Loudness growth in individual listeners with hearing losses: A review[a)]

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Abstract: This letter reanalyzes data from the literature in order to test two loudness-growth models for listeners with hearing losses of primarily cochlear origin: rapid growth and softness imperception. Five different studies using different methods to obtain individual loudness functions were used: absolute magnitude estimation, cross-modality matching with string length, categorical loudness scaling, loudness functions derived from binaural loudness summation, and loudness functions derived from spectral summation of loudness. Results from each of the methods show large individual differences. Individual loudness-growth functions encompass a wide range of shapes from rapid growth to softness imperception.

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1. Introduction

Research indicates that there are large individual differences in how loudness grows with increasing sound pressure level for listeners with sensorineural hearing losses of primarily cochlear origin (Dix *et al.*, 1948; Knight and Margolis, 1984; Hellman and Meiselman, 1990; Brand and Hohmann, 2001; Buus and Florentine, 2002; Whilby *et al.*, 2006). In fact, listeners with similar audiograms can have different loudness-growth functions (Hellman, 1994; Florentine *et al.*, 1997). The purpose of this review is twofold: to review individual loudness functions from hearing-impaired listeners (HIL) that have been obtained by various researchers using a variety of methods and to test models of loudness growth for HIL.

Four types (or models) of common loudness-growth functions have been proposed: typical, attenuation, rapid growth, and softness imperception (Florentine, 2004). Typical is the loudness function for normal-hearing listeners (NHL), and is widely known as the power law (Stevens, 1955). It states that loudness is related to the intensity raised to the power 0.3. Although widely cited, the power law is inaccurate in its details at threshold (Richardson and Ross, 1930; Hellman and Zwislocki, 1961) and at moderate levels (Florentine *et al.*, 1996). Buus and Florentine (2001) integrated these modifications and proposed an inflected exponential function (INEX function), which is shown in Fig. 1(a). The slope of the INEX function, shown in Fig. 1(b), is steeper than the power function at low levels and shallower at moderate levels. In addition, loudness at threshold is greater than zero. [For a review, see Florentine and Epstein (2006).]

Of the three common types of loudness growth for HIL, the attenuation type applies to conductive hearing loss and is parallel to the normal loudness function on a logarithmic scale. The rapid-growth type (the same as the classical view of recruitment) described the loudness growth as follows: (1) loudness at threshold is the same for NHL and HIL, (2) loudness from threshold to midlevels of HIL grows more rapidly than for NHL,[1] and (3) loudness is the same

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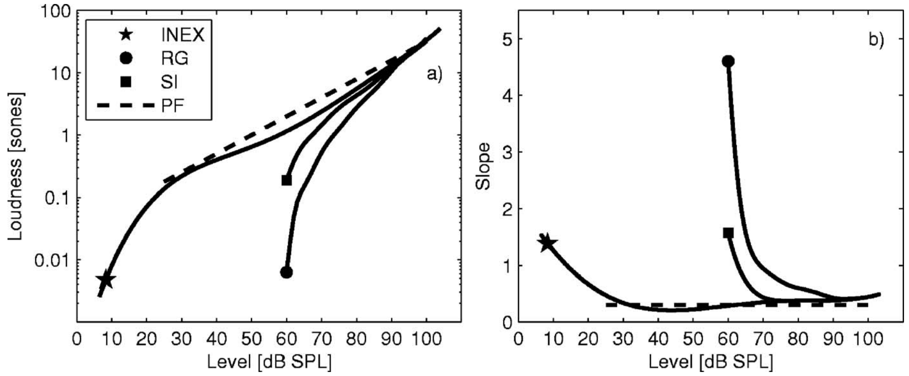

Fig. 1. Comparison of the loudness-growth models: power function (dashed line), INEX function (star); rapid growth (circle), and softness imperception (square). (a) Loudness in sones is plotted as function of sound pressure level. (b) Slopes of the functions shown in (a) are plotted as function of sound pressure level.

