10 Masking

The previous chapter dealt with auditory sensitivity. This one is concerned with masking, or how sensitivity for one sound is affected by the presence of another sound, and also with psychoacoustic phenomena that are for one reason or another typically associated with masking.

Suppose that the threshold for a sound A is found to be 10 dB SPL. A second sound B is then presented and the threshold of A is measured again, but this time in the presence of sound B. We now find that sound A must be presented at, say, 26 dB in order to be detected. In other words, sound A has a threshold of 10 dB when measured in quiet, but of 26 dB when determined in the presence of sound B. This increase in the threshold or *threshold shift* for one sound in the presence of another is called **masking**. Our definition of masking may be expanded to include the reduction in loudness that can occur when a second sound is presented, a process referred to as **partial masking** (Meyer, 1959; Scharf, 1964).

We may use the word "masking" to denote either the threshold shift, per se, or the amount (in dB) by which the threshold of a sound is raised due to the presence of another sound. Thus, sound A in our example has been *masked* by sound B, and the amount of *masking* due to the presence of B is equal to 26−10 dB, or 16 dB. In this case, 10 dB is the *unmasked threshold* of sound A, 26 dB is its *masked threshold*, and 16 dB is the *amount of masking*. These notions are illustrated in Fig. 10.1. We will adopt the convention of calling sound B the **masker**, and sound A the **signal**. (The signal is often referred to as the *test signal* or *probe signal*, and occasionally as the *maskee*.)

As will become obvious, masking not only tells us about how one sound affects another, but also provides insight into the frequency-resolving power of the ear. This is the case because the masking pattern to a large extent reflects the excitation pattern along the basilar membrane. In Chapter 13 we shall see how masking is modified under certain conditions of binaural hearing.

The basic masking experiment is really quite straightforward. First, the unmasked threshold of the test stimulus is determined and recorded. This unmasked threshold becomes the baseline. Next, the masker is presented to the subject at a fixed level. The test stimulus is then presented to the subject and its level is adjusted (by whatever psychoacoustic method is being used) until its threshold is determined in the presence of the masker. This level is the masked threshold. As just described, the amount of masking is simply the difference in decibels between this masked threshold and the previously determined unmasked (baseline) threshold. This procedure may then be repeated for all parameters of the test stimulus and masker. An alternative procedure is to present the test stimulus at a fixed level and then to vary the masker level until the stimulus is just audible (or just marked).

NATURE OF MASKING

The masking produced by a particular sound is largely dependent upon its intensity and spectrum. Let us begin with pure tones, which have the narrowest spectra. As early as 1894, Mayer had reported that, while low-frequency tones effectively mask higher frequencies, higher frequencies are not good maskers of lower frequencies. Masking, then, is not necessarily a symmetrical phenomenon. This spread of masking to frequencies higher than that of the masker has been repeatedly demonstrated for tonal maskers (Wegel and Lane, 1924; Ehmer, 1959a; Small, 1959; Finck, 1961). We must therefore focus our attention not only upon the amount of masking, but also upon the frequencies at which masking occurs.

Figure 10.2 shows a series of **masking patterns** (sometimes called **masking audiograms**) obtained by Ehmer (1959a). Each panel shows the amount of masking produced by a given pure tone masker presented at different intensities. In other words, each curve shows as a function of signal frequency how much the signal threshold was raised by a given masker presented at a given intensity. Masker frequency is indicated in each frame and masker level is shown near each curve. Several observations may be made from these masking patterns. First, the strongest masking occurs in the immediate vicinity of the masker frequency; the amount of masking tapers with distance from this "center" frequency. Second, masking increases as the intensity of the masker is raised.

The third observation deals with how the masking pattern depends upon the intensity and frequency of the masker. Concentrate for the moment upon the masking pattern produced by the 1000-Hz masker. Note that the masking is quite symmetric around the masker frequency for relatively low masker levels (20 and 40 dB). However, the masking patterns become asymmetrically wider with increasing masker intensity, with the greatest masking occurring for tones higher than the masker frequency, but with very little masking at lower frequencies. Thus, as masker intensity is raised, there is considerable spread of the masking effect upward in frequency but only a minimal effect downward in frequency. This phenomenon is aptly called **upward spread of masking**. Note too that there are peaks in some of the masking patterns corresponding roughly to the harmonics of the masker frequency. Actually, however, these peaks are probably not due to aural harmonics (see Chap. 12) because they do not correspond precisely to multiples of the masker (Ehmer, 1959a; Small, 1959). Small (1959) found that these peaks occurred when the masker frequency was about 0.85 times the test tone frequency.

