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Prediction of Aided Preferred Listening Levels for Hearing Aid Gain Prescription*

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ABSTRACT

Relative accuracy was assessed for two methods for predicting preferred listening levels as estimated by measurements of the upper limit of the comfortable loudness range (ULCL). Sixteen hearing-impaired subjects provided ULCL data for eight test stimuli on each of five occasions. The stimuli were four narrow bands of noise centered at 500, 1000, 2000, and 4000 Hz and four narrow bands of speech babble also centered at 500, 1000, 2000, and 4000 Hz. Best estimates of ULCL were determined to be the means of the five measurements for each subject for each of the eight test signals. Results revealed that the mean ULCL for each speech-band stimulus was predicted more accurately from that subject's first measurement of ULCL for that speech-band than from his/her threshold for the same signal. However, the accuracy with which noise-band ULCLs could be used to predict the mean speech-band ULCL varied with frequency and with the number of trials averaged. Relationship of ULCL to preferred listening levels was explored by comparing results obtained in this study with work of previous investigators. Implications of the results for hearing aid gain prescription are discussed.

The various hearing aid prescription procedures which have been proposed generally make the assumption that the frequency/gain function of a hearing aid should shape and deliver the speech spectrum to conform to the hearing-impaired individual's aided preferred listening levels across the frequency range (i.e., the levels in each frequency region at which the individual would choose to listen to the amplified speech signal after he/she had sufficient experience with aided listening to select the optimal settings). A review of these procedures indicates that there are two basic approaches to the problem of predicting an individual's aided preferred listening level (PLL). One approach,[10, 22] utilizes a measurement of comfortable loudness level as a predictor of the PLL. The alternative approach[2, 7] predicts the PLL on the basis of hearing thresholds. These threshold-based procedures can also be conceptualized as predicting comfortable loudness levels on the basis of hearing thresholds inasmuch as they attempt to prescribe an amount of gain which will result in delivery of speech signals at comfortable loudness levels.

Each of these two methods for predicting PLL has potential disadvantages. The main problem with the approach based on comfortable loudness measurements is the relatively poor repeatability associated with the measure usually used as an estimate of comfortable loudness, namely, the "most comfortable loudness" (MCL).[3, 8, 23] Clearly, if the measure used to predict PLL is unreliable, the resulting gain prescription is of limited usefulness. The disadvantage associated with the threshold-based approach is the wide range of preferred listening levels actually observed among experienced hearing aid wearers with essentially the same pure-tone hearing loss: Martin,[18] Brooks,[5] and Martin et al.[19] have all reported data showing that for any given hearing loss the range of used-gain values among experienced hearing aid wearers is 20 to 25 dB. Hence, utilization of the same gain figure for everyone with a given hearing loss is certain to result in an inaccurate prediction of PLL for many individuals.

As a result of these considerations, a study was performed which attempted to evaluate the relative accuracy of each of these methods for predicting PLL. For the purpose of this investigation, the PLL was inferred from measures of comfortable loudness. The primary question under investigation was whether an individual's "true" comfortable loudness level for a particular stimulus could be predicted more accurately from the threshold for that stimulus or from a single measure of comfortable loudness for that stimulus. Two secondary questions were also considered: (1) how well can an individual's comfortable loudness for a speech-like stimulus (a narrow band of speech babble) be predicted from the comfort-

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able loudness for a stimulus which is more readily available to the clinical audiologist (a narrow band of white noise); and (2) how repeatable was the measure used to estimate comfortable loudness in this investigation.

Estimator of Comfortable Loudness

It is well established that each individual has a range of listening levels which is judged to be comfortable.[4, 11, 16, 20] In this study, the upper limit of this comfortable loudness range was measured to estimate comfortable loudness for each individual. Measures of the upper limit of comfortable loudness (ULCL) were chosen in preference to measures of MCL for two reasons: first, because investigators of the ULCL[12, 25] have reported intrasubject repeatability which seems better than that reported by investigators of MCL,[3, 8, 23, 26] and second, because maximum scores on word discrimination tests for subjects with sensorineural hearing loss usually occur at intensity levels greater than MCL and thus closer to the ULCL.[9, 17, 21, 24] It seemed likely, therefore, that the ULCL region would encompass the individual's aided preferred listening level (assuming that the experienced hearing aid wearer would select an amount of gain which reproduces speech at a level close to ULCL in order to maximize speech intelligibility).

