Cross Modality Matching As a Loudness Measure

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Conventional MCL, UCL, and ABLB measures are inadequate to identify loudness tolerance problems in severely and profoundly deaf listeners. Cross modality matching of loudness to a visual stimulus was used to better define loudness growth patterns in this population. Subjects were 22 young adults with *M* PTA = 90 dB HL, and 10 normal-hearing adults. All were tested with a stiff spring-loaded tape that was pulled to a length that matched the loudness of a sound. At another session, five subjects also used an Apple IIe computer to perform a similar task by drawing a bar to match loudness. Stimuli were a pulsed 500-Hz tone and filtered words at intensities spanning listeners' dynamic ranges. For normal-hearing listeners, length-intensity functions, plotted logarithmically, approximated a straight line (slope = 0.8). For the hearing-impaired group, post hoc observation of the data indicated at least three patterns. Relations of these patterns to loudness growth are discussed.

Loudness, as a psychological phenomenon, presents an important measurement problem in hearing aid fitting. Abnormally rapid loudness growth (recruitment) can make amplification difficult to use or intolerable (Galloway, 1975). The selection of gain and maximum power output in a hearing aid should yield maximal speech understanding, comfort, and user satisfaction (Pascoe, 1978). Determination of hearing aid control settings, however, is often based on procedures that do not provide a complete picture of how loudness relates to intensity, particularly in cases of bilateral severe and profound hearing loss (Pascoe, 1980; Gottermeier & Sims, 1983). To guide hearing aid fitting practices, procedures must be developed to measure clients' loudness perceptions reliably and with validity.

The Alternate Binaural Loudness Balance test (ABLB) (Fowler, 1936) and Monaural Loudness Balance test (MLB) (Reger, 1936) were developed as clinical tools to measure loudness recruitment and, thus, determine site of

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lesion. Though the relation between recruitment and cochlear hearing impairment is less clear than originally thought (Priede & Coles, 1974), the ABLB and MLB are still accepted as the sole audiometric indicators of recruitment (Carver, 1978). Their limitation lies in the requirement of normal hearing in the nontest ear (for the ABLB) or at at least one frequency in the test ear (for the MLB). This precludes their use in cases of bilateral severe or profound hearing impairment. In the absence of a direct measure of recruitment in these cases, audiologists often use isolated loudness judgements such as the Most Comfortable Loudness Level (MCL) and the Uncomfortable Loudness Level (UCL). Attention is also given to user reports of tolerance problems such as fatigue, shortened wear time, discomfort, and changes in hearing sensitivity (Galloway, 1975). In general, the goal is to maximize hearing aid users' dynamic range.

In the laboratory, relations between loudness and intensity have been measured with the psychophysical procedures of magnitude estimation and magnitude production (Stevens, 1956). For example, in magnitude estimation, a signal of certain intensity may be presented as having a loudness equal to 10. Then, using 10 as a standard, subjects assign numbers to signals of other intensities as estimates of their loudness relative to the standard. If a signal seems twice as loud as the standard, subjects should respond with the number 20; if half as loud, subjects should respond, 5. Magnitude production is the reverse task. Subjects control signal intensity to produce a loudness level which, relative to a standard, equals 20, or 5, or other number assigned by the experimenter.

Using these procedures, S.S. Stevens and his colleagues demonstrated that loudness is one of a group of sensations that are related as power functions to the physical continua that give rise to them (Stevens, 1957). Through magnitude estimation, it has been shown that constant incremental ratios of physical energy result in constant incremental ratios of sensation. On log-log coordinates, this relationship appears normally as a straight line with a slope that is characteristic of that particular sensory experience. For the normal-hearing person, the psychophysical function for loudness has a slope of about 0.6 (Stevens, 1956). In cases of simulated or actual hearing loss, the appearance of the function changes in predictable ways, some of which can be interpreted as recruitment (Hellman & Zwislocki, 1964; Stevens, 1966; Margolis, 1985).

One of the limitations of direct psychophysical scaling is its dependence on subjects' facility with numerical concepts; that is, being able to make an analogy such as: 10 is to 20 as the standard is to a signal of twice the loudness. Scaling is also sensitive to idiosyncratic uses of numbers such as avoidance of or bias toward certain numerals. For these reasons, the classical methods are not ideal for clinic populations although Tecca and Goldstein (1984) reported encouraging results using magnitude estimation of hearing aid quality. Geller and Margolis (1984) were able to reduce the variability in results by imposing limits on the range of numbers available to their subjects during a magnitude estimation task. In a subsequent study with presbycusic listeners, Knight and Margolis (1984) compared ABLB results to those from the modified magnitude estimation procedure. They recommended clinical use of the psychophysical method and predicted no more difficulty than is encountered with current loudness matching tasks. Another modification of the loudness scale, used by Martin, Stevenson, and Grover (1978), was to change it from continuous to categorical. Loudness judgements obtained from two profoundly deaf teenagers with this procedure were reportedly successful in aiding selection of the frequency response of an auditory trainer so that amplification could be accomplished without discomfort.

A type of magnitude production task that does not require the use of numerical manipulation is cross modality matching (Stevens, 1959). Instead of relating a number to the magnitude of the stimulus, subjects make a match between the perceived magnitude of a stimulus in the modality under test and the perceived magnitude of a stimulus in another modality. Assuming no distortions in the reference modality, it can be used to measure distortions in the test modality.