Finally, notice that the masking patterns are very wide for low-frequency maskers and are considerably more restricted for high-frequency maskers. In other words, high-frequency

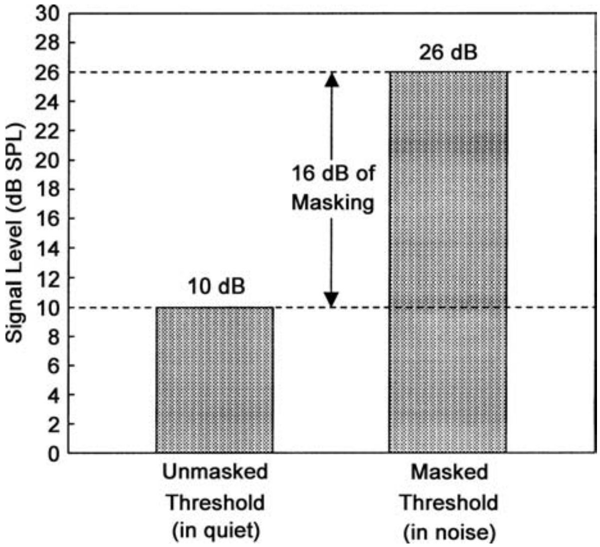

Figure 10.1 Hypothetical example in which a masker shifts the threshold of a test signal by 16 dB from 10 dB SPL to 26 dB SPL.

maskers only are effective over a relatively narrow frequency range in the vicinity of the masker frequency, but low frequencies tend to be effective maskers over a very wide range of frequencies.

These masking patterns reflect the activity along the basilar membrane, as illustrated in Fig. 10.3. Recall from Chapter 4 that the traveling wave envelope has a gradually increasing amplitude along its basal (high-frequency) slope, reaches a peak, and then decays rapidly with a steep apical (low-frequency) slope. It is thus expected that higher (more basal) frequencies would be most affected by the displacement pattern caused by lower-frequency stimuli. In addition, the high-frequency traveling wave peaks and "decays away" fairly close to the basal turn, so that its masking effect would be more restricted. Lower frequencies, on the other hand, produce basilar membrane displacements along most of the partition. In addition, the excitation pattern becomes wider as the signal level increases.

Although a great deal of information about masking has been derived from studies using tonal maskers, difficulties become readily apparent when both the masker and test stimulus are tones. Two major problems are due to the effects of beats and combination tones.

Beats are audible fluctuations that occur when a subject is presented with two tones differing in frequency by only a few cycles per second (e.g., 1000 and 1003 Hz) at the same time. Consequently, when the masker and test tones are very close in frequency, one cannot be sure whether the subject has responded to the beats or to the test tone. These audible beats can result in notches at the peaks of the masking patterns when the masker and signal are close in frequency (Wegel and Lane, 1924). The situation is further complicated because combination tones are also produced when two tones are presented together. Combination tones are produced at frequencies equal to numerical combinations of the two original tones (f_1 and f_2), such as f_2–f_1 or $2f_1$–f_2. Beats and combination tones are covered in Chapter 12. Beats may be partially (though not totally) eliminated by replacing the tonal maskers with narrow bands of noise centered around given frequencies; however, the elimination of combination tones requires more sophisticated manipulations (Patterson and Moore, 1986). The results of narrow-band noise