or approaches that of NHL at high levels (for a review see Brunt, 1994; Moore, 2003). A typical rapid-growth type of function is shown in Fig. 1(a) by the line identified by a circle. For comparison, the INEX function is represented in the same plot by a line identified by a star. Loudness at threshold is equivalent for both functions. In order to match up with the INEX function at high levels, the rapid growth loudness function must have a very steep slope at and near threshold, as well as at midlevels [see Fig. 1(b)]. The final type of loudness growth is softness imperception, so named because it refers to the inability of the listener to hear soft sounds. This model described loudness growth as follows: (1) loudness at threshold is higher for HIL than NHL, (2) loudness growth at and near threshold is similar for NHL and HIL, (3) the loudness of some HIL exhibits a loss of compression at midlevels that results in faster-than-normal loudness growth, and (4) the loudness-growth function approaches that of NHL at higher levels. A softness imperception type of loudness function is shown in Fig. 1(a) by the line identified by a square.

Because slopes of loudness-growth functions change with level and are essential to a basic understanding of loudness growth, the same data plotted in Fig. 1(a) are plotted with slope on the ordinate in Fig. 1(b). The slope of the softness imperception function starts at the same rate as the INEX function, whereas the rapid growth function starts with a steeper slope than the INEX function. All the functions approach the same slope at high levels.

The rapid loudness growth type is the most well known model. It is well accepted in the audiology community and presented in textbooks as the only model for HIL with sensorineural hearing loss of primarily cochlear origin. The recently proposed softness imperception model is still controversial. Moore (2004) tested the concept of softness imperception by asking four asymmetrical HIL to match the loudness of low SL pure tone across ears. He expected that for HIL with softness imperception, the SL of the tone in the normal ear will be significantly greater than the SL of an equally loud tone in the impaired ear near threshold. Results showed no differences in SL and, therefore, claimed to refute softness imperception. However, asymmetrical HIL have significantly steeper loudness functions than symmetrical HIL (Knight and Margolis, 1984); therefore, this conclusion should be restricted to this specific type of HIL. Buus and Florentine (2002) derived loudness at threshold from loudness matches between pure tones and four-tone complex. Their data indicate that loudness at threshold increases with hearing loss in at least some HILs, supporting the concept of softness imperception. However, according to Moore and Glasberg (2004) the same data can be fitted with a loudness model based on the idea that loudness at threshold is independent of hearing loss. In summary, it may be that neither of the two models correctly describes loudness-growth functions of all HIL. Some listeners may show rapid growth, some softness imperception, and some an intermediate behavior. In order to test these hypotheses, data from five different studies using five different methods to

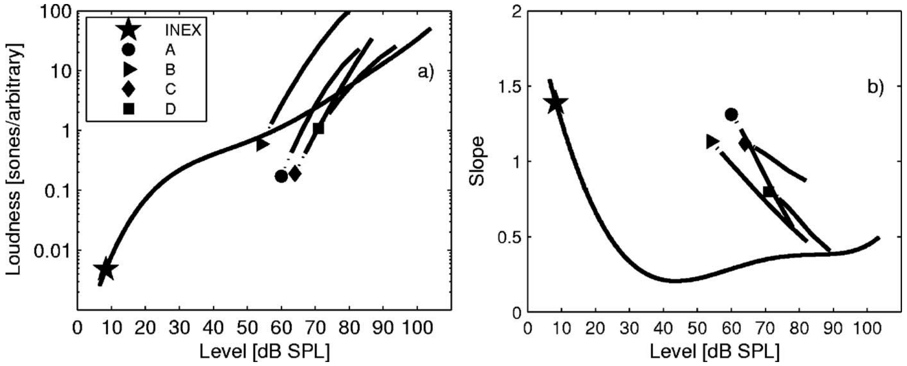

Fig. 2. (a) Individual data of four hearing-impaired listeners (see the inset) from Hellman and Meiselman (1990) are replotted compared with the INEX function in the same manner as Fig. 1(a). (b) Slopes of the loudness functions in (a) are plotted in the same manner as Fig. 1(b).

obtain individual loudness functions for HIL are compared to the models. The loudness function of a listener showing rapid growth should exhibit a steeper slope at and near threshold. A listener showing softness imperception should exhibit a loudness function similar to NHL at low levels, and loss of compression may result in a faster than normal loudness growth at moderate levels.

