in green color indicating the presence of a response. The yellow lines depict the energy level at the side bins and the grey lines are the representation of the noise floor. The vector length in the pictorial representation also indicates the amplitude of the Electroencephalogram (EEG) sample in μV.
10. A tabular representation of the data values is also displayed.
11. Once a response was indicated across all the frequencies and it had stable amplitude for the next consecutive two to three runs the test was terminated. Thus a maximum of 500 samples and a minimum of 250 samples were taken on an average.
12. Thus the test duration was dependent on the number of samples required for obtaining a "yes" response.
13. From the ASSR display, the amplitude of the response was noted at all the tested levels. Later, the intensity-amplitude function was plotted at each frequency for each participant.
14. The obtained data was subjected to appropriate statistical analysis using SPSS (version 17).

Results

Cross Modality Matching: Table 2 provides data of the mean and standard deviations in dBHL of the perceived loudness assigned to varying visual stimuli length. As expected with an increase in the length of the visual stimuli i.e. with increase in the card numbers there is an increase in the perceived loudness across all the frequencies.

From the Table 2 it can be noticed that there was variability in the perceived loudness across the frequencies. To investigate if these changes in mean values reached significance, one-way repeated analysis of variance (ANOVA) was carried out for each card separately. There was a significant difference across the frequencies at card numbers 2 and 3 ($p<0.05$ and $p<0.001$ respectively) A multiple Bonferroni comparison test was thus performed for cards 2 and 3, to assess the frequencies at which the mean difference reached significance. Results yielded significant differences between the following frequencies depicted in Table 3.

These differences were not expected in the data as majority of the data showed no significant differences across the frequencies. Thus these variations are attributed to chance factor which may have occurred due to the high inter subject variability seen in the CMM tasks.

The analysis of data from the present study differed from others studies which investigated cross modality matching such as Hellman and Meiselman (1988), Serpanos and Gravel (2000). In the present study mean intensity values required for each visual length is reported and a power estimate for all the frequencies combined is obtained.

Correlation coefficients of a power function fit to the data for perceived length across all the frequencies is 0.93.This value is in accordance with other investigators who obtained measurements of perceived length in normal hearing such as Collins and Gescheider(1989); Zwisloki and Goodman, 1980. There was no particular trend in the distribution of the standard deviation across the frequencies or across the intensities. The standard deviations are but similar to those obtained for loudness growth function obtained from other scaling procedures. Figure 2 shows the sensation of loudness perception calculated from the average of all subjects as a function of frequency. The increasing visual stimuli lengths are plotted in terms of increasing card numbers on the x axis and average intensity in dBHL assigned to each of these cards is plotted on the y axis. The increasing visual stimuli length was appropriately matched to increasing intensity level. The overlapping lines show that no significant differences were found across the four frequencies at various cards.

As it is seen from the previous results, that there is no significant difference across frequencies in the loudness estimation; the data of all the frequencies was combined. The combined data of the card length and intensity showed a non linear relationship. To predict the loudness from the intensity, regression curve was fitted. Among the non linear curves, the power function showed the best fit giving an r^2 value of 0.87 and a standard error of 0.13. The fitted power equation function is shown below in figure 3.

Table 2. Mean and standard deviations of perceived loudness across frequencies for varying length of visual stimuli

Card No (length of visual stimuli in cm)	**Mean in dBHL (SD)**			
	500 Hz	**1 kHz**	**2 kHz**	**4kHz**
1 (0.52)	33.10 (3.65)	32.52 (5.37)	33.31 (5.64)	32.91 (3.42)
2 (1.04)	45.40 (6.62)	45.65 (7.69)	47.43 (8.30)	49.35 (4.81)
3 (2.08)	54.49 (6.06)	52.86 (7.57)	59.58 (10.05)	59.19 (6.12)
4 (5.20)	61.99 (7.10)	62.75 (6.92)	66.10 (7.33)	65.61 (6.91)
5 (10.40)	69.39 (6.41)	70.32 (7.19)	72.64 (8.30)	72.77 (6.97)
6 (20.80)	76.26 (7.11)	74.13 (5.77)	78.84 (5.30)	78.86 (4.90)
7 (41.60)	85.33 (6.34)	82.21 (9.37)	86.74 (5.36)	84.92 (7.26)
8 (65.00)	91.58 (4.62)	91.58 (4.03)	92.11 (3.42)	91.60 (4.87)

