ADVANCEMENTS IN PSYCHOPHYSICS LEAD TO A NEW UNDERSTANDING OF LOUDNESS IN NORMAL HEARING AND HEARING LOSS

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Abstract

Psychophysics has brought us to a better understanding of loudness growth in subjects with normal hearing and hearing loss of primarily cochlear origin. Three trends in psychophysics have led the way: (1) investigations of the relationship between temporal integration of loudness and the loudness function, (2) investigations of individual differences in loudness functions among normal listeners and listeners with different types of hearing losses, and (3) investigations of how context affects loudness. These trends were aided by technological developments that permitted large amounts of data to be modeled. This has important theoretical implications for understanding loudness in people with normal hearing and hearing losses, as well as applied applications to improve hearing-aid design.

The purpose of this invited paper is to review some psychophysical developments that have led to a better understanding of loudness in subjects with normal hearing and hearing losses over the past twenty-five years at Northeastern University. As is the case in most of science, knowledge has progressed in incremental steps. Three major areas of investigation are noteworthy and are reviewed in the following sections.

1. Investigations of temporal integration of loudness and the loudness function

The puzzling question of how to reconcile two sets of loudness data from normal-hearing listeners has been solved. One set of data clearly indicates that the amount of temporal integration for loudness varies nonmonotonically with level and is greatest at moderate levels (Florentine et al., 1996; Buus et al., 1997). [This holds true for both monaural and binaural loudness summation (Whilby et al., 2006).] The second set of data indicates that the loudness functions for short and long noises (Stevens and Hall, 1966) and tones are parallel when plotted on a log scale (Epstein and Florentine, 2005). In other words, there is a constant vertical distance between loudness functions for short- and long-durations tones, i.e., the equal-loudness-ratio hypothesis holds (for review see Epstein and Florentine, 2005). A logical deduction followed: If the vertical distance between loudness functions for short and long sounds (plotted on a log scale as a function of level) is independent of level, then the loudness-growth functions for these stimuli must be shallower at moderate levels than at low and high levels. Computer modeling of large amounts of data in the literature ensued to answer this question. For example, polynomial fitting procedures reveal orderly deviations from a simple power function that are important (e.g., Marozeau et al., 2006). Careful examination of the loudness growth function reveals that it is shallower at moderate levels than at low and high levels (for review, see Florentine and Epstein, 2006). This is consistent with masking and peripheral nonlinearity (Oxenham and Bacon, 2004).

This new discovery that the loudness function is less steep at moderate levels than at low and high levels was combined with data that have been around for decades. The older data indicate that the loudness function becomes steep as it approaches threshold (Hellman and Zwislocki, 1961; also more recent data Marks, 1979; Canévet et al., 1986; Buus et al., 1998). Near threshold, the average slope is about unity or slightly larger. As level increases, the slope decreases as the function approaches moderate levels (see Buus et al., 1997; Buus and Florentine, 2002). These two deviations to the power law led to a non-stationary point of inflection law [or an inflected exponential (INEX) law] that appears to be the best description of currently available data for normal listeners. For review of the INEX law, see Florentine and Epstein (2006).

2. Investigations of individual differences in loudness functions among normal listeners and listeners with different types of hearing losses

In order to compare the data from normal and impaired listeners, an understanding of loudness at and near threshold is essential. Two sets of data support the contention that loudness at threshold is not zero for normal listeners. Both sets of data examine the form of the loudness function in normal listeners at low levels. The first set of data was derived from loudness-matching experiments between equally loud tones and tone complexes, i.e., spectral integration of loudness (Buus et al., 1998). Listeners matched the loudness of tone complexes comprised of sub-threshold components with pure tones above threshold. Results show that a tone complex composed of components at threshold can easily be heard and can be relatively loud. This result is only possible if all tones contributed to the loudness, even those below threshold. The second set of data consists of the slopes of the loudness function at threshold, which average 1.3 (Buus et al., 1998). These data are consistent with loudness functions obtained with a wide variety of methods that yield a slope close to unity. A slope close to unity indicates a positive loudness at threshold in accord with the new loudness standard. Some of the most surprising data and modeling indicate that loudness grows at a normal (or close to normal) rate near the elevated thresholds of listeners with cochlear hearing losses and that loudness at threshold may be greater than normal in <u>some</u> listeners (Buus and Florentine, 2002).