Thalmann (1965) used cross modality matching to evaluate the loudness function in a group of normal-hearing and unilaterally hearing-impaired adults. Subjects matched the magnitude of a 150-Hz vibratory stimulus on the fingertip to the loudness of a 1000-Hz pure tone at the ear. Results of the cross modality matches were compared to the loudness functions derived from tests of ABLB on the same listeners. In each instance, the cross modality matching function coincided fairly well with its corresponding loudness balance function in cases of (a) simulated recruitment with noise-masked normal-hearing ears, (b) no recruitment in ears with conductive impairment, and (c) actual recruitment in ears with moderate sensorineural hearing loss.

Thalmann (1965) also included a unilaterally impaired group with "extreme hearing loss of the recruiting type" (p. 1713) with whom an ABLB was not feasible. The cross modality matching task revealed a pattern of normal loudness growth in each individual's normal-hearing ear and extreme recruitment in the hearing-impaired ear. Thalmann concluded that cross modality matching was a valid indicator of recruitment in these cases of unilateral impairment; however, he cautioned against judging a cross modality matching function from an impaired ear without having reference to one from an unimpaired ear in the same listener. He reasoned that persons with bilateral hearing impairment of long duration may develop an idiopathic definition for categories of loudness based more on their experience than on the ear's response to physical input. Thus, for Thalmann, cross modality matching, as for ABLB, was restricted to cases of unilateral impairment.

An attempt to use cross modality matching as a measure of recruitment in children was viewed as unsuccessful by O'Loughlin (1978) in a replication of a study by Bond and Stevens (1969). Six normal-hearing children matched loudness of a tone to brightness of a light under conditions of simulated hearing loss and also performed an ABLB test. As expected, the results of the ABLB indicated recruitment; the cross modality matching functions, however, did not. O'Loughlin concluded that his subjects could not grasp the concepts necessary for making the required judgements. He interpreted the data to be indicative of the use of cognitive strategies, with a premium on consistency, rather than registering an immediate percept. He described Thalmann's (1965) study as a "quasi-MBLB" (p. 538) but not pertinent to cross modality matching. According to O'Loughlin, a tone and vibration of the frequencies used by Thalmann are from the same continuum.

The purpose of the present study was to prepare to validate cross modality matching as a measure of recruitment in adults with severe and profound bilateral hearing impairment. The goals included selecting an appropriate modality and task, instrumenting the procedure, assessing whether the concept of the task could be conveyed, and investigating its reliability.

After some experimentation, a visual spatial task was chosen because of the relative ease of illustrating the instructions and devising the instrumentation. Dimensions such as force of hand grip, magnitude of vibration or shock, and heaviness were rejected as less easily externalized experiences.

In the visual domain, our first choice was brightness because it was thought to be closely analogous to loudness and has been studied before (McPherson, 1975; Stevens, Mack, & Stevens, 1960). This dimension was rejected, however, for several reasons. We were reluctant to expose subjects' eyes to a magnitude of light that would match an uncomfortable loudness level. Also, the time required for dark adaptation between trials would unduly add to time on task and might influence subsequent judgements. We then considered the dimensions of area and volume, but chose to avoid the question of whether or not hearing-impaired individuals differ from normal-hearing persons in their spatial relations.

One appealing dimension in the visual modality was length. Its psychophysical function has an exponent of 1.0 (Stevens & Guirao, 1963), rendering a cross modality task using length very similar to direct magnitude estimation. Length also has the advantage of being easily instrumented and demonstrated without ambiguity or need for verbalization. Length of a bar was thus chosen as the stimulus for matching to loudness of sound in the present investigation.

PROCEDURE

Subjects

Subjects were 32 students at the Rochester Institute of Technology who were volunteers, paid for their participation. Nine females and one male, aged

18 to 23 years ($M = 20.3$ years), demonstrated hearing within normal limits bilaterally in the speech range.

Eleven females and eleven males, aged 19 to 37 ($M = 23.8$ years), had bilateral severe or profound hearing impairment, presumed to be congenital or with onset before the acquisition of speech and language. The cause of the hearing loss was thought to be heredity (nine cases), prematurity (two cases), Rh factor incompatibility (one case), anoxia (one case), chicken pox (one case), or high fever (one case), or was unknown (seven cases). These subjects' mean pure tone average for 500, 1000, and 2000 Hz in the preferred, test ear was 89.6 dB HL (ANSI, 1969) with a range of 63 to 113 dB ($SD = 13.2$). On a test of speech understanding using CID Everyday Sentences with key-word scoring, their performance ranged from 0 to 84% correct ($M = 25.7\%$; $SD = 24.6$). All were consistent hearing-aid users, but their educational histories represented varying degrees of special education support services.

Method

Stimuli. Subjects listened to a tone and/or filtered speech presented via a Grason Stadler 1701 or GSI-10 audiometer. The tone stimulus was a 500-Hz pure tone of ½-sec duration, repeated at 1-sec intervals. The speech stimulus was a modified list of the California Consonant Test, spoken by a male talker, and recorded on audio tape. The signal had been digitized and the silences between words removed. The abutted-word list was then passed through a one-third octave band digital filter centered at 500 Hz. This achieved some frequency specificity while retaining a speech-like quality.

Apparatus 1. Data were collected using a stiff spring-loaded tape, ½-in. wide, mounted on a board, as in Figure 1. Subjects were instructed to show how loud sound was by pulling the unmarked tape to the length that matched the loudness of the sound and adjusting the length back and forth until satisfied. After each match, the tape was measured to the nearest ¼ in. and then rewound for the start of the next trial. Maximum length was 16 in.