Table 3. Significant differences (Bonferroni multiple paired test) across frequencies at card number 2 and 3

Cards	500 &1 kHz	500 &2 kHz	500 & 4 kHz	1 & 2 kHz	1 & 4 kHz	2 & 4 kHz
2	NS	NS	S *	NS	NS	NS
3	NS	S **	S **	S**	S **	NS

Note: NS – not significant, S – Significantly different. *$p<0.05$, ** $p<0.001$

Cox Contour Loudness Test

Table 4 provides data on the mean intensity level assigned and its standard deviations in dBHL for the seven loudness categories. Within each frequency, the results show the expected increase in mean levels as loudness categories increased. The standard deviations reveal that the variability between-subjects was similar for a given loudness category across the frequencies. A monotic increase was observed as loudness progressed from soft to loud. The subjects judged the sounds as comfortable and uncomfortably loud at an average of 69.52 dBHL and 88.67 dBHL respectively regardless of the frequency of the stimulus.

From the above table it is evident that the intensity assigned to a particular category of loudness varied across frequency. To investigate if these variances lead to significant differences in loudness perception across frequencies a two-way repeated analysis of variance was carried out. ANOVA was carried out by considering within subject factors, loudness categories (7 levels) and frequencies (4 frequencies). Results revealed no significant main effect of frequencies [F (3, 30) = 0.22, p <0.88].However, loudness categories showed significant effect [F (6, 60) = 461.23, (p < 0.01)] as expected. Further there observed no interaction between frequency and loudness category [F (18, 180) = 1.2, p<0.

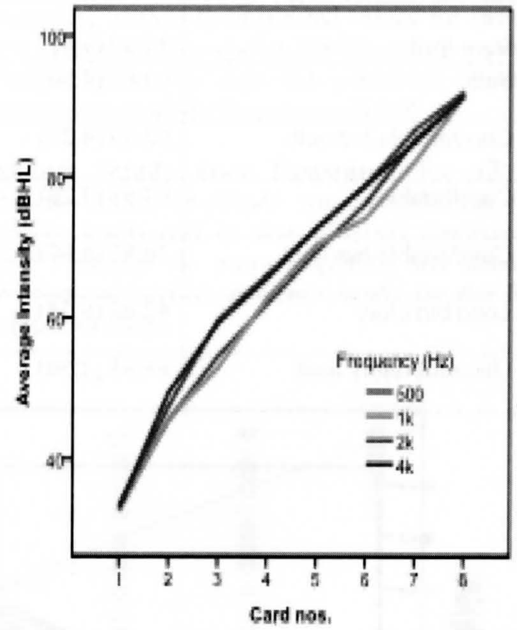

Figure 2. Growth of loudness as a function of intensity using the cross modality matching test.

Figure 3. Loudness growth function obtained with cross modality matching.

Table 4. Mean loudness category level and standard deviation for each stimulus expressed in dBHL

Loudness Categories	MEAN (SD)			
	500 Hz	1 kHz	2kHz	3kHz
Very Soft	37.07 (1.91)	37.77 (2.31)	38.05 (2.67)	37.78 (3.47)
Soft	50.62 (4.80)	51.38 (5.76)	54.28 (4.68)	54.38 (5.96)
Comfortable but soft	62.09 (4.27)	61.39 (7.03)	65.21 (6.08)	63.79 (6.85)
Comfortable	67.58 (7.20)	69.21 (7.37)	71.30 (8.04)	70.00 (7.81)
Comfortable but loud	76.87 (6.07)	76.29 (6.00)	77.59 (7.70)	77.61 (7.66)
Loud but okay	82.08 (6.78)	82.32 (5.90)	84.38 (5.69)	80.57 (7.31)
Uncomfortably loud	88.83 (1.94)	89.12 (1.49)	88.36 (3.05)	88.37 (2.32)

