11 Loudness

The intensity of a sound refers to its physical magnitude, which may be expressed in such terms as its power or pressure. Turning up the "volume" control on a stereo amplifier thus increases the intensity of the music coming out of the loudspeakers. This intensity is easily measured by placing the microphone of a sound-level meter near the loudspeaker. The perception of intensity is called **loudness**; generally speaking, low intensities are perceived as "soft" and high intensities as "loud." In other words, intensity is the physical parameter of the stimulus and loudness is the percept associated with that parameter. However, intensity and loudness are not one and the same; although increasing intensity is associated with increasing loudness, there is not a simple one-to-one correspondence between the two. Furthermore, loudness is also affected by factors other than intensity. For example, it is a common experience to find that loudness changes when the "bass" and "treble" controls of a stereo amplifier are adjusted, even though the volume control itself is untouched. (*Bass* and *treble* are the relative contributions of the lower and higher frequency ranges, respectively. Thus, raising the bass emphasizes the low frequencies, and raising the treble emphasizes the high.)

LOUDNESS LEVEL

We may begin our discussion of loudness by asking whether the same amount of intensity results in the same amount of loudness for tones of different frequencies. For example, does a 100-Hz tone at 40 dB SPL have the same loudness as a 1000-Hz tone also presented at 40 dB? The answer is no. However, a more useful question is to ask how much intensity is needed in order for tones of different frequencies to sound equally loud. These values may be appropriately called **equal loudness levels**.

Although the exact procedures differ, the fundamental approach for determining equal loudness levels is quite simple. One tone is presented at a fixed intensity level, and serves as the reference tone for the experiment. The other tone is then varied in level until its loudness is judged equal to that of the reference tone. Subsequent studies have employed adaptive testing strategies (see Chap. 7) to accomplish loudness matching (e.g., Jesteadt, 1980; Schlauch and Wier, 1987; Florentine et al., 1996; Buus et al., 1997). The traditional reference tone has been 1000 Hz, but Stevens (1972) suggested the use of 3150 Hz, where threshold sensitivity is most acute. A third frequency tone may then be balanced with the reference tone; then a fourth, a fifth, and so on. The result is a list of sound pressure levels at various frequencies, all of which sound equal in loudness to the reference tone. We can then draw a curve showing these equally loud sound pressure levels as a function of frequency. If the experiment is repeated for different reference tone intensities, the result is a series of contours like the ones in Fig. 11.1.

The contour labeled "40 phons" shows the sound pressure levels needed at each frequency for a tone to sound equal in loudness to a 1000-Hz reference tone presented at 40 dB SPL. Thus, any sound that is equal in loudness to a 1000-Hz tone at 40 dB has a loudness level of 40 phons. A tone that is as loud as a 1000-Hz tone at 50 dB has a loudness level of 50 phons, one that is as loud as a 1000-Hz tone at 80 dB has a loudness level of 80 phons, etc. We may now define the **phon** as the unit of **loudness level**. All sounds that are equal in phons have the same loudness level even though their physical magnitudes may be different. Since we are expressing loudness level in phons relative to the level of a 1000-Hz tone, phons and decibels of sound pressure level are necessarily equal at this frequency.

The earliest equal loudness data were reported by Kingsbury in 1927. However, the first well-accepted **phon curves** were published in 1933 by Fletcher and Munson, and as a result, **equal-loudness contours** have also come to be known as **Fletcher–Munson curves**. Subsequently, extensive equal loudness contours were also published by Churcher and King (1937) and by Robinson and Dadson (1956). Equal loudness contours have also been reported for narrow bands of noise (Pollack, 1952). The curves shown in Fig. 11.1 reflect the values in the current international standard (ISO 226–2003).

At low loudness levels, the phon curves are quite similar in shape to the minimum audible field (MAF) curve. Thus, considerably more intensity is needed to achieve equal loudness for lower frequencies than for higher ones. However, notice that the phon curves tend to become flatter for higher loudness levels, indicating that the lower frequencies grow in loudness at a faster rate than the higher frequencies, overcoming, so to speak, their disadvantage at near-threshold levels. This effect can be experienced in a simple, at-home experiment. We begin by playing music from a CD at a moderate level, with the bass and treble controls set so that the music is as "natural sounding" as possible. If we decrease the volume to a much softer level, the music will also sound as though the bass was decreased, demonstrating the de-emphasis of the low (bass) frequencies at lower loudness levels. If we raise the volume to a quite loud level, then the music will sound as though the bass was turned up as well. This "boomy" sound reflects the faster rate of growth for the lower frequencies with increasing loudness levels.

