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Relationship between Aided Preferred Listening Level and Long-Term Listening Range*

Robyn M. Cox

Memphis State University, Memphis, Tennessee

ABSTRACT

The long-term listening range was defined as extending, at any frequency, from the threshold of audibility to the upper limit of the comfortable loudness range. The relationship between the aided preferred listening level and the long-term listening range was investigated by analyzing data obtained from 16 hearing impaired subjects. Results support a tentative conclusion that the aided preferred listening level is equal to the midpoint of the long-term listening range. Application of this relationship to the specification of frequency/gain function is discussed.

In an earlier article, Cox and Bisset[7] reported an investigation of measurements of the upper limit of the comfortable loudness range (ULCL) for one-third octave noise bands. Their results indicated that: (1) noise band ULCLs occurred at about the same level as corresponding bands of filtered speech, and (2) the repeatability of ULCLs (when measured as in that investigation) was considerably better than repeatability which has been reported for most comfortable loudness (MCL) data.[1,3,9]

It was hypothesized that ULCL data might be suitable for clinical use as a basis for specification of frequency/gain function in hearing aid selection. However, no information was available about the relationship between a subject's measured, unaided ULCLs across the frequency range and the same subject's aided preferred listening levels (PLLs) for normal conversational speech. To provide a format for investigation of this relationship, the range of intensities which are comfortable to hear for an extended period of time (although not necessarily loud enough to understand) was labeled the "long-term listening range." The long-term listening range was defined to extend at each frequency from the listener's threshold of audibility to his ULCL. It was postulated that a hearing impaired individual's aided PLL would be within his long-term listening range.

A study was performed which attempted to define the frequency contour and level within the long-term listening range which the typical hearing impaired person chooses for listening to amplified conversational speech when instructed to adjust the volume for maximum intelligibility consistent with long-term comfort.

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METHOD

Subjects

Sixteen individuals with bilaterally symmetrical sensorineural hearing impairment served as subjects. Ages ranged from 22 to 77, with a mean of 51 years. Nine subjects had moderate hearing loss, six were in the moderately-severe category, and one had a severe loss. Audiogram configurations were: flat, 6 subjects; sloping 5 to 10 dB/octave, 7 subjects; sloping 10 to 20 dB/octave, 3 subjects.

The test ear was chosen randomly. This resulted in six left and ten right ears being used.

Stimuli and Instrumentation

Narrow bands of noise, with half-power bandwidth of approximately one-third octave and a 36 dB/octave rejection rate were used as stimuli. They were generated by a Grason Stadler (model 1701) audiometer and automatically pulsed at a rate of 2 pulses/sec with a 50% duty cycle. Six noise bands were tested. They were centered at: 500, 800, 1000, 1600, 2500, and 4000 Hz.

The stimuli were transduced by a subminiature, button-type, hearing aid receiver (Danavox SMW, 100 ohm) which was connected directly to the audiometer's 10-ohm earphone output (attenuation was linear). The receiver was connected, via a plastic adaptor, to the tubing of the subject's personal earmold. Prior to this connection, the earmold tubing was cut to the appropriate length for use with a postauricular hearing aid.

Calibration of the noise bands was achieved in terms of sound pressure level produced in a standard HA-2 coupler with entrance through 25 mm of tubing (2 mm internal diameter). This testing arrangement has also been described elsewhere.[4,5] It has the advantage that test results are expressed in equivalent HA-2 coupler sound pressure levels and so can be directly compared with hearing aid specifications.

Procedure

Using the SPL-calibrated pulsed noise bands, delivered via the button-type receiver and the client's personal earmold, three basic measures were derived at each frequency on each subject. They were defined as follows: (1) sound pressure hearing level (SPHL), threshold of audibility expressed in SPL instead of in terms of hearing loss; (2) loudness discomfort level (LDL), lowest sound pressure level at which short-term exposure would be "definitely uncomfortable;" (3) upper limit of comfortable loudness (ULCL), highest sound pressure level at which long-term listening would be comfortable.

The order in which measurements were made was designed to parallel an appropriate clinical protocol, proceding from SPHL, to LDL, to ULCL. All six frequencies were completed for any one measure before moving on to the next measure. Testing was begun at 500 Hz and progressed toward higher frequencies. As is customary in clinical practice, early measurements were repeated after all frequencies had been tested to assure acceptable reliability (changes in excess of 5 dB were not accepted; if this occurred, all frequencies were retested until reliable results emerged).