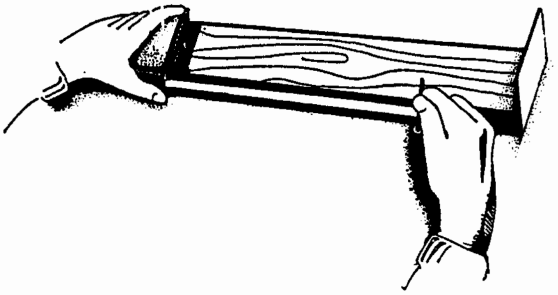

Figure 1. Drawing of Apparatus 1, a stiff spring-loaded tape mounted on a board, used to produce a bar whose length matched the loudness of a tone or words.

Apparatus 2. To automate and refine measurement of length productions, a second apparatus was developed. Subjects sat in front of an Apple IIe computer and 12-in. monitor. Contrast on the monitor and room lighting were adjusted to minimize screen glare and image persistence. Two short vertical lines appeared on the left and right sides of the monitor screen, marking the origin and maximum length, respectively, of the bar to be produced. (See Figure 2.) The computer keyboard was covered to allow access to only three keys. Pressing the open-apple key produced a horizontal bar, ⅜ in. wide, that originated at the left vertical line. The length of the bar increased as long as the key was held down, until the right-hand vertical line was reached. Pressing the solid-apple key reduced the length of the bar. Subjects used both keys successively until satisfied with the length of bar produced. Pressing the return key automatically recorded bar length and cleared the screen for the next trial. Maximum length was 8½ in., divided into 279 intervals by the computer program for the purposes of measurement.

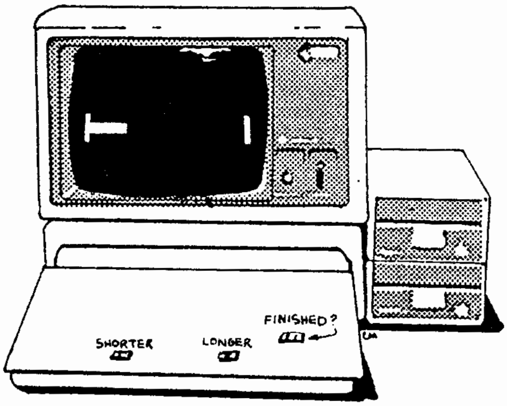

Figure 2. Drawing of Apparatus 2, an Apple IIe computer and monitor with a keyboard overlay. Pressing the open- and solid-apple keys controlled the length of a horizontal bar that originated at the left vertical line and could extend as far as the right vertical line.

Procedure. Subjects were told that they would hear a beeping tone (or a string of filtered words). They were instructed to produce a bar so that its magnitude in the length dimension matched the magnitude of the speech or tone in its loudness dimension. (They were told not to try to understand the words.) The minimum and maximum bar lengths were demonstrated to give an example that would match the softest and loudest sounds, respectively. No stimulus pair was defined as standard in order to allow subjects to develop their own criteria for loud (long) and soft (short).

Sound intensity was randomized, covering the entire auditory area from threshold to discomfort in 5-dB steps. Stimuli for normal-hearing subjects were delivered via TDH-50 earphones to the preferred ear for listening. Maximum earphone output was insufficient, however, to explore the range of interest in some of the hearing-impaired subjects. To extend the upper limit of signal intensity, the hearing-impaired group listened in the sound field with a custom-fit personal hearing aid. Before each session, subjects set the volume of the hearing aid to preferred listening level for a standard recorded sentence spoken by a male talker and presented at 58 dB HL (measured at 1 m from the loudspeaker where the subject sat). The maximum attenuator setting for the tone was 90 dB HL (considered to be the limit for tolerance for repeated stimulation), and for the words it was 85 dB HL (the maximum speech output of the audiometer).

Each intensity was matched four times in one test block for the tone (10 hearing-impaired subjects and all 10 normal-hearing subjects participated in this condition), followed by one block for the words (all subjects participated). On each trial, the tone or words continued until subjects said, "Stop," indicating that they had produced a bar of desired length. The next trial began after a 1- to 2-second interval. Any listener who reported that a signal could not be tolerated long enough to produce a match had the intensity of that signal eliminated from all runs. No feedback was given other than assurances that instructions were being followed correctly.

All subjects were tested individually using Apparatus 1. Apparatus 2 was presented to five of the normal-hearing subjects who returned 18 months later. The procedure was identical for both devices. To assess reliability, these five normal-hearing subjects performed the procedure with Apparatus 2 twice, with a one-week interval between sessions.

RESULTS

Apparatus 1: Effect of Hearing Status

Length of bar produced at each intensity was converted to proportion of maximum length; this allowed comparisons across the two different-sized apparatus. The geometric mean of the four proportional lengths produced to match each intensity was then plotted against sensation level, equating the thresholds of the two subject groups. (The geometric mean was chosen because of the logarithmic form of the psychophysical data.) We examined the resulting scattergrams which showed patterns of relative magnitude change and, by inference, patterns of loudness growth.