Since the same sound pressure level will be associated with different loudness levels as a function of frequency, it would be convenient to have a frequency-weighting network that could be applied to the wide-band sounds encountered in the environment. Such a weighting function would facilitate calculating the loudness of such sounds as highway noise, sonic booms, etc. This has been done to some extent in the construction of electronic-weighting networks for sound level meters. These networks are rough approximations to various phon curves. For example, the **A-weighting** network approximates the general shape of the

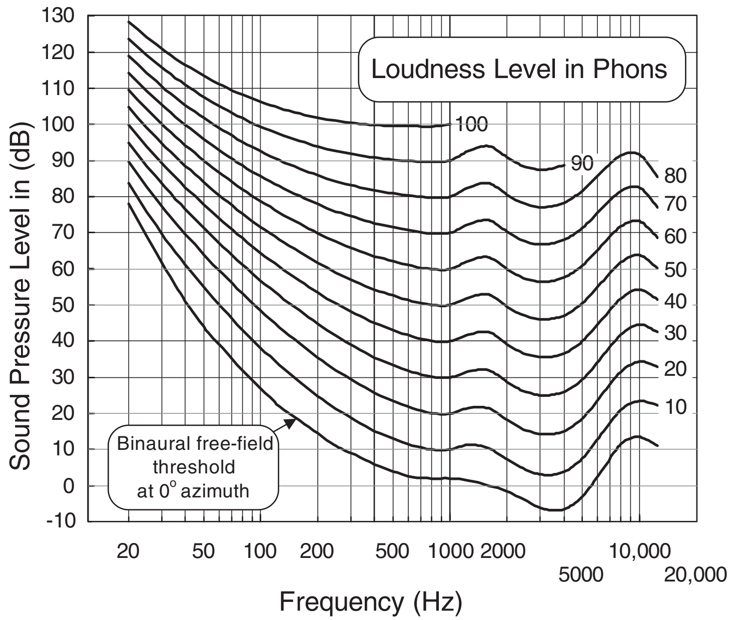

Figure 11.1 Equal loudness-level or phon curves (based on values in ISO 226–2003) and binaural free-field auditory threshold curve (based on values in ANSI S3.6–2004 and ISO 389–7-2005). Notice how the loudness level in phons corresponds to the number of decibels at 1000 Hz.

40-phon curve by de-emphasizing the low frequencies and more efficiently passing the high. The **B-weighting** network roughly corresponds to the 70-phon loudness level, and the **C-weighting** network is designed to mimic the essentially flat response of the ear at high loudness levels. These weightings are illustrated in Fig. 11.2. Sound levels that reflect the A-weighting network are expressed as **dB-A**, and **dB-C** refers to C-weighted sound levels (**dB-B** refers to B-weighted sound levels, but are rarely used).

The use of loudness levels represents a significant improvement over such vague concepts, as "more intense sounds are

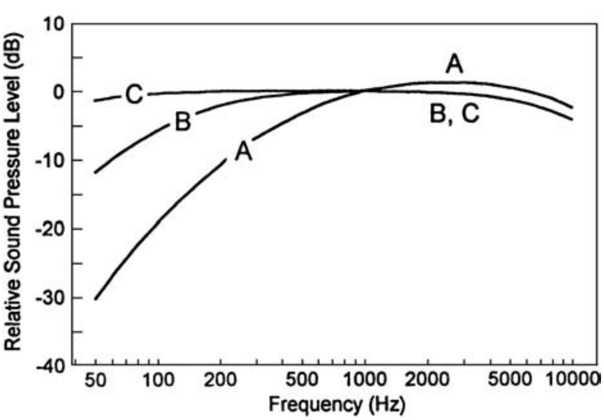

Figure 11.2 Frequency response curves for the A, B, and C weightings. Notice how the lower frequencies are de-emphasized significantly by the A weighting and less so by the B weighting, while the C-weighting network has a frequency response that is almost flat.

louder." However, the phon itself does not provide a direct measure of loudness, per se. We must still seek an answer to the question of how the loudness percept is related to the level of the physical stimulus.

LOUDNESS SCALES

Loudness scales show how the loudness percept is related to the level of the sound stimulus. Since we are interested not only in the loudness of a particular sound, but also in how much louder one sound is than another, the relationship between loudness and sound level is best determined with direct ratio scaling techniques (see Chap. 7). This approach was pioneered and developed by Stevens (1955), 1956a, 1956b, 1957a, 1959, 1975), whose earliest attempts to define a ratio scale of loudness used the fractionalization method (Stevens, 1936). Stevens later adopted the use of magnitude estimation and magnitude production (Stevens, 1956a, 1956b), and the preponderance of subsequent work has employed these techniques alone or in combination (e.g., Hellman and Zwislocki, 1963, 1964, 1968; Stevens and Guirao, 1964; Stevens and Greenbaum, 1966; Rowley and Studebaker, 1969; Hellman, 1976).

The intensity difference limen (DLI), or just noticeable difference (jnd), has also been proposed as a basis for loudness scaling, as has been the partitioning of the audible intensity range into equal loudness categories. However, the consensus of data supports ratio scaling. See Robinson's (1957) review and study, and also Gardner (1958) and Stevens (1959) for summaries of the controversy, as well see Marks (1974a) and Stevens (1975) for informative treatments within the more general context of psychophysics.

The unit of loudness is called the **sone** (Stevens, 1936), such that one sone is the **loudness** of a 1000-Hz tone presented at 40 dB SPL. Since sound pressure level in decibels and loudness level in phons are equivalent at 1000 Hz, we may also define one *sone* as the *loudness* corresponding to a *loudness level* of 40 *phons*. We may therefore express loudness in sones as a function of loudness level in phons (Robinson, 1957) as well as a function of stimulus level. Since loudness level does not vary with frequency (i.e., 40 phons represents the same loudness level at any frequency even though the SPLs are different), we can ignore frequency to at least some extent when assigning loudness in sones to a tone, as long as sones are expressed as a function of phons.