SPHL measurements were made using the Hughson-Westlake psychophysical procedure.[2]

LDL measurements were made using the procedure and instructions described by Cox.[4] Essentially, this procedure paralleled the Hughson-Westlake method. It utilized an ascending approach to the LDL, with 5 dB increments in level, and several pulses presented at each level. The subject was instructed to respond when the stimulus was "definitely uncomfortable, even for brief exposures." After a response, the level was immediately decreased by 10, 15, or 20 dB (chosen randomly) and another ascending run was started. This was repeated as often as necessary to define the LDL. The LDL was defined as the lowest level to which the subject responded on two out of three runs.

ULCL measurements were also made using a method based on the Hughson-Westlake procedure but with the modification that the approach to the ULCL was descending in level. The instructions were as follows:

> The purpose of this test is to find the level of sounds which would be comfortable for you to listen to from a hearing aid for a long period of time, for instance, while you are watching television or listening to the radio.
>
> The sound will be somewhat loud at the beginning and will gradually become softer. When it reaches a point which is comfortable for you, signal immediately by raising your hand.

Each ULCL measurement was begun with four or five pulses presented at a level 5 dB below the LDL at that frequency. The level was then decreased in 5 dB steps with 4 or 5 pulses presented at each level until the subject signaled as instructed above. Following this response, the level was increased by 5, 10, or 15 dB (chosen randomly, but not exceeding the LDL) and another descending run was started. This was repeated as often as necessary to define the ULCL. The ULCL was defined as the highest level to which the subject responded on two out of three runs.

It was postulated that the instructions to the subject, combined with a descending approach to the comfortable loudness range, would elicit responses at the upper limit of this range.

Hearing Aid Preselection

Three hearing aids were preselected for each subject. The only criterion used for preselection was the hearing aid's SSPL90 across the frequency range. Each subject's LDLs were used as the basis for SSPL90 specification as described in Cox.[4] First, 3 dB was added to the LDL at each frequency to derive an estimate of the LDL which would be obtained after repeated testing (a practice effect of about 3 dB is typical). Second, a correction was added to account for the difference in acoustic output impedance between the button-type SMW receiver used for testing and the smaller, internal receivers used in postauricular hearing aids (this necessitated the addition of −2 dB at 1000 Hz and +5 dB at 2500 Hz. At all other test frequencies this correction was 0 dB). The resulting figure (LDL + 3 + receiver correction) at each frequency defined the SSPL90 goal at that frequency.

A pool of nine commercial hearing aids was available: five provided moderate to high SSPL90 (HF av SSPL90 within the range 110 to 130 dB SPL), four provided low to moderate SSPL90 (HF av SSPL90 within the range 90 to 118 dB SPL). Each instrument had an SSPL90 control, a tone control, and a forward facing omnidirectional microphone. From this pool, three hearing aids were preselected and set to approximate the subject's frequency/SSPL90 function as closely as possible. These and all subsequent hearing aid adjustments were verified using a Phonic Ear HC 1000A hearing aid test box.

The SSPL90 was the only performance aspect on which the hearing aids were equated: their frequency/gain functions differed. The low-frequency slope of each hearing aid was described by subtracting the HA-2 coupler gain at 500 Hz from the HA-2 coupler gain at 1000 Hz. The tone controls were set in such a way that different low-frequency slopes were represented in each of the three hearing aids for a given subject. The mean low-frequency slope across all of the hearing aids was 11.7 dB with a S.D. of 5.5 dB. The range of low-frequency slopes offered to each subject differed. In one typical subject the low-frequency slopes of the preselected instruments were 8, 11, and 14 dB, spanning a range of 6 dB. The smallest range offered to any subject was 3 dB and the largest range was 19 dB.

Although the tone controls only produced variations in low-frequency gain, the hearing aids also differed in high-frequency gain. The high-frequency slope of each instrument was described by subtracting the HA-2 coupler gain at 4000 Hz from that at 1000 Hz. The mean high-frequency slope across all of the hearing aids was 6.3 dB with a S.D. of 8.3 dB. The range of high-frequency slopes offered to each subject differed. In one typical subject, the high-frequency slopes of the preselected instruments were −4, 1, and 10 dB, spanning a range of 14 dB. The smallest range offered to any subject was 5 dB and the largest range was 26 dB. None of the hearing aids had a wide band receiver: gain decreased rapidly above 4000 Hz.