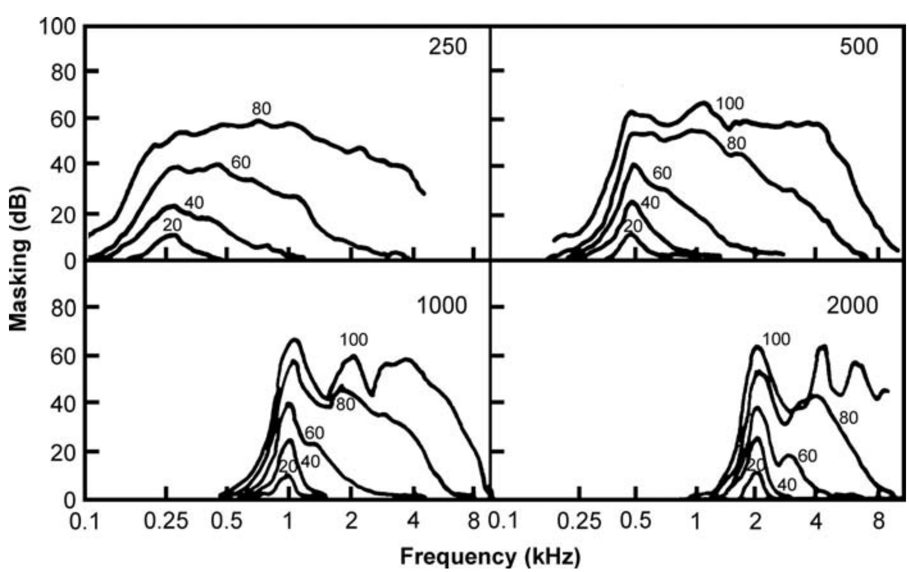

Figure 10.2 Masking patterns produced various pure tone maskers (masker frequency indicated in each frame). Numbers on curves indicate masker level. *Source*: Adapted from Ehmer (1959a, 1959b, with permission of *J. Acoust. Soc. Am.*

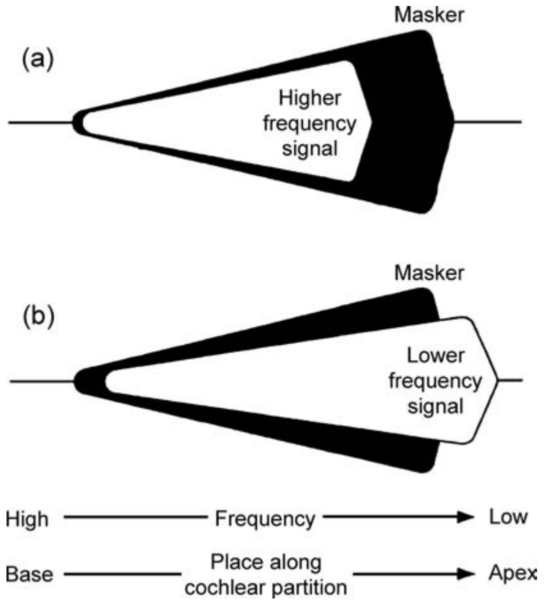

Figure 10.3 Artist's conceptualization of how upward spread of masking is related to traveling wave excitation patterns along the basilar membrane: The excitation pattern of a lower-frequency masker envelops that of a higher-frequency test signal (a), but a higher-frequency masker does not envelop the excitation pattern of a lower-frequency test signal (b).

masking experiments have essentially confirmed the masking patterns generated in the tonal masking studies (Egan and Hake, 1950; Ehmer, 1959b; Greenwood, 1961).

We have seen that upward spread of masking is the rule as masker level is increased. However, a very interesting phenomenon appears when the stimulus level is quite high, for example, at spectrum levels of about 60 to 80 dB. **Spectrum level** refers to the power in a one-cycle-wide band. In other words, spectrum level is level per cycle. It may be computed by subtracting 10 times the log of the bandwidth from the overall power in the band. Thus:

$$dB_{\text{spectrum level}} = dB_{\text{overall}} - 10 \log \text{(bandwidth)}$$

If the bandwidth is 10,000 Hz and the overall power is 95 dB, then the spectrum level will be 95 − 101og (10,000), or 95 − 40 = 55 dB.

Higher-frequency maskers presented at intense levels can also produce masking at *low* frequencies (Bilger and Hirsh, 1956; Deatherage et al., 1957a, 1957b). This is called **remote masking** because the threshold shifts occur at frequencies below and remote from the masker. In general, the amount of remote masking increases when the bandwidth of the masking noise is widened or its spectrum level is raised (Bilger, 1958). Although the acoustic reflex can cause a threshold shift at low frequencies, it is unlikely that this is the cause of remote masking because remote masking has been shown to occur in the absence of the acoustic reflex (Bilger, 1966). Instead, remote masking is most likely due primarily to envelope detection of distortion products generated within the cochlea at high masker intensities (Spieth, 1957; Deatherage et al., 1957a, 1957b). (See Chap. 4 for a discussion of cochlear distortion.)