If loudness at threshold is not zero, it may have a value that is different among individuals. It seems reasonable that disturbances in the cochlea that cause hearing loss could cause a corresponding change in loudness at threshold. To gain insight into this possibility, simple reaction times (RTs) were measured as a function of sensation level for 200-ms tones at different frequencies (Florentine, Buus, and Rosenberg, 2005). Because equal RTs for tones have been shown to correspond closely to equal loudness and because measurements of RTs are possible even when tones are set at threshold (for review see Wagner et al., 2004), RTs were used to assess loudness at threshold. In this paradigm, tones of various levels are presented to listeners and their task is to press a key as soon as they hear a sound; the louder the sound, the faster the RTs. Therefore, RTs were tested at two frequencies in listeners with high-frequency cochlear hearing losses. One frequency was chosen to have normal hearing or a mild hearing loss; the other was chosen to have a moderate to severe hearing loss. Results for six listeners with cochlear hearing losses consistently showed faster RTs to tones at and near threshold for the frequency with elevated threshold than for the frequency with normal or near-normal threshold. Normal controls showed an effect of frequency in some listeners, but the effect was not large enough to account for the difference attributable to hearing loss (Epstein and Florentine, 2006). This finding provides strong support for the concept that some hearing-impaired listeners have a greater loudness than normal listeners at threshold. In addition to the RT data from six impaired listeners described above, RT data from 22 impaired listeners and equal-loudness balances from 13 of the 22 listeners were obtained to check the relationship between RT and loudness (Florentine, Mumby, and Cleveland, 2004). Agreement is good in trained listeners.

This finding provides evidence against the pervasive and long-held notion that all listeners with hearing losses of primarily cochlear origin show abnormally rapid loudness growth near their elevated thresholds (i.e., recruitment). It also indicates that most hearing scientists have been using a faulty theoretical framework for over 60 years by assuming that all impaired listeners with losses of primarily cochlear origin perceive loudness growth in a similar manner. If loudness at threshold is greater than normal in some listeners with cochlear hearing loss, they have a reduced dynamic range, not only in terms of SPL, but also in terms of loudness. This phenomenon is known as "softness imperception," i.e., the inability to hear a range of low loudnesses that can be heard by normal listeners.

The new concept of softness imperception has very important theoretical and practical implications. It agrees with recent knowledge about basilar-membrane mechanics. It also provides a scientific basis for the design of hearing aids that apply expansion to low-level sounds to ensure that only sounds whose normal loudness is above the impaired listener's elevated threshold for loudness are amplified to audibility (e.g., Blamey, 2005). It also provides a basis for understanding the common observation that wide-dynamic-range-compression hearing aids have optimal compression rates that are considerably smaller than those derived from mapping the physical dynamic range of the impaired ear into that of the normal ear. This is because results from some subjects indicate that the reduction of physical dynamic range is accompanied by a reduction in the subjective dynamic range of loudness.

There are important individual differences in loudness growth functions of listeners with hearing losses of primarily cochlear origin. Marozeau and Florentine (2007) reanalysed data in the literature from these listeners in order to test both loudness-growth models: rapid growth (a.k.a. recruitment) 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. These results indicate that neither theory (i.e., classical recruitment or softness imperception) accounts for all the data. It is clear that some of the impaired listeners deviate markedly from the average, indicating that group data do not accurately represent the behavior of all impaired listeners.

3. Investigations of how context affects loudness

A new understanding has been reached regarding ways that context affects loudness and loudness judgments. Previously, these context effects were often regarded as unknown sources of variability. One of the most interesting and pervasive context effect is known as induced loudness reduction (ILR); it is also known as the slippery-context effect (Marks, 1992) and loudness recalibration (Marks, 1994; Arieh and Marks, 2001). It is a phenomenon by which a preceding higher-level tone (an inducer tone) reduces the loudness of a lower-level tone (a test tone). The strength of this effect depends on the following factors: tone levels, frequency separation between the inducer and test tone, duration of inducer and test tone, time separation between inducer and test tone, number of exposures to the inducer, and individual differences (for review see Epstein, 2007).