METHOD

Subjects

Eight males and eight females, aged 25 to 78 years, served as subjects. All had bilateral, mild to moderately severe, sensorineural hearing loss. Only the better ear was tested in each subject. This criterion resulted in the use of 10 left and 6 right ears. Table 1 shows the means, S.D.s, and ranges of the puretone thresholds of the test ears. None of these individuals had previous experience as a research subject.

Test Stimuli

Two types of stimuli were used: (1) narrow bands of noise, obtained by filtering wide band white noise produced by a General Radio Random Noise generator (model 1382); and (2) narrow bands of speech babble, obtained by filtering a six-talker speech babble (three males, three females).

The white noise and speech babble were each filtered by using a Krohnhite (model 3700R) bandpass filter cascaded with a Tektonix (model AF501) bandpass filter. This combination resulted in a filter rejection rate of 33 dB/octave and a signal-to-noise ratio of at least 45 dB for the tape-recorded stimuli.

Four narrow bands centered at 0.5 kHz, 1.0 kHz, 2.0 kHz, and 4.0 kHz, were produced for both speech and noise stimuli. The half-power bandwidths were 120 Hz, 200 Hz, 330 Hz, and 620 Hz, respectively. The narrow bands were thus one-third octave in width at 0.5 kHz and 1.0 kHz, and somewhat less than one-third octave at the two higher frequencies.

An estimate was obtained of the distribution of levels in the various test stimuli. One hundred randomly selected levels (the root mean square levels of the signal in a 40 Hz bandwidth encompassing the center frequency during a 50 msec interval) were measured for each narrow band stimulus by using a Spectral Dynamics (model 330A) spectrum analyzer. For each stimulus, at each frequency, the S.D. of the distribution of levels was computed. These are shown in Table 2. These data reveal that the distribution of levels for the speech-band stimuli were somewhat wider than for the noise-band stimuli at the three higher frequencies.

The test stimuli were calibrated using a pure tone recorded at the level of the average peaks when viewed on a standard VU meter.[1] Calibration was achieved in terms of the sound level developed by the earphone in an NBS-9A coupler. This form of calibration was chosen because it is readily achievable in most audiometric settings.

Instrumentation

The test stimuli were prerecorded and replayed on a Revox (model A-77) tape recorder, fed to the external stimulus input of a Grason-Stadler (model E-800) Bekesy audiometer and presented via a TDH-49 earphone in an MX-41/AR cushion. The level of the test stimulus was under the control of the subject, who held a response switch which could raise or lower the intensity or hold it constant. Attenuation rate for the Bekesy audiometer was 2.5 dB/sec.

Procedure

Each subject participated in six testing sessions, five for repeated measurements of ULCLs and one to obtain threshold for the test stimuli. Testing was performed in a sound-treated audiometric test room. Time between sessions ranged from one day to one month. Subjects responded to all stimuli in every session.

Each trial was conducted as follows: the stimulus was initially set at a level close to the subject's threshold and allowed to automatically increase in intensity. The subject was instructed to allow the loudness to increase until it reached the "level which is too loud, uncomfortably loud, or annoyingly loud." The subject then switched the instrument to the position which caused the intensity to decrease. As soon as the attenuating sound level attained a loudness which "would be com-

Table 1. Means, ranges [decibels hearing level (HL)], and S.D.s (decibels) of test ear thresholds for pure tones for the 16 subjects

	Test Frequency (Hz)			
	500	1000	2000	4000
Mean	37.5	46.6	55.3	69.7
Range	20–65	30–70	30–100	40–110
S.D.	14.5	10.3	18.0	22.6