It is apparent from Fig. 10.2 that masking increases as the level of the masker is raised. We may now ask how the amount of masking relates to the intensity of the masker. In other words, how much of a threshold shift results when the masker level is raised by a given amount? This question was addressed in the classical studies of Fletcher (1937) and Hawkins and Stevens (1950). Since the essential findings of the two studies agreed, let us concentrate upon the data reported by Hawkins and Stevens in 1950. They measured the threshold shifts for pure tones and for speech produced by various levels of a white noise masker. (It should be pointed out that although *white noise* connotes equal energy at all frequencies, the actual spectrum reaching the subject is shaped by the frequency response of the earphone or loudspeaker used to present the signal. Therefore, the exact masking patterns produced by a white noise depend upon the transducer employed, as well as on bandwidth effects that will be discussed in the next section.)

Figure 10.4 shows Hawkins and Stevens' data as masked threshold contours. These curves show the masked thresholds produced at each frequency by a white noise presented at various spectrum levels. The curves have been idealized in that the actual results were modified to reflect the masking produced by a true white noise. The actual data were a bit more irregular, with peaks in the curves at around 7000 Hz, reflecting the effects of the earphone used. The bottom contour is simply the unmasked threshold curve. The essential finding is that these curves are parallel and spaced at approximately 10-dB intervals, which is also the interval between the masker levels. This result suggests that a 10-dB increase in masker level produces a 10-dB

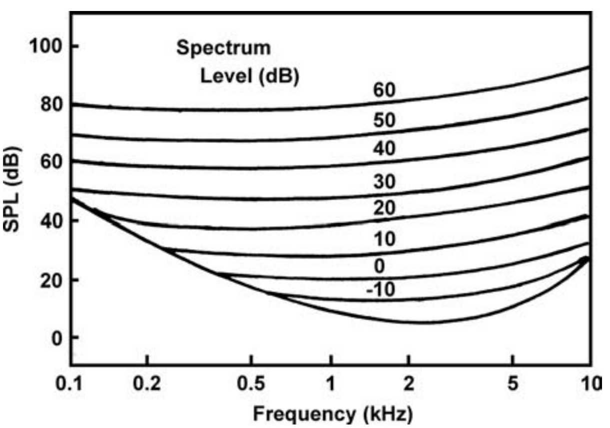

Figure 10.4 Masking contours showing masking as a function of frequency for various spectrum levels of an idealized white noise. Bottom curve is threshold in quiet. *Source*: Adapted from Hawkins and Stevens (1950), with permission of *J. Acoust. Soc. Am.*

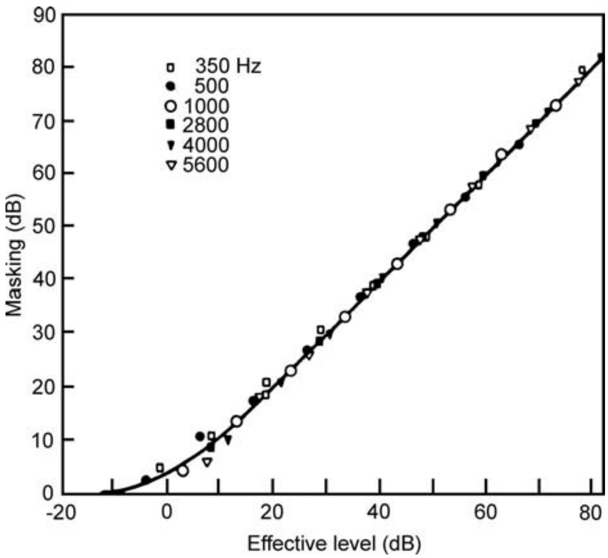

Figure 10.5 Masking produced at various frequencies as a function of the effective level of the masker. *Source*: Adapted from Hawkins and Stevens (1950), with permission of *J. Acoust. Soc. Am.*

increase in masked threshold; a point which will become clearer soon.

The actual amount of masking may be obtained by subtracting the unmasked threshold (in quiet) from the masked threshold. For example, the amount of masking produced at 1000 Hz by a white noise with a spectrum level of 40 dB is found by subtracting the 1000-Hz threshold in quiet (about 7 dB SPL) from that in the presence of the 40-dB noise spectrum level (roughly 58 dB). Thus, the amount of masking is $58-7 = 51$ dB in this example. Furthermore, because the masked thresholds are curved rather than flat, the white noise is not equally effective at all frequencies. We might therefore express the masking noise in terms of its effective level at each frequency. We may now show the amount of masking as a function of the effective level of the masking noise (Fig. 10.5). As Fig. 10.5 shows, once the masker attains an effective level, the amount of masking is a linear function of masker level. That is, a 10-dB increase in masker level results in a corresponding 10-dB increase in the masked threshold of the test signal. Hawkins and Stevens demonstrated that this linear relationship between masking and masker level is independent of frequency (as shown in the figure), and that it applies to speech stimuli as well as to pure tones.