Normal-Hearing Subjects. Figure 3 is a log-log plot of the results for the 10 normal-hearing subjects listening to the 500-Hz band of words (lower panel) and the 500-Hz tone (upper panel) and using Apparatus 1 (asterisks indicate superposition of data points). The y axis displays the logarithm of mean length production, transformed to the range 0 to 100, and scaled to be equivalent to the range of sound intensity on the x axis. When loudness is matched to length, the result is expected to be a straight line with a slope of about 0.6 because the exponent of the power function for length is 1.0, while the exponent of the power function for loudness is 0.6 (Stevens & Guirao, 1963; Stevens, Mack, & Stevens, 1960). For the matches between length and loudness of words, the best-fit straight line has a slope of 0.82 (Pearson $r = .95$, $SD(y) = 23.6$); for matches to the tone, the slope is 0.84 (Pearson $r = .94$, $SD(y) = 23.5$). Both of these functions for the normal-hearing listeners appear to be steeper than expected.

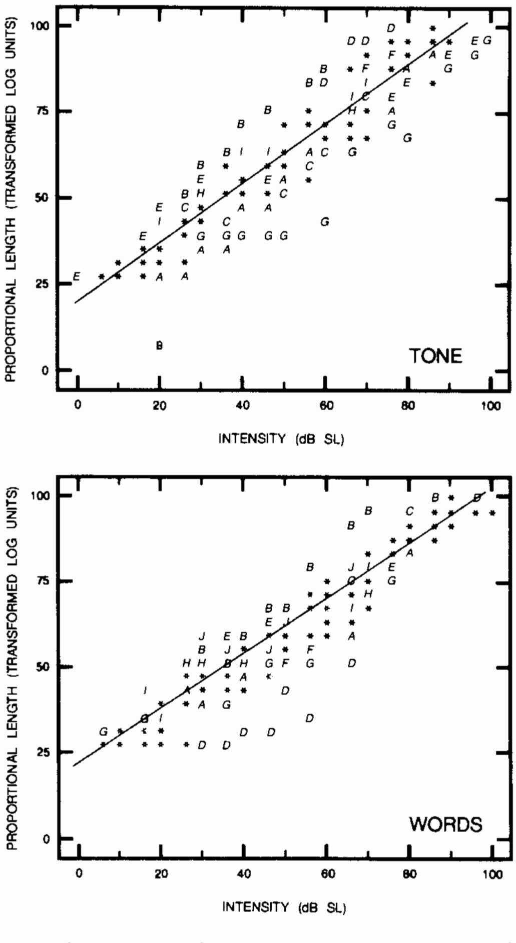

Figure 3. The results of cross modality matches by 10 normal-hearing listeners, Subjects *A-J*, between length of bar produced on Apparatus 1 and (a) a 500-Hz band of filtered words (lower panel) or (b) a 500-Hz pure tone (upper panel). Numbers on the ordinate are transformed units. Asterisks indicate superposition of data points. The solid line is the line of best fit.

When viewed on a log-linear plot, as in Figure 4, it can be inferred from length productions that loudness remained low over about half of the normal dynamic range and then, somewhat suddenly, began to grow at about 50 dB SL. Differences in the change in growth rate after this level resulted in some of the variability seen in Figures 3 and 4. Subject *B*, for example, indicated a breakpoint in loudness change (for the tone) beginning at 40-45 dB SL (Figure 4, upper panel). Subjects *D* and *G*, on the other hand, produced curves (for the words) that were delayed in rising until 70-80 dB SL (Figure 4, lower panel).

Hearing-Impaired Subjects. The data for the first group of 10 hearing-impaired subjects using Apparatus 1 are displayed in Figure 5 in log-log coordinates (lower panel, words; upper panel, tone). The line of best fit is

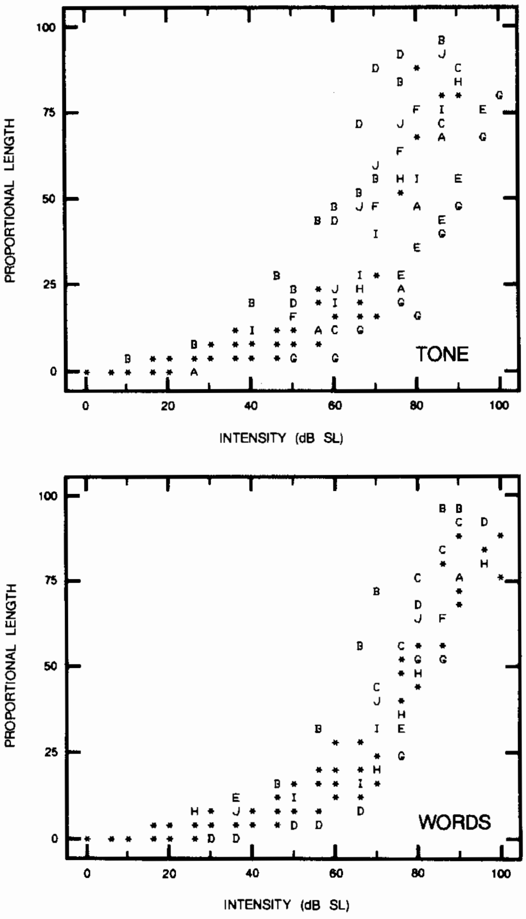

Figure 4. The same data as in Figure 3, replotted with linear length on the y axis.

drawn through the data points; the line below it is reproduced from the corresponding panel in Figure 3 (normal-hearing subjects). Though the slope of the lines is similar for the two subject groups, the pattern of the data is different. Pearson *r* correlation coefficients indicate that a straight line is a poorer approximation to the data from the hearing-impaired subjects. For length matches to words, the slope is 0.98 and $r=.66$ ($SD(y)=17.4$); for the tone data, the slope is 0.95 and $r=.69$ ($SD(y)=17.7$). Despite the apparent