Hearing Aid Selection

From the three preselected hearing aids, the final hearing aid was chosen on the basis of intelligibility of continuous discourse at the preferred listening level. This procedure was performed with the subject seated in the center of a 7 x 9ft sound-treated audiometric room, 1 meter from a wall-mounted loudspeaker located at 0° azimuth. A prerecorded 1-min continuous discourse passage, spoken by a male talker, was presented from the loudspeaker at a level of 70 dB SPL in the sound field. A competing speech babble was also presented from the same loudspeaker. Its level was adjusted for each subject to provide a moderately difficult listening task (aided intelligibility of 60 to 80%, if possible). Signal-to-babble ratios ranged from 0 to +10 dB across subjects. The S/B ratio was held constant for each subject. The subject's unaided ear was plugged and muffed.

Each hearing aid was adjusted to preferred listening level (PLL) while the subject listened to the continuous discourse mixed with speech babble. The subject was instructed to seek the most intelligible level consistent with long-term listening comfort. A bracketing procedure was used to locate the optimal volume control setting.

With the hearing aid set to the PLL, the subject then scored the intelligibility of the continuous discourse passage on a scale from 0 to 10. A score of 0 indicated that no words were understood. A score of 10 indicated that every word was understood. A score from 1 to 9 was used when some, but not all, words were understood: a 2 corresponded to estimated understanding of 20%, 7 corresponded to 70%, etc. A detailed description of this test may be found elsewhere.[8]

All of the hearing aids were set to PLL and then scored for intelligibility. Some or all of the instruments were then retried as

Table 1. Means and standard deviations (in parentheses) of the upper (ULCL) and lower (SPHL) limits of the long-term listening ranges. Data are expressed in equivalent HA-2 coupler sound pressure levels

	Frequency (Hz)					
	500	800	1000	1600	2500	4000
ULCL	105.2	105.9	104.1	103.9	105.7	97.3
	(7.8)	(9.1)	(9.1)	(10.1)	(10.7)	(9.8)
SPHL	61.5	65.0	65.1	69.2	75.1	67.0
	(11.5)	(10.0)	(11.0)	(12.4)	(9.6)	(10.1)

needed until the one resulting in the highest intelligibility at PLL was identified by the subject. It was anticipated that each subject would choose the hearing aid in which the frequency/gain function most closely approximated the optimal contour for that individual. This hearing aid's HA-2 coupler gain at the six test frequencies was then measured with the volume control at the PLL setting. Of the nine hearing aids in the original pool, six were chosen as optimal by at least one subject.

RESULTS

For each subject, the following data were available: (1) upper (ULCL) and lower (SPHL) limits of the long-term listening range, expressed in equivalent HA-2 coupler SPL. These data are summarized in Table 1. (2) HA-2 coupler gain for the most intelligible hearing aid when set at the PLL for continuous discourse presented at 70 dB SPL in the sound field.

It was of some interest to assess whether the subjects displayed any consistent pattern in their choice of the most intelligible hearing aid: for example, did subjects always choose the instrument with the most low-frequency amplification? To address this question, each subject's preselected hearing aids were categorized as follows: the one with the greatest low-frequency slope was labeled "hearing aid H;" the one with the smallest low-frequency slope was labeled "hearing aid L;" the remaining hearing aid was labeled "hearing aid M." The hearing aids chosen by the subjects were distributed in the following way: six subjects chose hearing aid H; seven subjects chose hearing aid M; three subjects chose hearing aid L. These data provide no evidence of a group preference for relative low-frequency emphasis; if anything, the preference was for a relative de-emphasis in this frequency region.

To address the question of whether subjects displayed a preference for relative high-frequency emphasis, the hearing aids were categorized on the basis of their high-frequency slope. For each subject, the instrument with the least high-frequency slope (the greatest high-frequency emphasis) was labeled "hearing aid H;" the one with the greatest high-frequency slope was labeled "hearing aid L;" the remaining hearing aid was labeled "hearing aid M." The hearing aids chosen by the subjects were distributed in the following way: six subjects chose hearing aid H; five subjects chose hearing aid M; five subjects chose hearing aid L. Since this distribution is essentially flat, there is no evidence here for a group preference on this characteristic.

To address the primary issue in this investigation, the relationship between PLL and the long-term listening range, it was necessary to determine the chosen hearing aid's output at each test frequency when the instrument was set to the PLL. To calculate this, the hearing aid's gain at each frequency was added to the estimated input to the hearing aid in that frequency region. The input at the hearing aid's microphone consisted of the speech signal modified by the head baffle effect occurring for a 0° azimuth signal.

The long-term RMS levels of one-third octave bands of speech were derived from studies of multi-voice babbles recorded in both anechoic and sound treated audiometric rooms (R. M. Cox, unpublished data, 1979). For an overall level of 70 dB SPL, the one-third octave band levels were: 250 Hz = 60dB, 500 Hz = 66.5dB, 800 Hz = 60dB, 1000 Hz = 55dB, 1600 Hz = 58dB, 2500 Hz = 53dB, 4000 Hz = 49dB.