FREQUENCY SELECTIVITY

Filters are used in our daily lives to select among various things that may be tangible or intangible. We have all seen change sorters. Even though mixed change is dropped into the same hole, dimes end up in one section, quarters in another, etc. The discrete and large size differences among coins make this straightforward. However, a selection process must work within the limits of the filters. A clear albeit distasteful example of this point relates to the inevitable grading process in college courses. Grading represents a filtering process: The input to a bank of filters is a continuum from 70% to 100%, and the output is an "A" or a "B" or a "C." The "B" filter goes from 80% to 89%. Thus, it can select between 78% and 81%, or 89% and 90%, but it cannot differentiate between 83% and 85%. Otherwise stated, values that fall within the range of the same filter cannot be differentiated, whereas values that fall across the border of two filters can be isolated from one another. The same issue of selectivity applies to hearing. The ear's ability to analyze a sound so that we can separate one frequency from the other also implies a filtering capability, which we call frequency selectivity. Our ability to analyze the components of a sound depends on the width of our **auditory filters**.

What does all of this have to do with masking? As we shall see, masking and related experiments reveal the frequency selectivity of the ear and provide insight into the nature of the underlying auditory filter.

Because a tone may be masked by another tone or by a narrow band of noise as well as by white noise, it is reasonable to ask how much of the white noise actually contributes to the masking of a tone. Otherwise stated, does the entire bandwidth of the white noise contribute to the masking of a given tone, or is there a certain limited ("critical") bandwidth around the tone that alone results in masking? Fletcher (1940) attacked this problem by finding masked thresholds for tones produced by various bandwidths of noise centered around the test tones. He held the spectrum level constant and found that the masked threshold of a tone increased as the bandwidth of the masking noise was widened. However, once the noise band reached a certain critical bandwidth, further widening of the band did not result in any more masking of the tone. Thus, Fletcher demonstrated that only a certain critical bandwidth within the white noise actually contributes to the masking of a tone at the center of the band, a finding which has been repeatedly confirmed (Schaefer et al., 1950; Hamilton, 1957; Greenwood, 1961; Swets et al., 1962; Bos and deBoer, 1966).

This finding is easily understood if we think of the critical bandwidth as a filter. More and more of the energy in the white noise will be made available by the filter as the filter's bandwidth is widened. On the other hand, energy present in the white noise that lies above and below the upper and lower cutoff frequencies of the filter is "wasted" from the standpoint of the filter (Fig. 10.6). Now, if this filter defines the critical bandwidth that contributes to the masking of a tone at the center of the band, then it is easy to see how only that portion of the noise that is inside the filter will be useful in masking the tone. Adding to the noise band beyond the limits of this filter (the areas labeled "b" in Fig. 10.6) will not add any more masking, although it will cause the noise to sound louder (see Chap. 11).

Fletcher (1940) hypothesized that the signal power (S) would be equal to the noise power (No) located within the critical

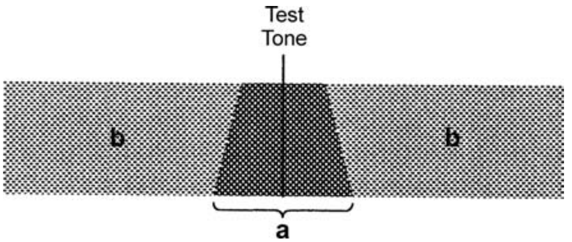

Figure 10.6 Energy within the critical band filter (a) contributes to the masking of the tone at the center, whereas energy outside of the filter (b) does not contribute to the masking (see text).

bandwidth (CB) when the tone was at its masked threshold: $S = CB \cdot No$. Thus, the **critical band** would be equal to the ratio of the signal power to the noise power, or $CB = S/No$. In decibels, this corresponds to $dB_S - dB_{No}$. Hawkins and Stevens (1950) found that the masked threshold of a 1000-Hz tone was approximately 58 dB in the presence of a white noise whose spectrum level was 40 dB. The resulting estimate of the critical band is therefore 58 dB − 40 dB = 18 dB, which corresponds to a bandwidth of 63.1 Hz. This estimate of the critical band is shown by the X in Fig. 10.7. Notice that this indirect estimate of the critical bandwidth based upon the power ratio of signal to noise is actually quite a bit narrower than the other more direct estimates of the critical band shown in the figure. For this reason, the indirect estimate based upon Fletcher's formula