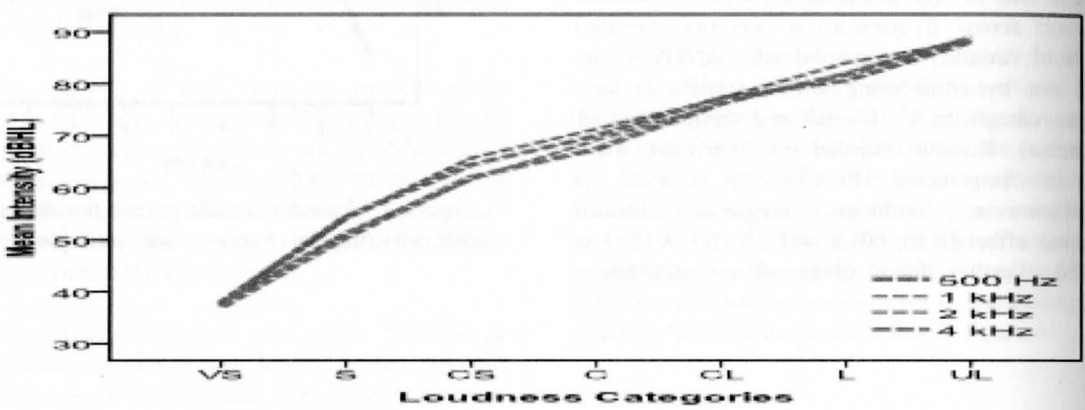

Figure 4. Loudness category scaling as a function of intensity levels of warble tones.

Figure 4 shows the sensation of loudness perception calculated from the average of all subjects for each presentation level as a function of frequency. The x axis depicts the various loudness categories from 'very soft' to 'uncomfortably loud' and the intensity (dBHL) values assigned to the different categories are plotted on the y axis. Within in each stimulus, the results show the expected increase in mean levels as loudness categories increased. Also there is the overlapping of the lines depicting that no significant differences exist across the four different frequencies tested.

As no significant difference was observed across the frequencies in the loudness estimation; the data of all the frequencies was combined. The combined data of the loudness category and intensity showed a non linear relationship. To predict the loudness from the intensity, regression curve was fitted. Among the non linear curves, power function showed the best fit giving an r^2 value of 0.91 and a standard error of 0.09. The fitted power equation function is shown below.

$$Y = 38.17 * X^{0.43}$$

The results of the present study had differences with the normative data reported by Cox in 1997 with respect to the mean intensity level corresponding to different loudness categories, barring the 'comfortable' category. This could be because of the fact that in this study normative was developed in children participants with ages ranging from 8 to 12 years as compared to adult participants in Cox, Alexander, Taylor and Gray (1997). Serpanos and Gravel (2000) have reported that at similar hearing levels (dB HL), actual sound pressure levels were different between adults and children as measured through real ear measures. Another contributing factor to the difference observed could be due to the fact that the interval level used in the present study is 10 dB as whereas an interval level of 5dB was used by Cox (1997). Ricketts and Bentler (1996) attributed these high variances between procedures to the number of spacing categories; type and bandwidth of the stimulus; presentation parameters; and instructions given to the subject. However, comparing normative references across loudness scaling procedures should be done with caution. This is because of the inherent differences amongst the different loudness scaling procedures (Elberling, 1999).

Loudness scaling procedures show great variance even in normal hearing subjects. In the present study, for the comfortable loudness level, a mean of 69.52 dB HL and one standard deviation of 7.61 dB were obtained. Though the standard deviation is considerably high, it is in line with those of other studies such as: Cox et al. (1997) with a standard deviation of 10.5 dB for the comfortable level category; Hohmann & Kollmeier (1995) with a standard deviation of 8.0 dB for the same loudness category; and Elberling & Nielsen (1993) with a 9.0 dB standard deviation. Comparatively a reduced standard deviation may have been obtained in the present study as a result of using both ascending and descending method to obtain the values for each of these categories. Correlation coefficients to a power function fit to the data for perceived loudness category across all the frequencies is 0.95.

Auditory Steady State Responses: For all the subjects, ASSR amplitude was recorded at five intensity levels and at four different frequencies. Table 5 depicts the mean amplitude and standard deviations at various intensity levels for the four frequencies tested.