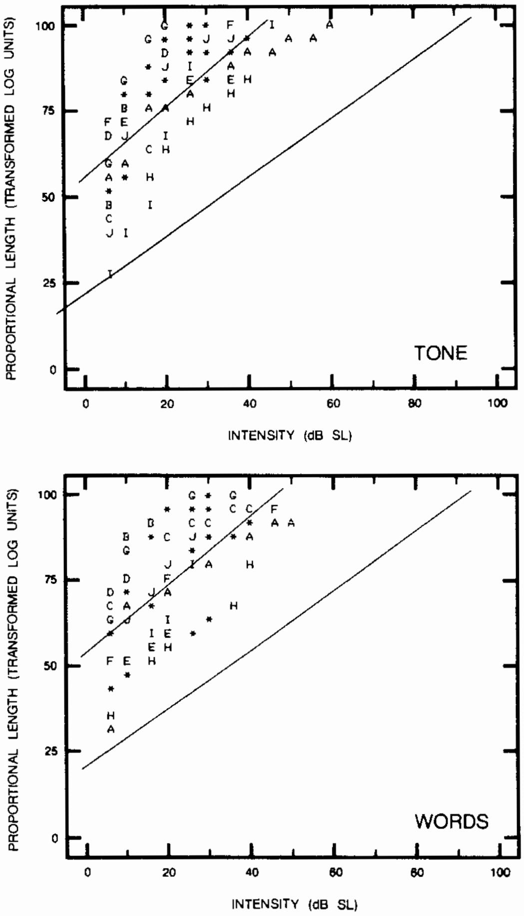

Figure 5. The results of cross modality matches by 10 severely and profoundly hearing-impaired subjects, A-J, between length of bar produced on Apparatus 1 and (a) a 500-Hz band of filtered words (lower panel) or (b) a 500-Hz pure tone (upper panel). Numbers on the ordinate are transformed units. Asterisks indicate superposition of data points. The upper solid line in each panel is the line of best fit for the data plotted. The lower solid line in each panel is the line of best fit for the data from the normal-hearing subjects (Figure 3) for the same material.

difference between groups, a 2 (subject groups) × 2 (stimulus levels) × 18 (intensity levels) ANOVA for repeated measures (Dixon, 1981) failed to show a significant main effect for hearing status when signal intensity was measured in HL ($F(1, 18) = 1.27$; $p > .05$).

Because of our interest in identifying loudness tolerance problems, we examined the data from the hearing-impaired subjects to discern any indication of grouping among individuals. We reasoned that the poorer linear correlation compared to the normal-hearing subjects may have been due to the presence of recruitment among some of the hearing-impaired subjects. Figure 6 displays the same data as in the lower panel of Figure 5 (words), but with the intensity dimension on the x-axis expanded. The hearing-impaired subjects' dynamic range now extends to about the same scale length as that of the nor-

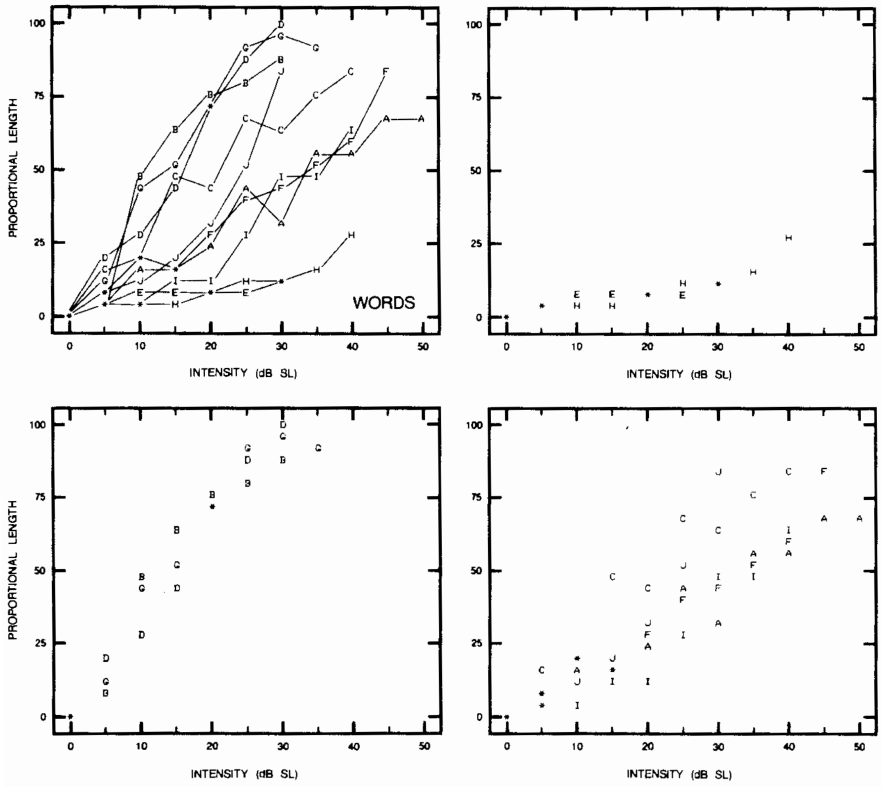

Figure 6. The same data as in Figure 5, lower panel (words), replotted with linear length on the y axis. *Upper left:* the data for all 10 subjects. *Upper right:* subjects E and H, who demonstrated a slow rate of loudness growth. *Lower left:* subjects B, D, and G, who indicated a rapid rate of loudness growth. *Lower right:* subjects A, C, F, I, and J, who showed an intermediate rate.