2. Methods

Data from five studies were reanalyzed. For three studies (cited later in Secs. 3.1, 3.3, and 3.5), the data were not directly accessible. Therefore, the data were extracted from the published figures using the software DATATHIEF (v1.0). The data were then fit with a six-order polynomial in order to reduce the extraction error. For two studies (cited later in Secs. 3.2 and 3.4) the data were directly accessible. The five studies were selected because they used different methods and they showed individual data. From each of these studies four individual listeners were selected to represent the range of responses, then their individual loudness functions were compared with averaged normal data from that study (i.e., the reference for the typical model). A symbol represents the loudness at threshold of each of the HIL in all of the following plots. If not measured, the loudness at threshold was extrapolated from the threshold SPL and the slope of the loudness function at the lowest levels measured. Extrapolated loudness functions are represented in the figures by a dashed line. The slope of every function was calculated from their derivative of the logarithm [$\text{slope}=d(\log(\text{loudness}))/d(\text{level})$].

3. Studies

3.1 Absolute magnitude estimation

Hellman and Meiselman (1990) comprehensively studied the loudness growth of 100 HIL. This review presents the data of only four representative HIL performing magnitude estimation. They were asked to judge the loudness of 1-s tones with a number. Frequencies varied from 500 to 4000 Hz. Figure 2(a) shows the results of the four typical listeners. For comparison, the INEX function is represented by a line identified by a star. The data show that there are individual differences. Figure 2(b) shows the slopes of these functions. For all listeners, the loudness growth at threshold is the same or shallower than the INEX function.

3.2 Cross-modality matching with string length

Marozeau and Florentine (unpublished) asked eight HIL to judge the loudness of 200–ms monaural and binaural tones by cutting a piece of string as long as the sound was loud. [The same procedure was used with NHL in Marozeau *et al.* (2006)]. The tones were either 1 or 2 kHz. Figure 3(a) shows the results of four of their listeners and the average data of eight NHL (from

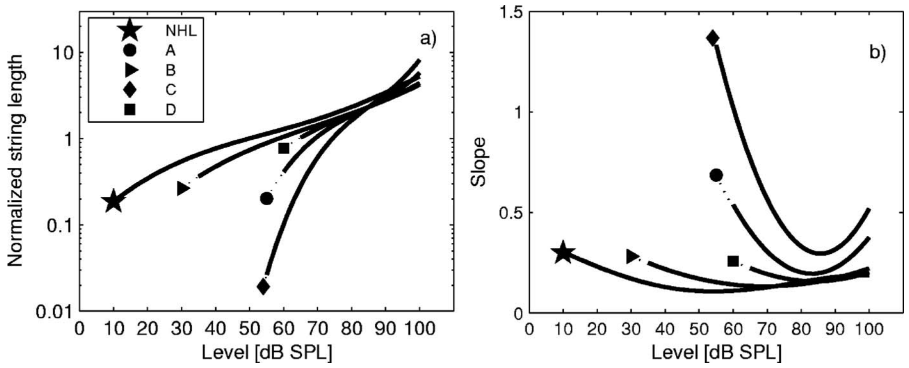

Fig. 3. (a), (b) Individual data of four hearing-impaired listeners from Marozeau and Florentine (unpublished) compared with the group average of eight NHL (Marozeau *et al.*, 2006) plotted in the same manner as Figs. 2(a) and 2(b).

Marozeau *et al.*, 2006). As expected, the slopes are shallower for the cross-modality method than for other methods [see Epstein and Florentine (2005)]. Figure 3(b) shows that listeners B and D share the same slope at threshold and high levels as NHL. Listener C shows a rapid growth of loudness at threshold and listener A shows an intermediate behavior.

3.3 Categorical loudness scaling

Brand and Hohmann (2001) asked eight NHL and eight HIL with different etiologies to rate the loudness of narrowband noises centered at 4 kHz on an 11-category scale, ranging from "very soft" to "very loud." Figure 4(a) shows the individual results in linear scale [as represented in Figs. 3 and 6 of Brand and Hohmann (2001)]. Figure 4(b) shows that listener BH has the same slope as NHL at threshold and high levels; listener BK shows a slope steeper than normal slope at threshold, and the same as normal at high levels; listener MI seems to show a loudness function parallel to the normal function as in the attenuation type of loss; and finally listener DD shows a constant, moderately steep slope at every SPL.