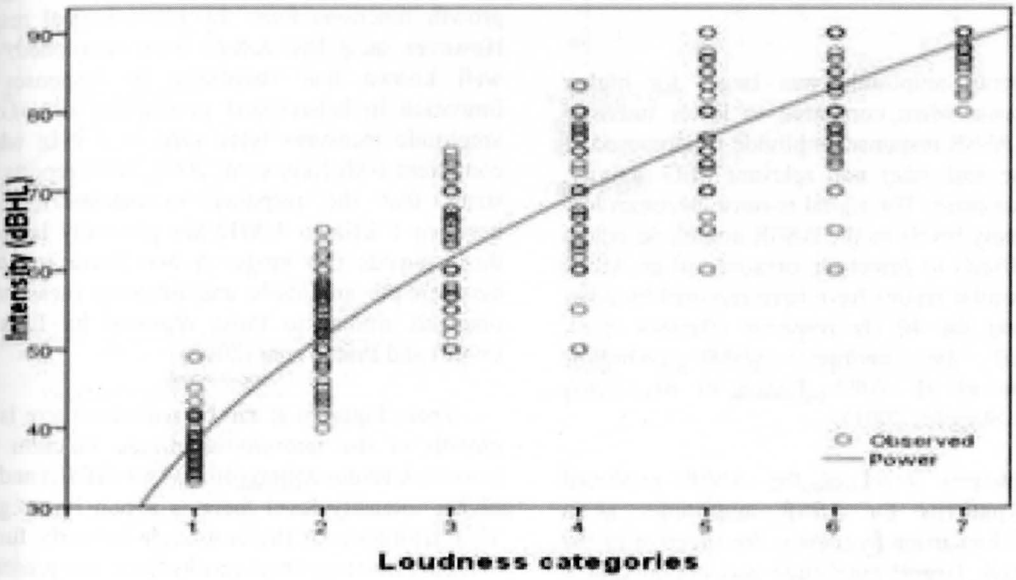

Figure 5. Loudness growth function obtained through cox contour loudness test.

Table 5. Mean Amplitude and standard deviation of ASSR recordings as a function of intensity across frequency

Intensity(dBHL)	Mean amplitude in μV (SD)			
	500Hz	1 kHz	2 kHz	4 kHz
40	0.05 (0.01)	0.06 (0.03)	0.05 (0.01)	0.05 (0.01)
50	0.06 (0.02)	0.08 (0.02)	0.06 (0.02)	0.06 (0.01)
60	0.05 (0.02)	0.08 (0.02)	0.06 (0.02)	0.05 (0.01)
70	0.07 (0.02)	0.10 (0.03)	0.06 (0.02)	0.07 (0.02)
80	0.08 (0.03)	0.10 (0.02)	0.08 (0.02)	0.10 (0.05)

The amplitude measures as a function of intensity shows variation across the frequencies. Also it is notable that at high intensities, the differences between the amplitudes across the frequencies were larger than those obtained at lower intensities. To investigate if these differences in amplitude were statistically significant, Wilcoxon's test was administered. Comparison between the parameters of ASSR amplitude at different intensities across the frequencies was made. Results revealed that there were significant differences between the frequencies at moderate to high intensities (60, 70 and 80 dBHL). Table 4.6 shows the results of Wilcoxon's test depicting the pairs of frequencies in which significant differences was obtained.

In general, amplitude was larger for higher intensity levels when compared to lower intensity levels. The ASSR response amplitude is composed of the response and other non relevant EEG activity, referred to as noise. The signal to noise becomes low at low intensity levels as the ASSR amplitude is less and it is difficult to detect the presence of an ASSR response. Similar results have been reported by other authors using the 40 Hz response (Barajas et al, 1988), and the multiple ASSR technique (Dimitrijevic et al, 2002; Picton et al., 2005; Herdman & Stapells, 2001).

The intensity level of the ASSR produced variegated patterns for ASSR amplitudes as a function of the carrier frequency. Irrespective of the intensity level, largest amplitude was obtained at 1 kHz. Figure. 6 shows the trend of growth in the ASSR amplitude as a function of intensity across the four frequencies tested. The intensity of the stimulus in dBHL is plotted on the x-axis and the amplitude obtained in µv is plotted on the y-axis. There is no overlapping of the lines which depict that there is significant difference between the four different frequencies tested as against the previous two measures.