mal-hearing subjects in previous figures. The combined group plot in the upper left panel of Figure 6 indicates areas of considerable overlap, but some post hoc grouping is suggested. Subjects E and H performed similarly. For them, the words never attained a magnitude greater than about a fourth of what they considered to be maximum loudness (Figure 6, upper right panel). A straight line through a log-log plot of these data has a slope of 0.89 (Pearson $r = .95$; $SD(y) = 10.4$). In contrast, subjects B, D, and G reported a rapid growth in the magnitude of the signal as it increased in intensity (lower left panel). Slope of the best fit line for these three curves in a log-log plot is 1.2 (Pearson $r = .87$; $SD(y) = 12.5$). The remaining five subjects, A, C, F, I, and J, did not demonstrate either a uniformly slow or a uniformly fast growth pattern (lower right panel). Slope of the best fit line for this group's data in a log-log plot is 1.0 (Pearson $r = .84$; $SD(y) = 15.8$).

The subject groupings for Figure 6 were imposed on the tone data to observe whether or not similar response patterns could be inferred. In general,

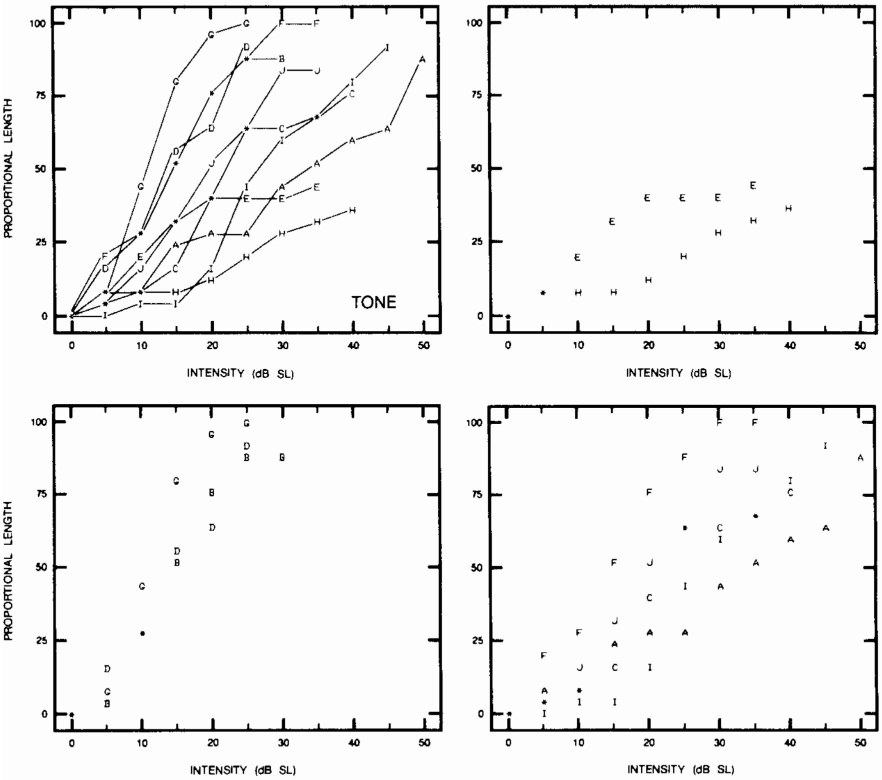

Figure 7. The same data as in Figure 5, upper panel (tone), replotted with linear length on the y axis. The subject groupings are the same as those in Figure 6.

the patterns remained the same for all but two subjects, E and F, and are displayed in Figure 7. The curve for subject E (Figure 7, upper right panel) indicates an intermediate growth rate rather than a slow growth rate as expected for both E and H. Curves for subjects B, D, and G (lower left panel) accelerate more quickly than normal, as in Figure 6. The group that showed an intermediate growth rate for the loudness of words responded similarly to the tone except for subject F (lower right panel). Subject F apparently perceived the tone to grow much more rapidly than the words.

To further substantiate the impression that the hearing-impaired subjects were not a homogeneous group in their perceptions of loudness, we examined the responses of the additional 12 hearing-impaired subjects who listened to one block of word stimuli and used Apparatus 1 as described above. Their data are displayed in Figure 8. Five subjects — N, R, S, T, U — produced