Table 2. S.D. (decibels) of the distribution of root mean square levels for each test stimulus

	Center Frequency (Hz)			
Stimulus	500	1000	2000	4000
Speech bands	6.7	8.5	7.7	7.7
Noise bands	5.5	5.1	4.4	4.4

fortable to listen to from a hearing aid for a long period of time," the subject switched it to the position which caused the level to remain constant. It was stressed that the subject should halt further attenuation of the signal as soon as it dropped into the comfortable loudness range. It was anticipated that this procedure would elicit responses at the ULCL. The constant level chosen by the subject was taken as the ULCL for that trial. The ULCL measured for each stimulus on a given day was the mean of three consecutive trials.

During stimulus presentation, the noise bands were pulsed at a rate of 2.5 pulses per second with a rise-decay time of 25 msec and a 50% duty cycle (pulsed noise bands were chosen in anticipation of generalizing the results to audiometric practice in which pulsed noise bands are typically used). The speech bands were not pulsed because this presentation would have greatly reduced their resemblance to real speech, thereby destroying their face validity as criterion stimuli. In addition, problems with auditory fatigue seemed unlikely with the speech bands because of their inherently intermittent character.

All experimental variables were counterbalanced or randomized, except that the stimuli centered at 1000 Hz were always used for practice trials at the beginning of data collection for both speech bands and noise bands.

RESULTS AND DISCUSSION

Treatment of the Data

The data were submitted to an analysis of variance for repeated measures[14] which examined the effects on ULCL of: (1) the five tests sessions, (2) the different test frequencies, and (3) the two types of stimuli (noise bands and speech bands). Post hoc analyses were performed by using the Student-Newman-Keuls multiple range test and tests of simple main effects and simple, simple main effects.[15] In addition, Pearson product-moment correlation coefficients were computed to investigate relationships between various measures, and least squares linear regression analyses were performed when the prediction of one measure from another was of interest. Because the 1000 Hz stimulus was used in the practice trials at the beginning of each session, the order of presentation of this frequency was not controlled. However, it was found that inclusion of the data obtained with these stimuli did not alter any of the conclusions drawn from this investigation. Hence, these data are reported for the interested reader.

Estimating the True ULCL

The mean ULCL across subjects and stimuli for the five experimental sessions were: 93.6, 94.7, 95.2, 95.7, and 96.1 dB sound pressure level (SPL). Although a slight tendency toward an increasing level is discernable, the differences across sessions were not statistically significant. In addition, there was no significant effect due to stimuli, or to a session X stimuli interaction. The means and S.D.s of ULCLs across sessions and subjects for each test stimulus are shown in Table 3. The differences between speech bands and noise bands were not statistically significant at any frequency. The range of results (90 to 102 dB SPL) is consistent with the estimates of the upper limit of the comfortable loudness range reported for pulsed pure tones by Gabrielsson et al.,[12] Dirks and Kamm,[11] Kamm et al.,[13] Lucker et al.,[16] and Brandt and Loushine.[4] Because there were no significant effects due to stimuli or test sessions, best estimates of the true ULCL for each subject for the various stimuli were derived by obtaining the means of the five separate measurements of each stimulus.

Relationship between ULCL and PLL

It was postulated that the best estimates of ULCL for speech bands were systematically related to each subject's PLL for amplified speech in that frequency region. To evaluate the adequacy of this postulate, the relationship observed in this study between thresholds and the best estimates of ULCL for speech bands was compared with reported relationships between thresholds and preferred listening levels for experienced hearing aid users. The results from this study are compared in Table 4 with those of previous investigators. In this table, linear regression equations 1 and 2 were derived by Brooks[5] and by Byrne and Fifield[6] respectively, from measurements of hearing thresholds and hearing aid gain at preferred listening levels. Equations 3 and 4 show linear regression equations reported by Byrne and Tonisson[7] and Martin et al.,[19] respectively, in studies which derived the relationship between hearing thresholds and pre-

Table 3. Mean ULCL (decibels SPL), and S.D. at each test frequency for speech bands and noise bands