A great span in the amplitude ranging from 0.03 µV to 0.23 µV irrespective of the intensity levels was noticed in the ASSR recordings for a range of intensities from 40 dB HL to 80 dB HL. The amplitude of the physiological response at a given intensity level also varied significantly between subjects. At the highest intensity the amplitude varied between 0.3 µv to 0.14 µV among the individuals tested. This high variability was greater for the low carrier frequencies than for higher carrier frequencies similar to findings reported by Picton et al, (2005) and Zenker et al (2008). Picton et al (2005) pointed out that this high variability can be justified by the amount of synchronized current in generators, the orientation of these generators in relation to the recording electrode and the impedance of the volume conductor. This high between-subject variability found over the amplitude of the ASSR can be a drawback in the estimation of individual loudness growth functions from the physiological response. However, as it has already been mentioned, and is well known that variability in responses is a limitation in behavioural procedures also. Greatest amplitude measures were seen at 1 kHz which is consistent with John et al, 2000, 2002 reports which states that the response to carrier frequencies between 1 kHz to 3 kHz are generally larger than those outside this range. A non linear relationship between the amplitude and intensity measures was obtained similar to those reported by Lins et al (1995) and Picton et al (2003).

From Figure 6 it can be seen that there is linear growth of the intensity-amplitude function at the lower intensities tested (40 and 50 dBHL) and at the higher intensity level there is a non linear growth. This saturation of the amplitude-intensity functions at higher intensity level results from the presentation of multiple stimuli simultaneously and has also been reported by John et al (1998) with a multiple discrete level procedure, and Picton et al (2007) with a sweep technique. For normal-hearing listeners, the OHCs enhance discrimination in the cochlea at low stimulus intensity. So only the fibers tuned to the characteristic frequencies near the carrier frequency would be activated. At higher stimulus intensities, the spread of activation in the cochlea would be wider, thereby activating more inner hair cells leading to a non linear response.

Table 6. Significant differences for comparison of frequencies across intensities using ASSR

Intensities	1 kHz & 2 kHz	2 k Hz & 500 Hz	4 kHz & 500 Hz	2 kHz & 1 kHz	4 kHz & 1 kHz	4 kHz & 2 kHz
40	0.28	0.66	0.16	0.41	0.16	0.18
50	0.06	1.00	0.79	0.11	0.51	0.79
60	0.01*	0.89	0.58	0.07	0.01*	0.05*
70	0.01*	0.61	0.26	0.00**	0.01*	0.32
80	0.01*	0.31	0.03*	0.01*	0.53	0.20