The mechanism of ILR is still a matter of debate, but any hypotheses about the basis for ILR will have to take into account the existence of contralateral ILR. For example, Nieder et al. (2007) measured loudness reduction induced by a contralateral tone. The ILR of a weaker tone caused by a preceding stronger tone was measured with both tones in the same ear (ipsilateral ILR) and also in opposite ears (contralateral ILR). The two tones were always equal in duration and were presented repeatedly over several minutes. When the tone duration was 200 ms, for 24 listeners the loudness reduction averaged 11 dB under ipsilateral ILR and 6 dB under contralateral ILR. When the duration was 5 ms, ILR was 8 dB for both the ipsilateral and contralateral conditions. For each duration, ipsilateral and contralateral ILR were strongly correlated (r around 0.80). Furthermore, any over-arching explanation of ILR will have to take into account that it can occur even when the frequency separation between the inducer and test tone is wider than four equivalent rectangular bandwidths (Marozeau and Epstein, 2008).

In two elegant little experiments, Epstein and Gifford (2006) showed that the majority of ILR studies have used an experimental paradigm that resulted in an underestimation of the amount of ILR, because the level of the comparison tone in the baseline condition tends to be substantially higher than in the experimental condition. Because of this difference, exposure to the baseline condition immediately prior to the experimental condition causes an unintended ILR for the comparison tone. Therefore, it is highly likely that loudness data in the literature are confounded by ILR.

The discovery of ILR has implications for psychophysical procedures. For example, the marked reduction in loudness under ILR, which persists across frequency and over many minutes, means that care must be taken in the sequence of sound presentation. Some of the measurement differences in the literature could result from differences in psychophysical procedures. To gain insight into this possibility, Silva and Florentine (2006) used four adaptive two-interval, two-alternatives-forced-choice procedures to obtain equal-loudness matches between 5- and 200-ms 1-kHz tones as a function of level for each of six normal listeners. The procedures differed primarily in the sequence in which the stimuli were presented. The variations tested included: the ordering of stimuli by amplitude across blocks of trials (both increasing and decreasing amplitudes), randomizing the order across those blocks, and randomizing the order within blocks. The random-within-block procedure yielded a significantly greater amount of temporal integration than the other three procedures. The results show significant differences in temporal integration measurements at moderate levels for the same listeners across different procedures. Therefore, although there are individual differences among listeners in the amount of temporal integration measured across paradigms, the choice of paradigm also affects the amount of temporal integration measured at moderate levels. It is likely that ILR is responsible for the differences among the psychophysical procedures.

Given the large inter-subject differences in the amount of ILR (Epstein 2007), loudness functions and loudness growth may vary substantially depending on stimulus order and context. This is likely to influence measurements in the laboratory as well as the clinic, which could influence differences in hearing-aid programming depending on the evaluation procedure.

4. Looking toward the future

Over the past twenty-five years, significant progress has been made in understanding the interconnections among loudness data, individual differences in loudness of listeners with normal hearing and hearing losses, and loudness context effects. These findings restrict the possibilities for the development of a theory of loudness and its physiological basis. Recent research has led to a new appreciation of individual differences and promising new ideas for understanding normal hearing and hearing loss rehabilitation. Understanding loudness of people with hearing losses is important for their rehabilitation. According to the National Institute of Deafness and Communication Disorders, one out of ten people have a hearing loss and many people will develop a hearing loss as they age. The most common treatment for hearing loss is hearing aids. Kochkin's survey (2005) of 1500 hearing-aid users indicates that only 60% of them reported being satisfied when asked about comfort with loud sounds. It is highly likely that attention to individual loudness differences will lead to customize hearing aids with effective level algorithms to compensate for alterations in loudness and for binaural loudness summation (Marozeau and Florentine, 2009). Prospects for the future are quite hopeful as knowledge from different areas and psychoacoustics merge.

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