The **sone scale** is illustrated in Fig. 11.3 and is easily understood. Having assigned a value of one sone to the reference sound, we assign a loudness of two sones to the intensity that sounds twice as loud as the reference, 0.5 sones to the level that sounds half as loud, etc. For the most part, loudness in sones is a straight line when plotted as a function of sound level on log–log coordinates, revealing a **power function** relationship. In other words, the perception of loudness (L) may be expressed as a power (e) of the physical stimulus level (I), according to the formula

$$L = kI^e \tag{11.1}$$

where k is a constant. (The value of the constant k depends upon the units used to express the magnitudes.) The manner in which loudness is related to the intensity of a sound is usually considered to be a case of **Stevens' power law** (1957b), which states that sensation grows as of stimulus level. Notice in the figure, however, that the straight-line function actually applies above about 40 dB. The exponent indicates the rate at which the sensation grows with stimulus magnitude. Thus, an exponent of 1.0 would mean that the magnitude of the sensation increases at the same rate as the stimulus level (as is the case for line length). Exponents less than 1.0 indicate that the sensation grows at a slower rate than physical stimulus level (examples are *loudness* and *brightness*), whereas exponents greater than 1.0 indicate that the perceived magnitude grows faster than the physical level (examples are *electric shock* and *heaviness*). Conveniently, the exponent also corresponds to the slope of the function.

Early studies resulted in a median exponent of 0.6 for loudness as a function of sound pressure level so that a 10-dB level increase would correspond to a doubling of loudness (Stevens, 1955); and Robinson (1957) reported that loudness increased twofold with a change in loudness level of 10 phons. This is essentially equivalent to saying that a doubling of loudness corresponds to a tripling of signal level. However, not all studies have reported this value. For example, Stevens and Guirao (1964) reported exponents averaging 0.77, and Stevens (1972) proposed an exponent of 0.67 (in which case a doubling of loudness would correspond to a 9-dB increase). There is a fair amount of variability in loudness function exponents among subjects, although the individual exponents are very reliable (Logue, 1976; Walsh and Browman, 1978; Hellman, 1981; Hellman and Meiselman, 1988). Overall, the preponderance of the available data seems to point to an exponent of 0.6 as the most representative value (Marks, 1974b; Hellman, 1976, 1981; Scharf, 1978; Canevet et al., 1986; Hellman and Meiselman, 1988, 1993).

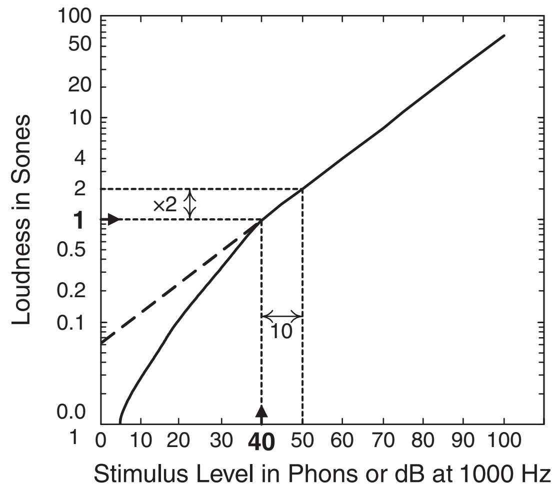

Figure 11.3 The sone scale depicts the relationship between loudness and stimulus level, where 1 sone is the loudness of a 40-dB tone at 1000 Hz (or 40 phons at other frequencies). Loudness doubles (halves) when the stimulus increases (decreases) by 10 dB (phons). Instead of continuing as a straight line for lower stimulus levels (represented by the dashed segment), the solid curve (based on values in ANSI S3.4–2007, Table 7) shows that the actual function curves downward below 40 phons, revealing faster growth of loudness at lower stimulus levels.

The straight-line relationship between loudness in sones and stimulus level in phons (or dB at 1000 Hz), as just described, actually does not occur at stimulus levels below about 40 dB (e.g., Hellman and Zwislocki, 1961, 1963; Scharf, 1978; Canevet et al., 1986; Buus, Muesch, and Florentine, 1998; ANSI S3.4–2007). Instead, the loudness function actually becomes steeper at lower stimulus levels, indicating faster loudness growth. Thus, the function actually curves downward below 40 phons as in Fig. 11.3. Moreover, instead of auditory threshold having a loudness level of 0 phons and a loudness of 0 sone, the ANSI S3.4–2007 incorporates the more correct actual values of 2 phons and 0003 sones (see, e.g., Moore et al., 1997; Buus et al., 1998; Glasberg and Moore, 2006).

Various methods for calculating the loudness of a given actual sound have been developed over the years (e.g., Zwicker, 1958; Stevens, 1961, 1972; ISO 532–1975; ANSI S3.4–1980; Moore, Glasberg, and Baer, 1997; Zwicker and Fastl, 1999; Glasberg and Moore, 2006; ANSI S3.4–2007). The current approach is described in ANSI S3.4–2007 and is based on a model by Moore and colleagues (Moore et al., 1997; Glasberg and Moore, 2006).