Note: $*p<0.05$, $** p<0.001$

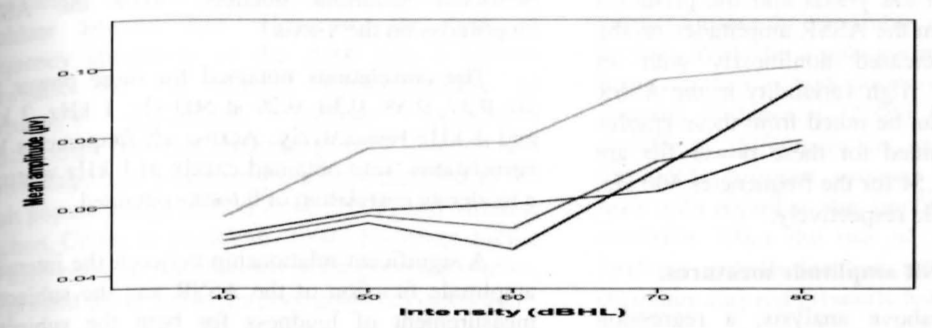

Figure 6. ASSR amplitude as a function of intensity

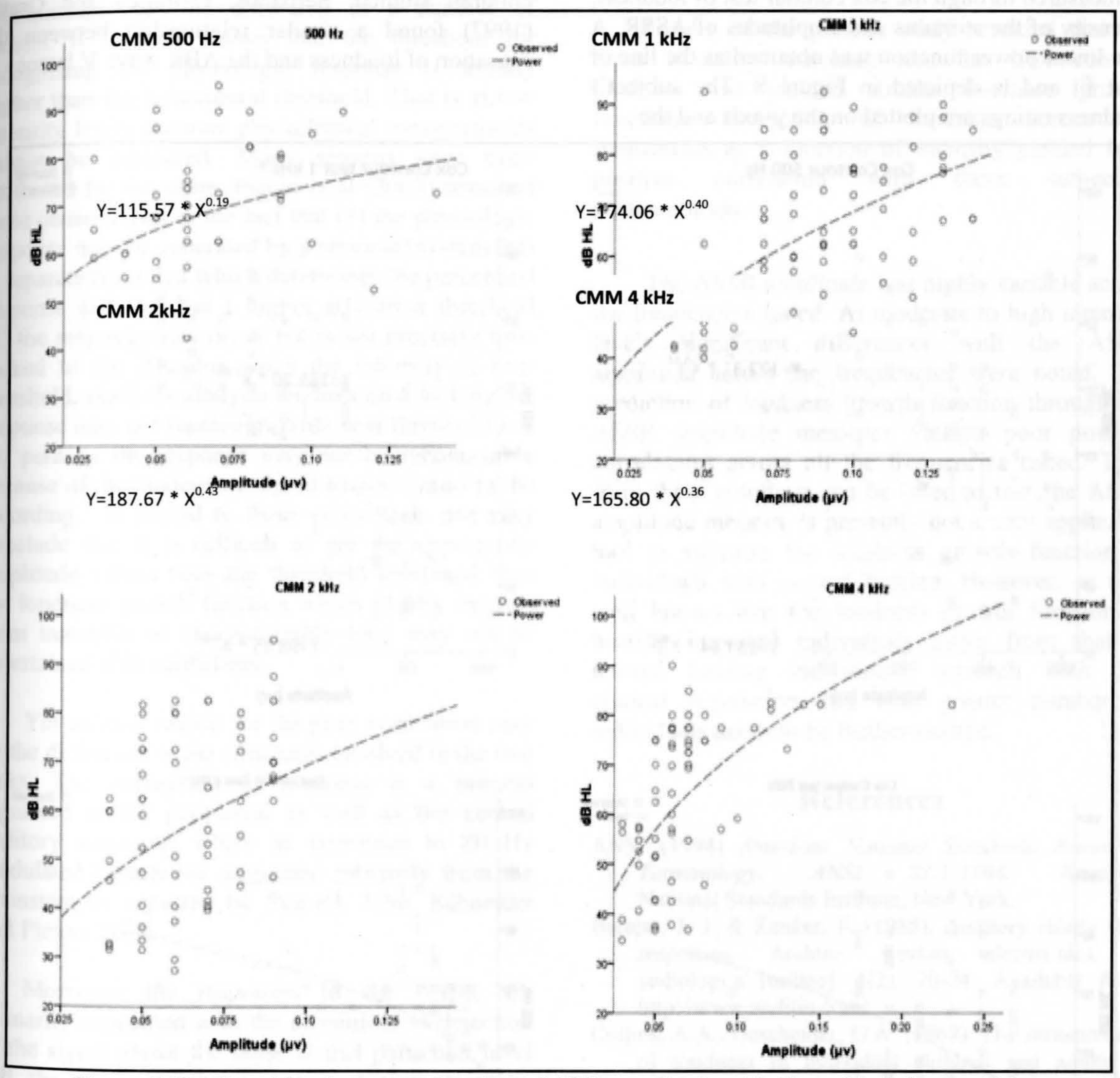

Figure 7. Predicted loudness as a function of ASSR amplitude with Cross Modality matching.

Prediction of loudness through ASSR amplitude measures

Cross Modality Matching and ASSR Amplitude Measures: A regression analysis was performed from the sensation of loudness as obtained from CMM, intensity of the stimulus and amplitudes of ASSR. The prediction of loudness was established by the amplitude obtained physiologically in relation to the modulated tones intensity levels of the ASSR.

As it is well established that the loudness growth function is a non linear function, line of best fit was estimated from the non linear curves available. The non linear power function fitted the best and was thus taken. These lines of best fits for the four frequencies tested are shown in Figure 7. The subject's loudness ratings are plotted on the y-axis and the predicted loudness obtained from the ASSR amplitudes on the x-axis. Loudness increased nonlinearly with an increase in amplitude. High variability in the ASSR amplitude measures can be noted from these graphs. The correlations obtained for these power fits are 0.35, 0.58, 0.35 and 0.54 for the frequencies 500 Hz, 1 kHz, 2 kHz and 4 kHz respectively.