	Stimulus	
Center Frequency (Hz)	Speech	Noise
500	92.3	92.7
	(9.2)	(10.0)
1000	91.6	90.9
	(8.8)	(9.9)
2000	96.2	94.8
	(8.7)	(9.5)
4000	100.3	101.8
	(10.2)	(10.1)

Table 4. Comparison of linear regression equations derived from this and other studies[a]

	Regression Equation	Sy.x
1.	Coupler gain (1 kHz) = 0.5 (Avg. HL) + 1.1	[b]
2.	Functional gain (1 kHz) = 0.46 (HL @ 1 kHz) +[b]	8.4
3.	Speech PLL = 0.51 (Avg. HL) +[b]	7.6
4.	Speech PLL = 0.42 (HL @ 1 kHz) + 73.9	[b]
5.	Avg. Speech ULCL = 0.47 (Avg. SPHL)[c] + 69.5	6.1

[a] *Lines 1 to 4 show regression equations and S.E. of estimate (Sy.x) reported in four studies of the relationship between PLL and hearing loss.[5–7, 19] Line 5 shows analagous information derived from the data obtained in this investigation.*

[b] *Not reported.*

[c] *SPHL, hearing threshold level expressed in SPL.*

ferred listening levels for speech. Equation 5 is the linear regression equation derived from the data obtained in this study. This regression equation was calculated for the prediction of average ULCL for speech bands across the test frequencies from average thresholds across the test frequencies. The relationship shown in equation 5 closely remembles that shown in all the previous studies, indicating that both the preferred listening level and the mean ULCL for speech bands increase at a rate of 4 to 5 dB for every 10 dB increase in hearing loss. In addition, for a given hearing loss, the absolute level of the speech ULCL calculated by using equation 5 is almost identical with the PLL for speech calculated from equation 4. (Equation 4 is the only equation which is both appropriate and complete enough for this comparison.)

It was concluded, therefore, that it would be appropriate to use ULCL data to infer preferred listening level to investigate the question of whether an individual's preferred listening level could be predicted with greater accuracy from his/her hearing threshold or from the first ULCL measurement.

Accuracy of ULCL Predictions

Linear regression equations and S.E.s of estimate were derived for the prediction of the best estimates of ULCL from either the threshold at that frequency or from the first measure of ULCL. Results are shown in Table 5 for the speech-band stimulus (The results for the noise-band stimulus were essentially the same as these.) The main point to be made about the information in Table 5 is that the S.E.s of estimate were smaller at every frequency when the best estimate of ULCL was predicted from a single measurement of ULCL than when it was predicted from the individual's threshold at that frequency. This suggests that an individual's PLL for speech in a particular frequency region can be more accurately predicted from a single measurement of that individual's ULCL for a narrow band of speech than from the individual's threshold for the same stimulus.

Predicting ULCL for Speech Bands from ULCL for Noise Bands

The data shown in Table 5 depict the outcome when the best estimate of ULCL for a speech-band was predicted from a single measurement of ULCL for that speech-band. However, in a typical audiology facility, speech-band stimuli are not available. Because pulsed noise bands usually are available to the audiologist, it is of some importance to know whether an individual's ULCL for a speech band can be accurately predicted from that individual's ULCL for a pulsed band of noise at the same frequency. To answer this question in a general sense, a regression analysis was performed to determine the accuracy of prediction of the best estimates of speech band ULCLs from the best estimates of noise bands ULCLs. The results revealed that the S.E.s of estimate for this prediction at each of the four test frequencies was 2 to 3 dB. This seems to indicate that speech band ULCLs can usually be predicted fairly accurately from noise bands ULCLs. However, such a conclusion would probably be too optimistic because the best estimates of noise band ULCLs were derived from five separate measurements. In a realistic clinical procedure, repeated measurements of noise-band ULCLs at each frequency are not usually feasible.