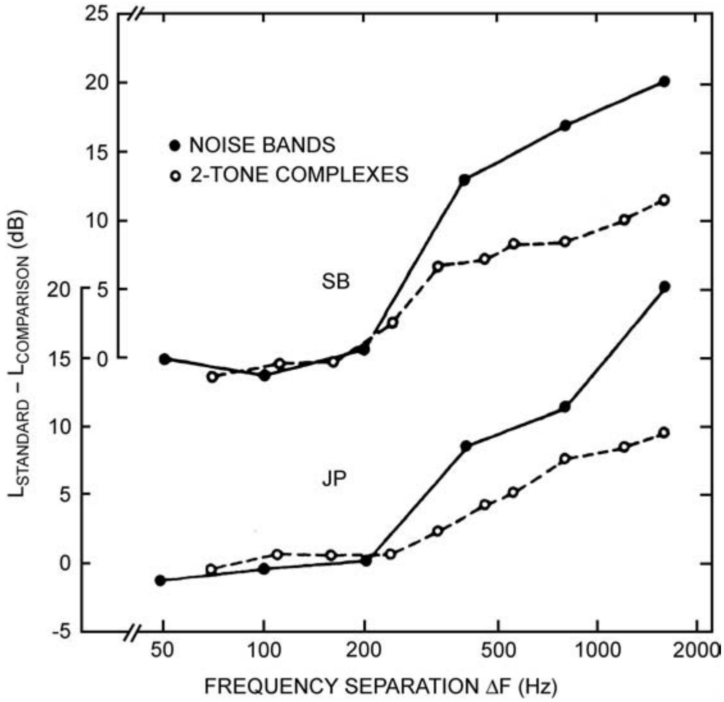

Figure 11.4 Effect of critical bandwidth upon loudness summation for a two-tone complex (open circles) and bands of noise (filled circles) for two subjects (SB and JP). Test level was 65 dB SPL and center frequency was 1000 Hz (see text). *Source*: From Florentine et al. (1978), with permission of *J. Acoust. Soc. Am.*

It can be used to calculate the loudness of any continuous sound containing noise and/or tonal components, presented either monaurally (to one ear) or binaurally (to both ears). The procedure itself should be performed by using computer software that is readily available (Glasberg and Moore, 2007; ANSI S3.4–2007) because it is quite laborious when done manually. We will not attempt to outline the details, but the general framework is as follows. The spectrum reaching the cochlea is determined by adjusting the stimulus spectrum to account for the transfer functions (a) from the sound field [1] or the earphones to the eardrum, and (b) through the middle ear (see Chap. 3). From this, the excitation level in the cochlea is determined for each auditory filter, expressed as the equivalent rectangular bandwidth (ERBs; see Chap. 10),[2] which is in turn converted into loudness values in sones per ERB. The overall loudness of the sound in sones is then calculated by summing the values for all of the ERBs. Consistent with existing date (Fletcher and Munson, 1933; Hellman and Zwislocki, 1963; Marks, 1978, 1987), binaural loudness is calculated to be twice that of monaural loudness when the same sound is presented to both ears.

[1] Different transfer functions are provided for free field and diffuse field measurements.

[2] The current approach employs ERBs instead of the critical bands used in earlier methods (e.g., ANSI S3.4–1980;), among other considerations.

LOUDNESS AND BANDWIDTH

The critical band concept was introduced with respect to masking in the last chapter. As we shall see, loudness also bears an intimate relationship to the critical bandwidth, and loudness experiments provide a direct estimate of the width of the critical band. As Scharf (1970) pointed out, it is convenient to think of the **critical band** as the bandwidth where abrupt changes occur. Consider the following experiment with this concept in mind.

Suppose pairs of simultaneous tones are presented to a subject, both tones always at the same fixed level. The first pair of tones presented is very close together in frequency, and the subject compares their loudness to the loudness of a standard tone. The frequency difference between the two tones is then increased, and the resulting loudness is again compared to the standard. We find that the loudness of the two tones stays about the same as long as the tones are separated by less than the critical bandwidth, but that there is a dramatic increase in loudness when the components are more than a critical bandwidth apart. The open circles in Fig. 11.4 show typical results for two subjects. In this figure, the amount of **loudness summation** is shown as the level difference between the standard and comparison stimuli (ordinate) as a function of bandwidth (abscissa). Notice that the loudness of the two-tone complex stays essentially the same for frequency separations smaller than the critical bandwidth (roughly 200 Hz in this example), whereas loudness increases

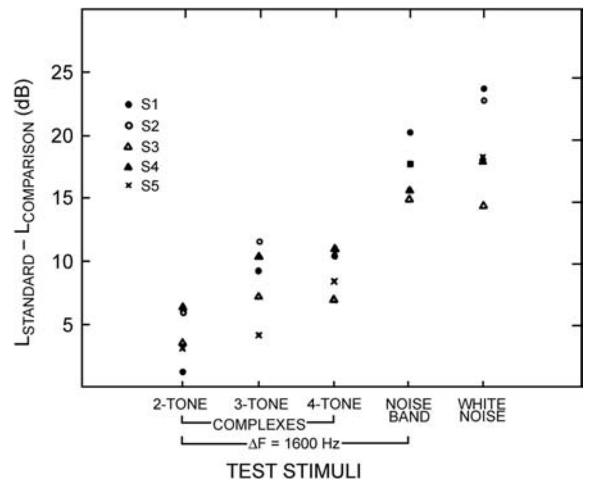

Figure 11.5 Loudness summation for tonal complexes and for noise (symbols show data for individual subjects). *Source*: From Florentine et al. (1978), with permission *J. Acoust. Soc. Am.*

when the frequency difference is greater than the width of the critical band.