Cox contour and ASSR amplitude measures:

Similar to the above analysis, a regression analysis was obtained from the sensation of loudness as measured through the cox contour test of loudness, intensity of the stimulus and amplitudes of ASSR. A non linear power function was obtained as the line of best fit and is depicted in Figure 8. The subject's loudness ratings are plotted on the y-axis and the predicted loudness obtained from the ASSR amplitudes on the x-axis.

The correlations obtained for these power fits are 0.37, 0.58, 0.30, 0.29 at 500 Hz, 1 kHz, 2 kHz and 4 kHz respectively. Across all frequencies low correlations were obtained except at 1 kHz where in a moderate correlation of 0.6 was obtained.

A significant relationship between the intensity-amplitude function of the ASSR and the subjective measurement of loudness for both the subjective methods was found for the sample of normal-hearing children studied. Serpanos, O'Malley and Gravel (1997) found a similar relationship between the sensation of loudness and the ABR wave V latency

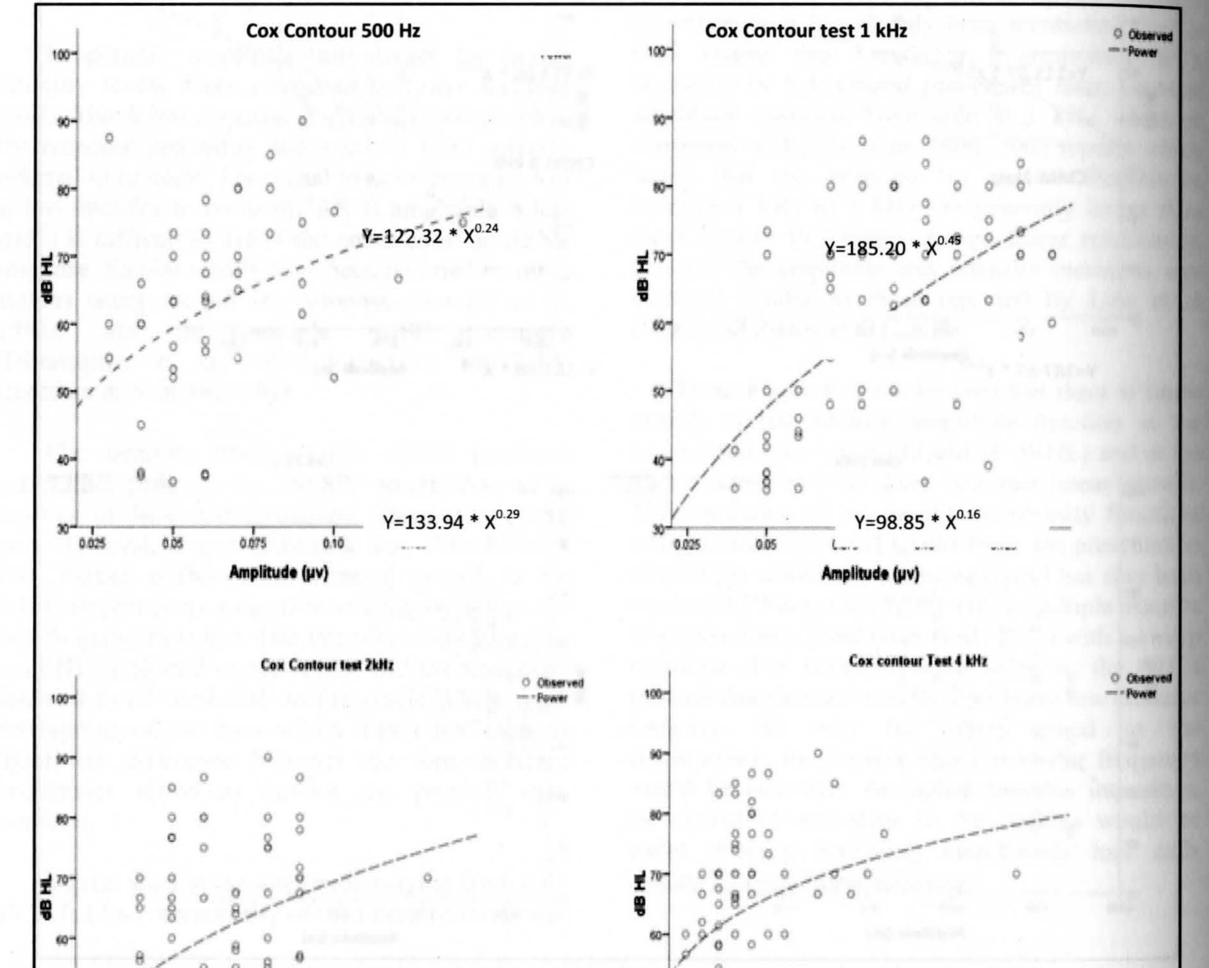

Figure 8. Predicted loudness as a function of ASSR amplitude with the Cox contour test.

for listeners with normal hearing and those with flat cochlear hearing loss. However, the lack in frequency specificity of the ABR was a serious drawback for the clinical implementation of Serpanos's procedure. Similar significant relationships between loudness growth function and ASSR amplitude measures have been reported in the adult population by Zenker et al. (2008) and Menard, Vachon, Collet, & Thai-Van, 2008). However, unlike the high correlations obtained in the previous studies, the present study showed a poor positive correlation.

This poor correlation obtained from these relationships may be attributed to a number of factors. It is well known that the threshold for recognizing the physiologic response is usually higher than the behavioural threshold. That is at low intensity levels accurate physiological measurements cannot be measured. Many reasons have been attributed for the same. Picton et al (2003) reasoned these observations to the fact that (1) the physiologic response may be generated by a neuronal system that is separate from that which determines the perceptual response and that has a higher activation threshold (2) the response may occur but is not precisely time locked to the stimulus when the intensity is near threshold, since the analysis requires time locking the response may not be recognizable near threshold and (3) perhaps the response may not be recognizable because of the inadequate signal-to-noise ratio in the recording. In regard to these entire facts one may conclude that it is difficult to get the appropriate amplitude values near the threshold level and thus the loudness growth function which ideally extends from inaudible to uncomfortably loud may not be ascertained with confidence.