Therefore, another regression analysis was performed to determine the accuracy of predictions of the best estimate of ULCL for a speech-band stimulus based on a single measurement of ULCL for a noise-band stimulus at the same frequency. The S.E.s of estimate are shown in Table 6. Lines 1 and 2 repeat the S.E.s of estimate shown in Table 5 for predictions based on thresholds and first ULCL measurement for speech-bands, respectively. Line 3 shows the S.E.s of estimate when the first ULCL measurement for noise bands was used to predict the best estimate of speech-band ULCLs. Line 4 shows the corresponding data when the average ULCL from noise-band trials one and two was used as the predictor of the speech-band ULCL.

The data in Table 6 indicate that a single measurement of noise-band ULCL at 2 or 4 kHz could be used to predict the ULCL for speech bands at these frequencies

Table 5. Regression equations and S.E. of estimate (Sy.x) for prediction of the best estimate of speech band ULCL from: (A) first measurement of speech band ULCL (ULCL1), or (B) thresholds

Test Frequency (Hz)	Regression Equation	Sy.x
500	(A) ULCL = 0.65 (ULCL1) + 33.0	5.2
	(B) ULCL = 0.28 (SPHL)[a] + 79.7	7.1
1000	(A) ULCL = 0.77 (ULCL1) + 22.3	4.3
	(B) ULCL = 0.35 (SPHL) + 74.7	7.7
2000	(A) ULCL = 0.86 (ULCL1) + 15.2	3.2
	(B) ULCL = 0.36 (SPHL) + 75.3	7.1
4000	(A) ULCL = 0.87 (ULCL1) + 13.6	3.6
	(B) ULCL = 0.49 (SPHL) + 66.5	6.7

[a] *SPHL, hearing threshold level expressed in SPL.*

Table 6. S.E. of estimate (decibels) associated with various methods for predicting the best estimate of ULCL for speech bands

Predictor	Frequency (Hz) 500	1000	2000	4000
1. Threshold	7.1	7.7	7.1	6.7
2. Speech band ULCL, one measurement	5.2	4.3	3.2	3.6
3. Noise band ULCL, one measurement	6.3	6.8	3.1	4.9
4. Noise band ULCL, two measurements	5.5	5.3	2.6	4.7