The head baffle effects occurring at a forward facing hearing aid microphone for a 0° azimuth signal were taken from data reported by Studebaker et al.[10] The values were: 250 Hz = 0 dB, 500 Hz = +1.0 dB, 800 Hz = −0.5 dB, 1000 Hz = −1.0 dB, 1600 Hz = 0 dB, 2500 Hz = +1.0 dB, 4000 Hz = −1.0 dB.

The speech spectrum and head baffle effects were summed to estimate the input at the hearing aid's microphone.

Using linear regression analyses, the following issues were investigated for each test frequency: (1) the relationship between the hearing aid's output at the PLL setting and the ULCL, (2) the relationship between the hearing aid's output at the PLL setting and the SPHL, and (3) the relationship between the hearing aid's output at the PLL setting and various proportions of the long-term listening range (one-fourth of the range above SPHL, one-third of the range below ULCL, etc.). The most interesting results are summarized in Table 2. This table shows the Pearson product-moment correlation coefficients between the hearing aid's output at the PLL setting and (1) the ULCL, (2) the SPHL, and (3) the middle of the long-term listening range (½ LTLR).

As Table 2 reveals, the level produced by the hearing aid at the PLL setting was most highly correlated with the midpoint of the long-term listening range for the three lowest test frequencies. At 1600 Hz, the highest correlation was again observed with the ½ LTLR level but the correlation with the ULCL was almost as high. Actually, the correlation between the level produced by the hearing aid at the PLL setting and the middle of the long-term listening range was the highest of all the correlations tested at

Table 2. Pearson product-moment correlation coefficients at each test frequency between the output level produced with the hearing aid set to the PLL and (1) the upper limit of comfortable loudness (ULCL), (2) thresholds (SPHL), and (3) the midpoint of the long-term listening range (1/2 LTLR). N = 16

	Frequency (Hz)					
	500	800	1000	1600	2500	4000
(1) ULCL	0.71	0.87	0.73	0.77	0.81	0.70
(2) SPHL	0.71	0.72	0.79	0.72	0.65	0.45
(3) ½ LTLR	0.80	0.91	0.82	0.79	0.76	0.62

Table 3. Means and standard deviations (in parentheses) of the midpoint of the long-term listening ranges (½ LTLR) and of the levels produced with the hearing aid set to the PLL (PLL setting). Data are expressed in equivalent HA-2 coupler sound pressure levels

	Frequency (Hz)					
	500	800	1000	1600	2500	4000
½ LTLR	83.4	85.4	84.6	86.5	90.4	82.2
	(8.6)	(8.3)	(9.3)	(10.7)	(9.8)	(9.2)
PLL setting	84.0	85.1	82.8	86.5	85.4	71.5
	(14.5)	(15.0)	(13.7)	(12.1)	(11.6)	(10.7)

each of these frequencies; no other level within the long-term listening range predicted the level at the PLL setting better than the midpoint.

The two highest frequencies, 2500 and 4000 Hz, revealed a different pattern. At both of these frequencies, the hearing aid's output level at the PLL setting was more highly correlated with the ULCL than with any other level investigated.

It should be pointed out that, at any one frequency, the differences between the three correlations shown in Table 2 are not large enough to be statistically significant at the 0.05 level for a group of 16 subjects. Hence, the conclusions drawn from these data must be considered tentative, pending the study of a larger group of subjects. However, the systematic pattern of the results across the test frequencies strongly suggests that the observed effects did not occur by chance.

Table 3 shows the means and standard deviations at each frequency of the ½ LTLR level and the aided levels at the PLL setting. These data reveal that in the 500 through 1600 Hz range, the mean level produced by the hearing aid at the PLL setting coincided very closely with the mean midpoint in the long-term listening range. However, at 2500 Hz the mean level at the PLL setting was 5 dB below the mean ½ LTLR level and at 4000 Hz the mean difference between these two levels increased to 11 dB.

Two interpretations are available for the results of this investigation, as revealed in Tables 2 and 3. The first interpretation is straightforward. It would hypothesize that (1) the aided preferred listening level is approximately coincident with the midpoint of the long-term listening range from 500 through 1600 Hz, and (2) above 1600 Hz the aided preferred listening level is principally determined by the ULCL. Although this explanation is consistent with the data, it is difficult to envision a physiological or psychological explanation for such a relatively abrupt change in the subject's criterion for aided preferred listening level.