3.4 Binaural loudness summation

Whilby *et al.* (2006) asked eight HIL and eight NHL to adjust the level of a monaural tone to match the loudness of a binaural tone and vice versa. Stimuli were 200-ms 1-kHz tones. Individual loudness functions were extracted from these data. Figure 5(a) shows the individual results and the group average of NHL. Figure 5(b) shows that listener A has a loudness growth

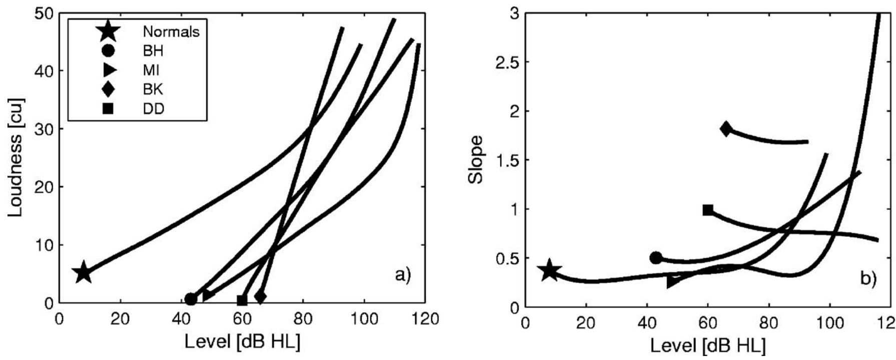

Fig. 4. (a), (b) Individual data of four hearing-impaired listeners from Brand and Hohmann (2001) compared with the group median of eight NHL from the same study plotted in the same manner as Figs. 2(a) and 2(b).

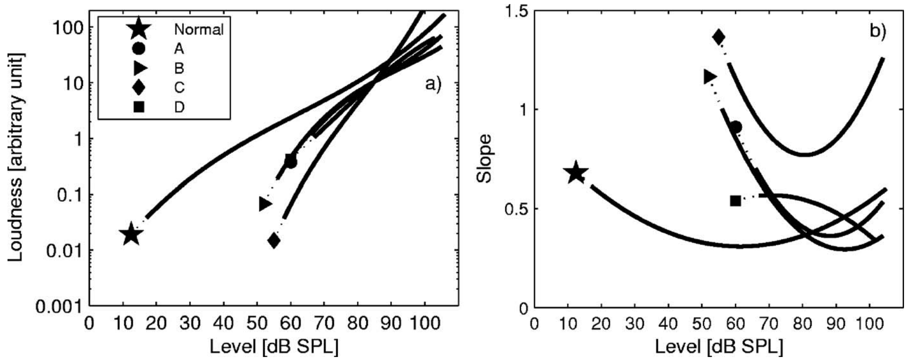

Fig. 5. (a), (b) Individual data of four hearing-impaired listeners from Whilby *et al.* (2006) compared with the group average of eight NHL from the same study plotted in the same manner as Figs. 2(a) and 2(b).

similar to NHL at threshold and high levels.[2] Listener B shows a steeper than normal slope at threshold and a slope similar at high levels. Listener C shows an overall steeper than normal slope. Listener D's function decreases with level.

3.5 Spectral integration of loudness

Buus and Florentine (2002) asked five hearing-impaired listeners to adjust the level of a 1600-Hz tone to match the level of a complex tone centered around that frequency and vice versa. The stimuli were 500 ms. They implemented a method to extract the slope of individual loudness functions from these data. This method allows estimation of the loudness function at and near threshold. Figure 6(a) shows the individual loudness functions and the INEX function. Figure 6(b) shows that loudness growth of all listeners at threshold is the same or shallower than the INEX function. At high levels, loudness growth is similar for both normal and impaired listeners.