That loudness remains essentially the same for bandwidths (or frequency separations) smaller than the critical band, but increases when the critical band is exceeded, has been demonstrated for two-tone and multitone complexes, and also for bands of noise (Zwicker and Feldtkeller, 1955; Zwicker and Feldtkeller, 1955; Feldtkeller and Zwicker, 1956; Zwicker et al., 1957; Scharf, 1959; Florentine et al., 1978). This loudness summation effect is minimal at near-threshold levels, and the greatest loudness increases occur for moderate signal levels (Zwicker and Feldtkeller, 1955; Zwicker et al., 1957; Scharf, 1959). As Figure 11.5 shows, loudness summation becomes greater as the number of components of a multitone complex is increased, with the most loudness summation occurring for bands of noise wider than the critical band (Florentine, Buus, and Bonding, 1978). This relation is shown in Fig. 11.4, in which the same loudness results from both two-tone complexes (open circles) and noise bands (filled circles) narrower than the critical band, but much greater loudness summation results for the noise when the critical bandwidth is exceeded.

TEMPORAL INTEGRATION OF LOUDNESS

Temporal integration (summation) at threshold was discussed in Chapter 9, where we found that sensitivity improves as signal duration increases up to about 200 to 300 ms, after which thresholds remain essentially constant. Temporal integration was also covered with respect to the acoustic reflex in Chapter 3. A similar phenomenon is also observed for loudness (e.g., Miller, 1948; Small et al., 1962; Creelman, 1963; Ekman et al., 1966; J.C. Stevens and Hall, 1966; Zwislocki, 1969; McFadden, 1975; Richards, 1977). Increasing the duration of a very brief signal at a given level above threshold will, within the same general time frame as in the cases previously discussed, cause it to sound louder.

There are two basic techniques that may be used to study the temporal integration of loudness. One method is similar to that used in establishing phon curves. The subject is presented with a reference sound at a given intensity and is asked to adjust the level of a second sound until it is equal in loudness with the first one (Miller, 1948; Small et al., 1962; Creelman, 1963; Richards, 1977). In such cases, one of the sounds is “infinitely” long (i.e., long enough so that we may be sure that temporal integration is maximal, say 1 s), and the other is a brief tone burst (of a duration such as 10 ms, 20 ms, 50 ms, etc.). Either stimulus may be used as the reference while the other is adjusted, and the result is an equal loudness contour as a function of signal duration. The alternate method involves direct magnitude scaling from which equal loudness curves can be derived (Ekman et al., 1966; J.C. Stevens and Hall, 1966; McFadden, 1975).

Figure 11.6 shows representative curves for the temporal integration of loudness. These curves are based upon the findings of Richards (1977). In his experiment, test tones of various durations were balanced in loudness to a 500-ms reference tone presented at either 20, 50, or 80 dB SPL. The ordinate shows the test tone levels (in dB SPL) needed to achieve equal loudness with the reference tone. This quantity is plotted as a function of test-tone duration on the abscissa. Notice that loudness increases (less intensity is needed to achieve a loudness balance with the reference tone) as test-tone duration increases. This

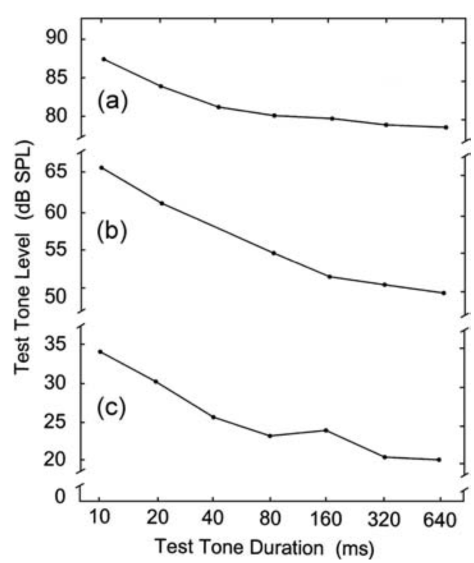

Figure 11.6 Temporal integration of loudness at 1000 Hz based upon loudness balances to a 500-ms tone presented at (a) 20 dB SPL, and (b) 50 dB SPL, and (c) 80 dB SPL. The steeper portions of the functions have slopes of (a) 10.5, (b) 12.5, and (c) 12.0 dB per decade duration change. *Source*: Based upon data by Richards (1977).

increase in loudness is greater for increases in duration up to about 80 ms, and then tends to slow down. In other words, increases in duration from 10 to about 80 ms has a steeper loudness summation slope than increases in duration above 80 ms. However, Richards did find that there was still some degree of additional loudness integration at longer durations.