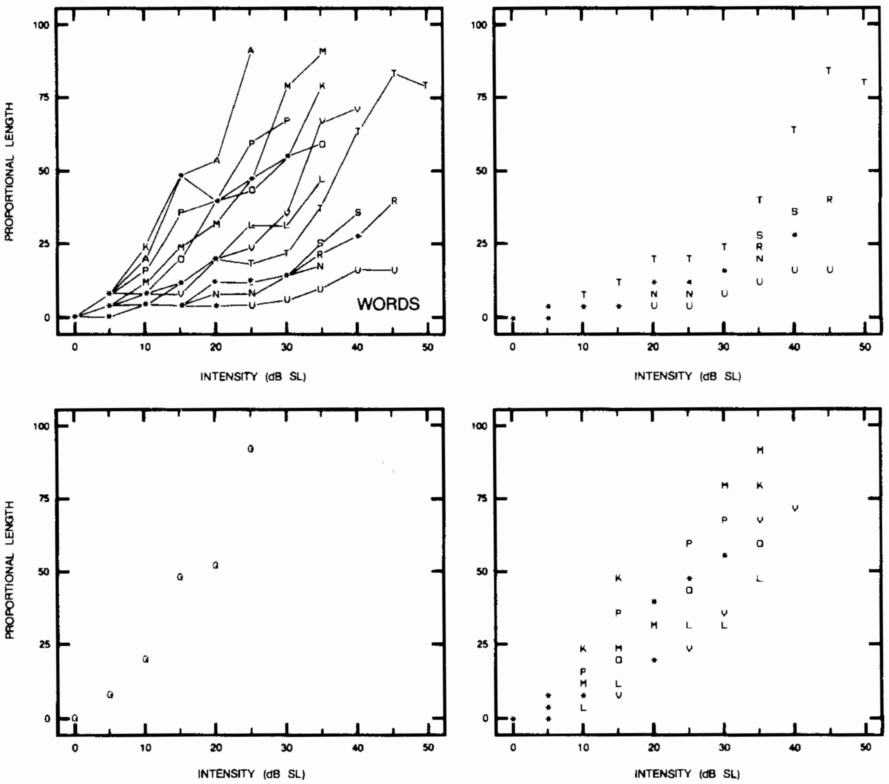

Figure 8. The results of cross modality matches by 12 severely and profoundly hearing-impaired subjects, K-V, between length of bar produced on Apparatus 1 and a 500-Hz band of filtered words. The subject groupings were determined in the same way as in Figure 6.

matches that were similar in pattern to those of the slow growth rate group (Figure 8, upper right panel; slope in a log-log plot is 1.2). Only one subject (Q) produced a pattern that indicated a fast rate of loudness growth (lower left panel; slope in a log-log plot is 2.0). The patterns of six others — K, L, M, O, P, V — resembled those of the intermediate growth rate group (lower left panel; slope in a log-log plot is 1.5).

Apparatus 2: Comparison with Apparatus 1

Five normal-hearing subjects used both Apparatus 1 and Apparatus 2. A 2 (apparatus) × 2 (stimulus levels) × 19 (intensity levels) ANOVA with repeated measures indicated that there was no significant difference between the results with the two different devices ($F(1, 4) = 3.28$, $p > .05$) even after an 18-month interval. Linear regression analysis (Dixon, 1981) was used to determine the strength of the correlation between the length productions made with the first and with the second apparatus. Pearson *r*s ranged from .94 to .99 when the five subjects listened to words, and .97 to .99 when listening to the tone. The 95% confidence interval for the mean word data was $r = .94$ to .99; for the mean tone data, the interval was $r = .96$ to .99.

Apparatus 2: Reliability

The five normal-hearing subjects returned to repeat the procedures with Apparatus 2 within one week. Again, a 2 (sessions) × 2 (stimulus levels) × 19 (intensity levels) ANOVA with repeated measures showed no significant difference between the length productions from the first and second sessions with Apparatus 2 ($F(1, 4) = 0.00$, $p > .05$). Pearson *r*s for the word data ranged from .97 to .99 (the 95% confidence interval for the mean data was $r = .97$ to .99), and for the tone data the range was .97 to .99 (the 95% confidence interval for the mean tone data was $r = .97$ to .99).

Effect of Material

In the 2 × 2 × 19 ANOVA that evaluated differences due to hearing status, the main effect for material did not reach significance ($F(1, 18) = 0.21$; $p > .05$). The normal-hearing subjects' responses to the tone and words remained statistically similar in the ANOVAs that evaluated effect of type of apparatus ($F(1, 4) = 1.88$; $p > .05$) and reliability ($F(1, 4) = 0.13$; $p > .05$) as well.

DISCUSSION

Loudness Perceptions of Normal-Hearing Subjects

The cross modality matches of the normal-hearing subjects resulted in notable individual differences in the function relating intensity to length and, by inference, to loudness. This result is not unexpected, as previous researchers have reported subject variability (Schneider, 1981; Stevens &

Guirao, 1963; Thalmann, 1965). Procedural choices in the present study, specifically the elimination of a standard, contributed to this variability. In a free modulus experiment, each subject is assumed to select a different modulus from other subjects and a different number range. Lane, Catania, and Stevens (1961) introduced a procedure for reducing variance due to differing choice of moduli which might have rendered the individual functions more similar in detail. The general form of the functions, however, was similar across subjects and across materials such that a straight line is a good approximation to the data plotted on log-log coordinates.

The slope of the functions was steeper than the previously-reported 0.6 for loudness. One influence may have been the imposition of a limit on maximum length and the use of a shorter maximum length than is typical for such studies. Of greater note is differences in the range of intensities studied. Whereas we explored subjects' entire dynamic range (within practical limits), the classical data typically included only the mid-to-high intensities. If a flattening of loudness judgements occurs at the upper end of the intensity continuum, then observation of only this tail would yield a shallower function, perhaps close to 0.6.