4. Discussion

Four out of the five studies presented in this review show the average results from NHL. It is interesting that the loudness functions averaged over many NHL changed among the studies. This indicates that one should be careful when considering a loudness function out of context. It seems reasonable to state that a loudness function does not reflect only the "psychological" dimension of loudness, but this dimension transformed into a measurable quantity (number, classes, string length, etc.). Therefore, a loudness function should only be compared to another

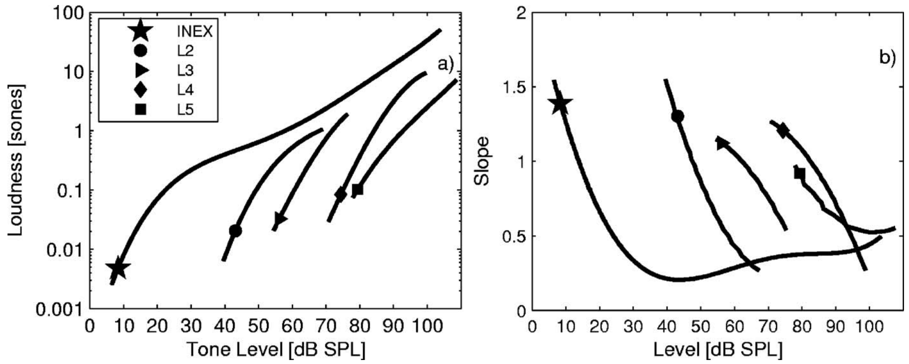

Fig. 6. (a), (b) Individual data of four hearing-impaired listeners from Buus and Florentine (2002) compared with the INEX function from the same paper plotted in the same manner as Figs. 2(a) and 2(b).

loudness function derived with the same method. Furthermore, because Hellman and Meiselman (1990) showed that slope distributions depend strongly on the procedure, it is important to consider this source of variance while analyzing the data. Results from NHL could help to estimate this procedural variability.

The data presented in this review from various published sources strongly indicate that there are large individual differences among the individual loudness functions of HIL. These important differences would be masked if the individual data were averaged. These substantial differences are present in all data sets using five different methods for obtaining loudness functions. The comparison between loudness growth of NHL and individual HIL at low levels shows which type of loudness function is most appropriate. Individual loudness functions range from the rapid growth to the recently described softness imperception. For example, listener C in study 2, listener BK in study 3, and listener C in study 4 can be modeled by rapid growth. Listener A in study 1, listener B in study 2, listener BH in study 3, and listener A in study 4 can be modeled by softness imperception. Listener A in study 2, listener DD in study 3, and listener C in study 4 cannot be modeled by either model in their present form.

These results dispel the notion that all listeners with sensorineural hearing losses of primarily cochlear origin perceive loudness in a similar way. This notion can be traced through the literature since the inception of the concept of recruitment. Textbooks that try to package and simplify information perpetuate this fallacy. Although it is useful to have conceptual models of loudness growth, it is essential that we do not allow one model to dominate our thinking. When one takes the time to examine loudness-growth functions of individual listeners, considerable variation can be found. The individual differences that are apparent in this review should be noted—and perhaps even treasured—because they are likely to reveal important mechanisms that contribute to loudness. These variations may be important for optimal rehabilitation of impaired listeners.

Whereas it is tempting to speculate what mechanisms contribute to the observable variations in loudness, it is not warranted because too little is known about the etiologies of the listeners. More data are needed from larger groups of listeners with well-diagnosed etiologies.

5. Conclusions

This review reviews five experiments using different methods to obtain individual loudness functions of hearing-impaired listeners. Results suggest that: (1) individual differences are more important for hearing-impaired listeners than for normal listeners, (2) some hearing-impaired listeners seem to show rapid growth, some softness imperception, and some a combination of both, and (3) averaging the results across hearing-impaired listeners will mask these differences.

Acknowledgments

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References and links

[1] Moore (2004) describes loudness-growth functions of HIL as follows: (1) HIL and NHL have the same loudness at threshold, (2) both groups show the same loudness growth from 0 to 5dB SL, and (3) HIL show a steeper slope after 5dB SL.

[2] The parabolic shape of the slope is due to the loudness function model using a third order polynomial. In order to model a loudness function with a similar shape as the INEX function, a higher degree polynomial is needed.

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