These data are basically typical of most findings on temporal integration of loudness. That is, there is an increase of loudness as duration is increased up to some "critical duration," and loudness growth essentially stops (or slows down appreciably) with added duration. On the other hand, the critical duration is quite variable among studies and has generally been reported to decrease as a function of sensation level (e.g., Miller, 1948; Small et al., 1962), though not in every study (e.g., J.C. Stevens and Hall, 1966). In addition, the rate at which loudness has been found to increase with duration varies among studies. McFadden (1975) found large differences also among individual subjects. Richards (1977) fitted the steeper portions of the temporal integration functions with straight lines and found that their slopes were on the order of 10 to 12 dB per decade change in duration. The mean values are shown in Fig. 11.6 and agree well with other studies (Small et al., 1962; J.C. Stevens and Hall, 1966). Temporal integration for loudness is also affected by the sensation level (SL) at which the loudness matches are made, with a greater amount of temporal integration occurring at moderate levels (between roughly 20–50 dB SL) compared to higher or lower sensation levels (Florentine et al., 1996; Buus et al., 1997). One might note at this point that the results of loudness integration experiments have been shown to be affected by the methodology used, and by the precise nature of the instructions given to the patients, and also by confusions on the part of subjects between loudness and duration of the signal (Stephens, 1974).

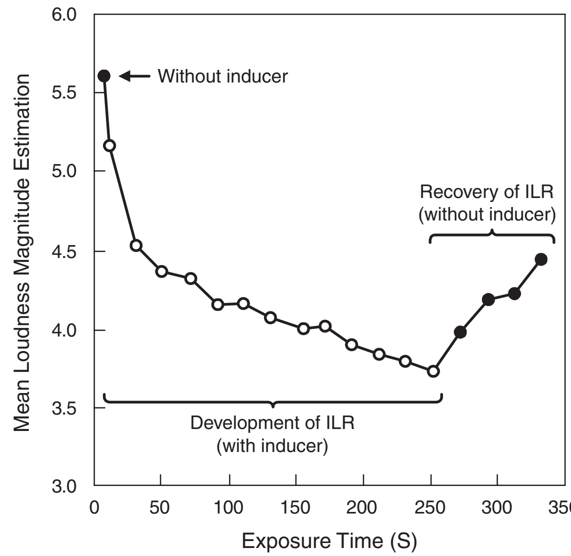

Figure 11.7 The development and recovery from induced loudness reduction (ILR) or loudness recalibration. Loudness magnitude estimates for 70-dB SPL test tone bursts presented alone (filled symbols) and following 80-dB SPL inducer tone bursts (open symbols). See text. *Source*: Reprinted with permission from Wagner and Scharf, 2006, *Journal of Acoustical Society of America, Vol 119*, p. 1017, © 2006, Acoustical Society of America.

INDUCED LOUDNESS REDUCTION (LOUDNESS RECALIBRATION)

Induced loudness reduction (ILR) or **loudness recalibration** is a commonly encountered phenomenon in which the loudness of a test tone decreases when it follows the presentation of a stronger tone (e.g., Mapes-Riordan and Yost, 1999; Arieh and Marks, 2003a, 2003b; Nieder, Buus, Florentine, and Scharf, 2003; Arieh, Kelly, and Marks, 2005; Wagner and Scharf, 2006). For example, Wagner and Scharf (2006) asked listeners to make loudness magnitude estimates for a series of 70-dB test-tone bursts presented either alone or following 80-dB SPL inducer tone bursts at the same frequency. Figure 11.7 summarizes their results, which are averaged across frequencies because mean ILRs did not differ with frequency between 500 and 8000 Hz. The average loudness magnitude estimate for the test tone alone was 4.3, represented by the left-most filled symbol in the figure (labeled "without inducer"). In contrast, the loudness estimates were lower when the test tones are preceded by the stronger inducer tones, shown by the open symbols. Notice that the amount of ILR increased with continued presentations of the inducer tones over time [labeled "development of ILR (with inducer)"] and began to decrease with time after the stronger inducer tones were discontinued [labeled "recovery of ILR (with inducer)"].

In general, induced loudness reduction occurs when the test tone and the stronger inducer tone are the same or relatively close in frequency, and the inducer ends at least several tenths of a second before the test tone starts. Moreover, as we observed in the example, the amount of ILR increases as the stronger inducer tone is repeated over time, and then decreases over time after the inducer is removed. The underlying mechanism of ILR is not known, but similarities between it and loudness adaptation (discussed next) suggest that these phenomena may involve a common mechanism (Nieder et al., 2003; Wagner and Scharf, 2006).

LOUDNESS ADAPTATION

Loudness adaptation refers to the apparent decrease in the loudness of a signal that is continuously presented at a fixed level for a reasonably long period of time. In other words, the signal appears to become softer as time goes on even though the sound pressure level is the same. Hood's (1950) classic experiment demonstrates this phenomenon rather clearly. A 1000-Hz tone is presented to the subject's right ear at 80 dB.

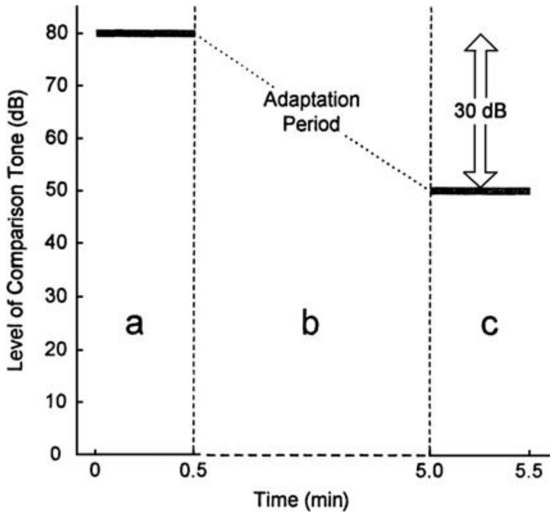

Figure 11.8 Loudness adaptation as shown by the level of the comparison stimulus. *Source*: Based on drawings by Hood (1950).