Yet another reason for the poor correlation may be the difference in the structures involved in the two tasks. The perception of loudness is a process regulated at the peripheral as well as the central auditory structures where as responses to 80 Hz modulated signals are originated primarily from the brainstem as reported by Purcell, John, Schneider and Picton, 2004.

Moreover the responses to the ASSR are primarily concerned with the physiological detection of the signal above the noise at that particular level and the phase of the response at that intensity. Though for recording the ASSR in MASTER a F-ratio which is primarily 'an amplitude only' measure is used it has been reported by John and Prucell, (2008) that in reality, both amplitude and phase contribute to the characteristics of the ASSR that is measured, regardless of what measure is relied on to detect the response whereas the perception of the loudness does not take into account these above mentioned factors.

For any measure to be used with confidence to predict a value the variability of that measure should be less. With the amplitude measures of the ASSR however, there is high variability. Though Kaf, Sabo, Durrant, Rubinstein (2006) found no statistically significant differences in mean estimated ASSR thresholds between sessions such complementary tests with regard to the amplitude measures are not available. Thus the use of ASSR for estimating loudness growth function based on the amplitude measures may not presently hold good clinical value.

Conclusions

Results of the present study revealed that the cross modality matching and the Cox contour loudness test yielded similar loudness growth functions. Prediction of loudness across the frequencies as a function of intensity yielded high positive correlation with these subjective measurements.

The ASSR amplitude was highly variable across the frequencies tested. At moderate to high intensity levels significant differences with the ASSR amplitude across the frequencies were noted. The prediction of loudness growth function through the ASSR amplitude measures yielded poor positive correlations across all the frequencies tested. Thus from these results it can be inferred that the ASSR amplitude measure is presently not a very applicable tool to measure the loudness growth function in individuals with normal hearing. However, as it is well known that the loudness growth function of hearing impaired individuals differ from that of normal hearing individuals, research with this clinical population and with greater number of individuals needs to be further studied.

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