Loudness Perceptions of Hearing-Impaired Subjects

The loudness relations inferred from the cross modality matches of the hearing-impaired subjects are remarkably similar to the categories of results expected from an ABLB test. Figure 9 presents the loudness matches to words of all 22 hearing-impaired subjects. Line A is the line of best fit for the word data from the normal-hearing subjects in the present study (Figure 3, lower panel) positioned as it would be if intensity were in HL. Curve B illustrates the expected ABLB test results with a case of over-recruitment; intermediate curve C, complete recruitment; and lower curve D, decruitment (Carver, 1978). The subject groupings inferred from the hearing-impaired group's data are distinguished by the dashed lines for the fast loudness-growth group, solid lines for the intermediate loudness-growth group, and dotted lines for the slow loudness-growth group. The individual data do not all conform clearly to one or another of the stylized ABLB curves in Figure 9; nevertheless, patterns such as these, as well as those for partial recruitment and no recruitment, are approximated by several subjects' data.

These results are also consistent with clinical observation of the presence or absence of loudness-tolerance problems. This is especially notable considering the limitations imposed by the need to test in the aided sound field. In effect, the data describe the ear-plus-hearing-aid system and may be underestimates of the actual loudness percept at each attenuator setting. The use of compression amplification or other special hearing aid circuitry was not monitored during the project. A recommendation for future study is that measurement be made of the signal at the tympanic membrane simultaneously with recording of loudness judgements in the aided sound field.

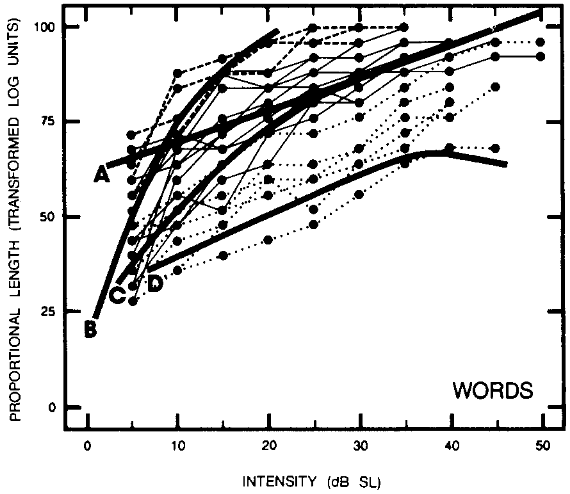

Figure 9. The results of cross modality matches by 22 severely and profoundly hearing-impaired subjects between length of bar produced on Apparatus 1 and a 500-Hz band of filtered words. These are the combined data from Figure 6, upper left panel, and Figure 8, upper left panel, replotted with log length (in transformed units) on the y axis. Inferred groupings are distinguished by dashed lines for fast loudness-growth rate, solid lines for intermediate loudness-growth rate, and dotted lines for slow loudness-growth rate. Line A is the line of best fit for the normal-hearing subjects' data (Figure 3, lower panel). Curves B-D illustrate stylized ABLB test results (curve B, over-recruitment; curve C, complete recruitment; curve D, decruitment).

Recruitment has long been associated with sensorineural (cochlear) hearing impairment and, so, might have been expected in each hearing-impaired individual tested in this study. It is recruitment, perhaps, that partially accounts for an optimal listening level of typically only 20 or 30 dB SL when the degree of impairment is severe or profound (Erber & Witt, 1977). It is also not surprising to encounter over-recruitment in this group of subjects. Audiologists might identify these cases as the individuals who cannot wear amplification successfully. In the presence of profound hearing impairment, a history of severe loudness-tolerance problems may be used to indicate candidacy for a vibratory aid or a cochlear implant as an alternative to conventional auditory amplification.

Absence of recruitment and indications of decruitment are not typical of the severely or profoundly congenitally impaired individual. One case review in the literature (Hawkins, 1982) recently related a history that matches the experience of the subjects in the slow growth-rate group of the present study. The hearing loss was marked by progressive downward shifts in threshold and there was frequent need for more powerful hearing aids. At maximum output the signal was still "soft"; nothing was rated as loud. Overamplification was implicated in the change in threshold, but the high UCL was unexplained.

Etiology as a determinant of recruitment must also be considered in an evaluation of the present results. Those subjects whose etiology was Rh incompatibility (subject U) and anoxia (subject V) might not have had a primarily cochlear hearing loss. Figure 8 indicates that neither subject showed a fast rate of loudness growth.

TOPICS FOR FUTURE RESEARCH

It is not known if a cross modality matching task can be applied to typical clinical populations. Although none of the subjects had any difficulty following the instructions for cross modality matching, the concept of matching magnitudes in two different dimensions may be difficult to convey to younger subjects. The time requirements of the task would not be prohibitive. A block of four trials per intensity required about 20 min for normal-hearing subjects, and only about 10 min for hearing-impaired subjects due to their narrower dynamic range. The task was reliable (in normal-hearing subjects), indicating that one might be able to use even shorter blocks over several sittings.

The validity of cross modality matching as a measure of loudness perception and recruitment is another topic for future research. It is expected that hearing aid fitting procedures with severely and profoundly impaired clients will benefit from this method of defining loudness and, possibly, confirming cases of recruitment where only indirect measures were previously available. The post hoc nature of the analysis of the current data must be emphasized. A goal of future research is to verify that meaningful differences exist among listeners. Cluster analysis is an approach that would allow evaluation of predicted groupings on the basis of other measured hearing characteristics. For example, results could be compared from unilaterally hearing-impaired subjects' performance on both an ABLB test and a cross modality matching task. The eventual goal is to relate results of loudness judgements via cross modality matching to satisfied hearing aid use so that audiologists may have objective criteria for selecting hearing aid characteristics.

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