This adapting stimulus remains on continuously. At the start, a second 1000-Hz tone is presented to the left ear, and the subject adjusts the level of this second (comparison) tone to be equally loud as the adapting tone in the right ear (part a in Fig. 11.8). Thus, the level of the comparison tone is used as an indicator of the loudness of the adapting tone in the opposite ear. This first measurement represents the loudness prior to adaptation (the preadaptation balance).

The comparison tone is then turned off, while the adapting tone continues to be applied to the right ear (adaptation period b in Fig. 11.8). After several minutes of adaptation, the comparison signal is reapplied to the opposite ear, and the subject readjusts it to be equally loud with the 80-dB adapting tone. This time, however, the comparison tone is adjusted by the subject to only 50 dB in order to achieve a loudness balance with the adaptor (segment c in Fig. 11.8), indicating that the loudness of the adapting tone has decreased by an amount comparable to a 30-dB drop in signal level. Thus, there has been 30 dB of adaptation due to the continuous presentation of the tone to the right ear. Because the loudness decrease occurs during stimulation, the phenomenon is also called perstimulatory adaptation. This phenomenon contrasts, of course, with the temporary threshold shift (TTS) described in the previous chapter, which constitutes poststimulatory fatigue.

The method just described for the measurement of adaptation may be considered a simultaneous homophonic loudness balance. In other words, the subject must perform a loudness balance between two tones of the same frequency that are presented, one to each ear, at the same time. Other studies employing this approach have reported similar findings (Egan, 1955; Wright, 1960; ; Small and Minifie, 1961).

A problem inherent in these early studies of loudness adaptation was their use of simultaneously presented adapting and comparison tones of the same frequency. Although the presumed task was a loudness balance between the ears, the experiments were confounded by the perception of a fused image due to the interaction of the identical stimuli at the two ears. As we shall see in Chapter 13, the relative levels at the two ears will determine whether the fused image is perceived centralized within the skull or lateralized toward one side or the other. It is therefore reasonable to question whether the loudness adaptation observed in such studies is confounded by interactions between the ears, such as lateralization.

One way around the problem is to use a comparison tone having a different frequency than the adapting tone. This procedure would reduce the lateralization phenomenon because the stimuli would be different at each ear. In 1955, Egan found no significant difference in the amount of loudness adaptation caused by this heterophonic method and the homophonic approach described above. Subsequently, however, Egan and Thwing (1955) reported that loudness balances involving lateralization cues did in fact result in greater adaptation than techniques that kept the effects of lateralization to a minimum.

Other studies have shown that loudness adaptation is reduced or absent when binaural interactions (lateralization cues) are minimized (Stokinger and Studebaker, 1968; Fraser et al., 1970; Petty et al., 1970; Stokinger et al., 1972a, 1972b; Morgan and Dirks, 1973). This may be accomplished by using adapting and comparison tones of different frequencies (heterophonic loudness balances), or by a variety of other means. For example, Stokinger and colleagues (Stokinger et al., 1972a, 1972b) reduced or obliterated loudness adaptation by shortening the duration of the comparison tone and by delaying the onset of the comparison tone after the adapting tone was removed. Both of these approaches had the effect of reducing or removing the interaction of the two tones between the ears. Moreover, the presentation of an intermittent tone to one ear induces adaptation of a continuous tone in the other ear (Botte et al., 1982; Scharf, 1983). Thus, it appears that lateralization methods foster misleading impressions about loudness adaptation effects, especially with regard to monaural adaptation (Scharf, 1983).

What, then, do we know about loudness adaptation based upon experimentation which directly assesses the phenomenon? Scharf (1983) has provided a cohesive report of a large number of loudness adaptation experiments using, for the most part, magnitude estimations of loudness that were obtained at various times during the stimulus. Several of his findings may be summarized for our purposes as follows. First, there appears to be a noticeable amount of variability among people in terms of how much adaptation they experience. Second, the loudness of a pure tone adapts when it is presented to a subject at levels up to approximately 30 dB sensation level (i.e., 30 dB above his threshold). This relationship is shown in Fig. 11.9, although one might note that adaptation was found to continue beyond the value of 70 s shown in the graph. The relationship between sensation level and loudness adaptation was subsequently qualified by Miskiewicz et al. (1993), who