The second interpretation would suggest that the aided preferred listening level is approximately coincident with the midpoint of the long-term listening range at all the test frequencies. To support this interpretation, it may be hypothesized that the preselected hearing aids did not provide the option of achieving the PLL at 2500 and 4000 Hz without overamplifying the low-frequency region. The subjects, therefore, disregarded these higher frequencies when choosing the best hearing aid, concentrating instead on selecting the instrument which, when set at an optimal volume, most closely approximated the midpoint of their long-term listening ranges in the bandwidth from 500 through 1600 Hz. This explanation would account for: (1) the decreased correlation between the PLL and the ½ LTLR level at the higher frequencies, and (2) the progressive decrease in level at the PLL setting relative to the ½ LTLR level at 2500 and 4000 Hz.

Future investigation, utilizing amplification systems in which the various test frequencies can be independently controlled, may possibly add support to the first interpretation. Until such data are generated, it seems appropriate to tentatively accept the more parsimonious second interpretation of these results.

APPLICATION TO HEARING AID SELECTION

The hypothesis that the midpoint of the long-term listening range is coincident with the aided preferred listening level for the typical hearing impaired person can be used as the basis for specification of frequency/gain function.

It is of considerable interest to consider the errors likely to occur when an individual's aided PLLs at several frequencies are predicted on the basis of the midpoint of his long-term listening ranges for those frequencies. Such errors would arise from at least two sources: (1) Unreliability in the estimate of ½ LTLR. Since the ½ LTLR level is a mean of SPHL and ULCL, its variability will be less than that of the more variable of these measures. (2) Inaccurate prediction of the relationship between ½ LTLR and aided PLL in the individual case.

One way to estimate the size of the cumulative error is to compare the gain used by a subject at a particular frequency when the chosen hearing aid was set to the PLL with the gain which would have been predicted for that subject on the basis of his SPHL/ULCL data at that frequency. Table 4 depicts the results of two types of comparisons. It should be pointed out that the errors depicted in Table 4 incorporate an additional component which arises because each subject's hearing aid was selected from a relatively small group of instruments and thus represents the best available compromise rather than the truly optimal frequency/gain function.

Line (1) of Table 4 shows the unbiased standard errors of estimate derived from the least squares regression analyses for which the correlation coefficients are reported in Table 2 (the ½ LTLR data). This statistic reveals the standard deviation of the distribution of errors which

Table 4. Line (1) shows the unbiased standard errors of estimate (in decibels) resulting from prediction of needed gain based on least square regression equations derived for this group of subjects. Line (2) shows the unbiased standard errors of estimate resulting from prediction of needed gain based on the midpoint of the long-term listening range alone

	Frequency (Hz)					
	500	800	1000	1600	2500	4000
(1)	9.0	6.5	8.1	7.7	7.8	8.7
(2)	9.5	8.5	8.6	7.8	9.5	14.6

might be expected at each frequency if a regression equation was used to predict the needed gain from the ½ LTLR level.

It is also possible to predict the needed gain based on the assumption that the aided PLL is equal to the ½ LTLR level. No regression equation is used in this procedure. Line (2) of Table 4 shows the unbiased estimate of the standard error of estimate which resulted from this predictive strategy.

Comparing line (1) with line (2) in Table 4 indicates, as expected, that the use of a regression equation to predict needed gain resulted in the more accurate predictions for this group of subjects. However, the change in standard error of estimate was usually quite small except for the 4000 Hz test frequency. This result at 4000 Hz should not be unexpected since, as discussed earlier, real hearing aids do not usually provide as much gain at 4000 Hz as is called for.

Derivation of Needed Gain

Since Table 4 shows that the use of regression equations to predict needed gain in this group of subjects produced only modest improvements in accuracy compared to a more simple predictive strategy utilizing the ½ LTLR level, it seems appropriate to use the simpler predictive scheme. However, investigation of a larger group of subjects should be undertaken to further explore whether significant improvements in accuracy could be obtained by use of regression equations.

To derive the required gain at each test frequency, it is necessary to (1) measure both SPHL and ULCL, (2) calculate from these the midpoint of the long-term listening range, and (3) subtract from it the anticipated input to the hearing aid (the speech spectrum plus head baffle effects at that frequency). Finally, the correction described earlier must be added, to account for the difference between the SMW receiver and the receivers used in postauricular hearing aids. Tables have been constructed in which the gains appropriate for various SPHL/ULCL combinations are given.[6]

This rationale for the specification of frequency/gain function has been employed in a clinical setting for many adventitiously hearing impaired adults and has resulted in a high rate of apparently successful hearing aid fittings in this population.

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Address reprint requests to Robyn M. Cox, Ph.D., 807 Jefferson Ave., Memphis, TN 38105.

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