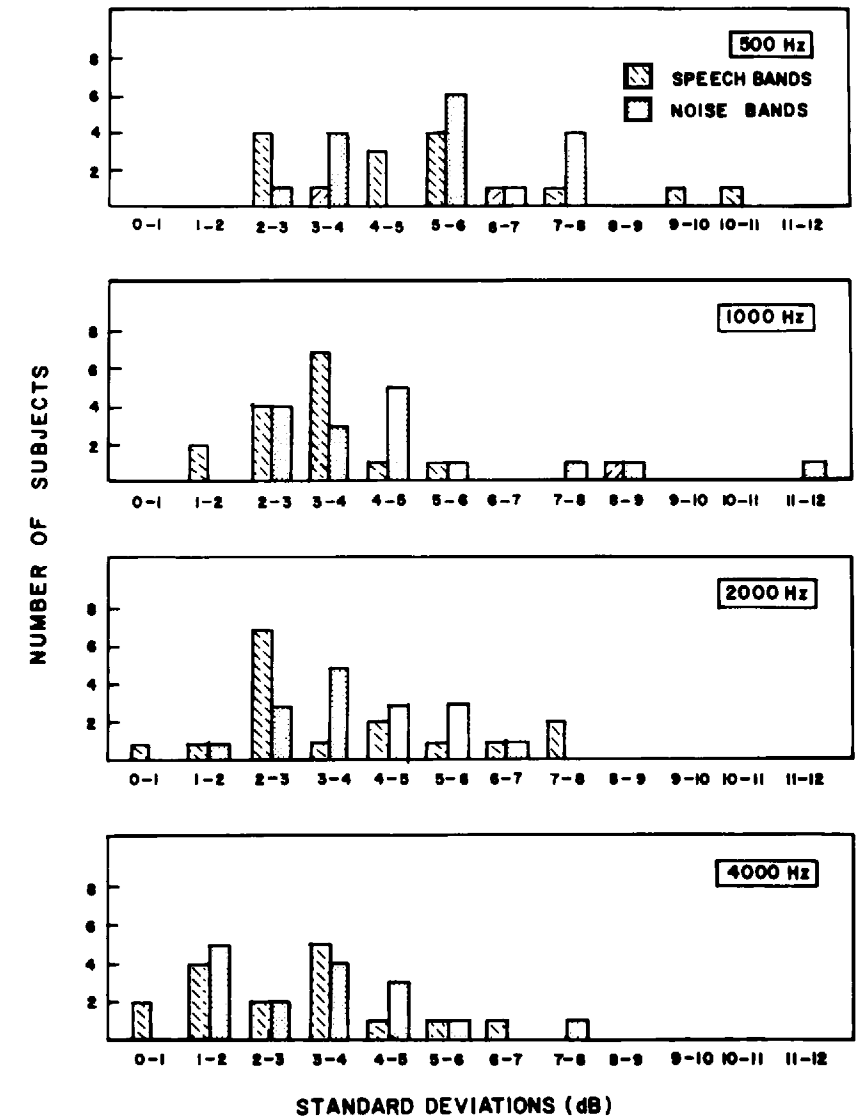

Figure 1. Distribution of intrasubject S.D.s for repeated measurement of ULCL for narrow bands of speech babble and narrow bands of white noise at four center frequencies.

with an accuracy which was considerably better than that seen with threshold-based predictions. In the two lower frequencies, predictions of speech-band ULCLs based on a single measure of noise band ULCLs was only marginally better than threshold-based predictions (for example, at 500 Hz the S.E.s of estimate were 6.3 and 7.1 dB for ULCL-based and threshold-based predictions, respectively). The data in line 4 demonstrate that when the mean of two ULCL measurements for noise bands was used to predict the ULCL for speech bands, the accuracy of the resulting predictions was improved at all frequencies.

Repeatability of ULCL Measurements

To evaluate the repeatability of ULCL measurements, unbiased standard deviations were calculated for the five measures of each stimulus at each frequency for each subject. The distribution of results is shown in Figure 1. This figure depicts the number of subjects whose S.D. for repeated ULCL measurements fell within each 1 dB interval at the different frequencies. At each frequency the distributions were roughly the same for both speech bands and noise bands. There was a tendency toward smaller S.D.s at higher frequencies. These data are very similar to those reported by Gabrielsson et al.[12] for the intrasubject repeatability of ULCL measurements for a 1700 Hz pulsed tone.

To put these data in perspective, it was instructive to compare the average S.D.s for repeated measurements of ULCL on the same subject with those reported by Witting and Hughson[27] for repeated measurements of pure-tone thresholds on the same subject. The results are seen in Table 7. These data suggest that at 500 Hz the repeatability of ULCL measurements was, on the aver-

Table 7. Repeatability of pure-tone thresholds and ULCLs. Data are in the form of average intraindividual S.D. (decibels)

	Frequency (Hz)			
Test	500	1000	2000	4000
Thresholds[a]	3.9	3.3	3.9	4.2
ULCL (Speech)	5.1	3.5	4.4	2.9
ULCL (Noise)	5.3	3.8	3.8	3.2

[a] *From Witting and Hughson.*[27]

age, somewhat worse than that of pure-tone thresholds, but at the other test frequencies the two measures were about equally repeatable.

A Caveat

The extent to which the results of this investigation can be validly applied to the problem of prescribing hearing aid gain depends upon the relationship of the ULCL to the aided preferred listening level. This relationship was not specifically investigated in the current study, although the similarity between the various equations in Table 4 supports the hypothesis that there is a predictable relationship between ULCL and PLL on the average. However, it is probably naive to expect that an estimate of comfortable loudness will be all that is needed to make very accurate predictions of aided preferred listening level in each individual case. Investigations are needed of factors other than comfortable loudness which determine an individual's aided PLL. Such factors might include: speech intelligibility, distortion, background noise, or personality traits, among others.

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