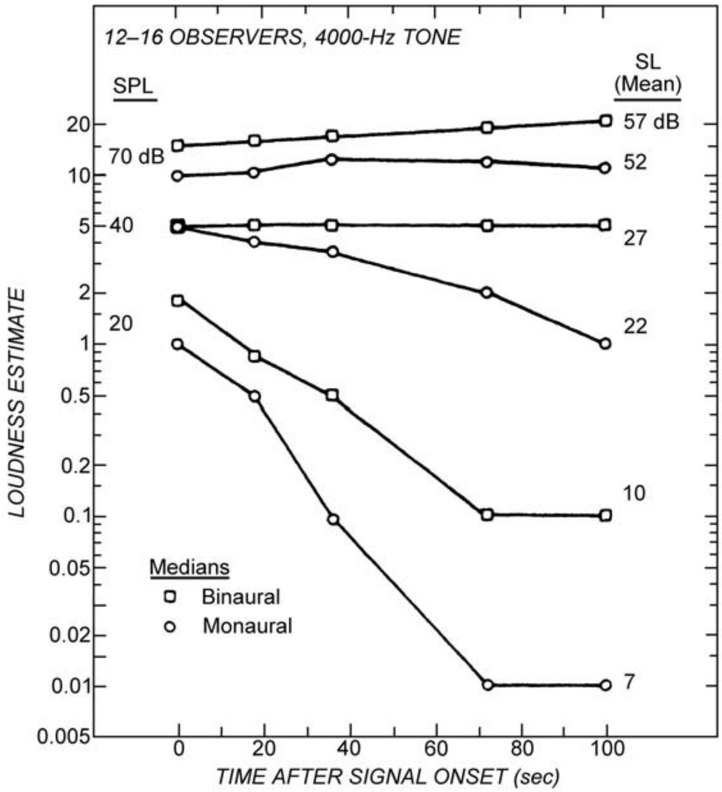

Figure 11.9 Adaptation (medians) for a 4000-Hz tone measured by successive magnitude estimations as a function of the duration of the tone. The parameter is sensation level, or the number of decibels above the subjects' thresholds. See text. *Source*: From Scharf, Loudness adaptation, in *Hearing Research and Theory, Vol.* 2 (J.V. Tobias and E.D. Schubert, eds.), Vol. 2, ©1983 by Academic Press.

found that loudness adaptation also occurs above 30 dB SL for high-frequency sounds (12,000, 14,000, and 16,000 Hz). Third, there is more adaptation for higher-frequency tones than for lower-frequencies tones or for noises. Fourth, adaptation appears to be the same whether the tones are presented to one ear or to both ears. In the latter case, the amount of adaptation that is measured seems to be primarily determined by the ear with less adaptation. For example, if the right ear adapts in 90 s and the left ear in 105 s, then the binaurally presented tone would be expected to adapt in 105 s. Here, of course, we are assuming that both ears are receiving similar continuous tones. Clearly, these points represent only a brief sampling of Scharf's extensive findings and theoretical arguments. The student should consult his paper for greater elucidation as well as for an excellent coverage of the overall topic.

NOISINESS AND ANNOYANCE

It is interesting to at least briefly consider the "objectionability" of sounds before leaving the topic of loudness. After all, it is probably fair to say that louder sounds are often more objectionable than softer ones. Some common examples include the noises of airplane fly-overs, sirens, traffic, and construction equipment, as well as somebody else's loud music. On the other hand, some sounds are quite objectionable regardless of their intensities, such as the noise of squeaky floorboards and the screech of fingernails on a blackboard. Thus, sounds (generally noises) may be experienced as objectionable above and beyond their loudness, per se.

The term **perceived noisiness** (or just **noisiness**) is often used to describe the *objectionability* or *unwantedness* of a sound (Kryter, 1985). Specifically, noisiness is the unwantedness of a sound that does *not* produce fear or pain and is neither unexpected nor surprising. Moreover, noisiness is *not* related to the meaning or implications of the sound. In other words, noisiness has to do with the physical parameters of the noise. The amount of noisiness is given in **noys**, analogous to loudness in sones, and equally objectionable sounds share the same number of **perceived noise decibels** (**PNdB**) analogous to loudness level in phons (Kryter, 1959; Kryter and Pearsons, 1963, 1964). Thus, if sound A has twice the noisiness of sound B, then A will have double the number of noys and it will be 10 PNdB higher. As we would expect, the physical parameters that increase loudness also increase noisiness (e.g., noisiness increases as the sound level rises). Noisiness is also influenced by parameters of the offending sound, such as its time course and spectrum: Lengthening the duration of a sound beyond 1 s increases the amount of noisiness. Sounds that rise in level over time are noisier than sounds that fall in level over the same amount of time, and noisiness increases as the build-up gets longer. A noise whose spectrum has a lot of energy concentrated inside of a narrow range of frequencies is noisier than a noise with a smoother spectrum.

In contrast to noisiness, the **annoyance** describes the objectionability of a sound involving such things as its meaning or interpretation, implications for the listener, novelty, etc., as well as its physical parameters, per se (Kryter, 1985). Hence, it is not surprising that in addition to its obvious dependence on the level of the offending noise, annoyance is also related to a variety of other factors, such as the source of the noise and the individual's noise susceptibility. For example, residential noise annoyance appears to be affected by concerns about the dangers and other (including nonnoise) consequences of the noise source, attitudes about the importance of the noise source, the amount of isolation from noise at home, beliefs about noise prevention, and the person's general noise sensitivity (Fields, 1993). Transportation noise annoyance appears to be greatest for aircraft (followed by road traffic and then by railroad noises) and is substantially affected by fears about the noise source, concerns about how noise and pollution affect health, perceived disturbance from the noise, self-assessed noise sensitivity, coping capacity, and perceived ability to control the noise situation (Miedema and Vos, 1998, 1999; Kroesen, Molin, and van Wee, 2008). Several informative discussions of noise sensitivity and related matters are readily available for the interested reader (e.g., Job, 1988; Fields, 1993; Miedema and Vos, 2003).

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