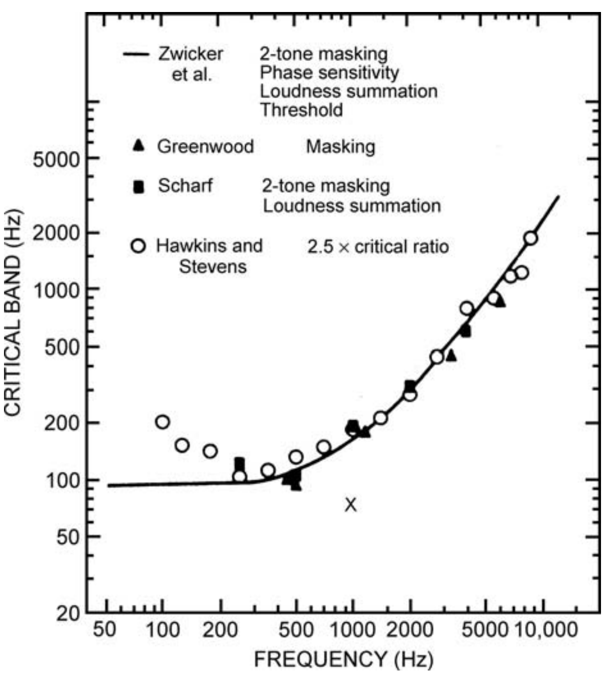

Figure 10.7 Critical bandwidth as a function of center frequency for various studies. The X is the critical ratio estimate of Hawkins and Stevens (1950) for a 1000-Hz tone. *Source*: Adapted from Scharf, Critical bands, in: *Foundations of Modern Auditory Theory* (J. V. Tobias, ed.), Vol. 1, ©1970, Academic Press.

is referred to as **critical ratios**, as opposed to the *critical bands* obtained by other, direct means. Good correspondence to the critical band is obtained when the critical ratio is multiplied by a factor of 2.5 (Zwicker et al., 1957; Scharf, 1970). This correspondence is demonstrated by the open circles in Fig. 10.7, which are the values of the critical ratios multiplied by 2.5, based upon Hawkins and Stevens' (1950) data. Note that there is good agreement with Greenwood's (1961) masking data, as well as with the critical bands directly derived from loudness studies (see Chap. 11).

Bilger (1976) proposed that the listener performs an intensity discrimination between the noise power in the critical band and the combined power of the noise plus signal at the masked threshold; as a result the critical ratio is equated to the familiar Weber fraction (Chap. 9):

$$\frac{S}{CB \cdot N} = \frac{\Delta I}{I}$$

This equation is solved for critical bandwidth by multiplying S/N by the reciprocal of the Weber fraction

$$CB = \frac{S}{N} \cdot \frac{I}{\Delta I}$$

Since the critical ratio is multiplied by 2.5 to obtain the critical band, this leads to a Weber fraction of $1/2.5 = 0.4$, or a difference limen of 1.46 dB, a value that is in reasonable agreement with intensity DL data.

Figure 10.7 indicates that the critical band becomes wider as the center frequency increases. Scharf (1970) has provided a table of critical bandwidth estimates based upon the available data. Examples are a critical bandwidth of 100 Hz for a center frequency of 250 Hz, a 160-Hz band for 1000 Hz, and a 700-Hz band for 4000 Hz. Similar data and formulas for calculation of the critical bandwidth and critical band rate (the bark scale) have been provided by Zwicker and Terhardt (1980). Actually, one should be careful not to conceive of a series of discrete critical bands laid as it were end to end, but rather of a bandwidth around any particular frequency that defines the phenomenon we have discussed with respect to that frequency. [One should remember in this context Scharf's (1970, p. 159) elegant definition: "the critical band is that bandwidth at which subjective responses rather abruptly change."] We should thus think of critical bandwidths as overlapping filters rather than as discrete, contiguous filters.

It would appear that the original concept (Fletcher, 1940) of the critical bandwidth as defining an internal auditory filter is fundamentally correct. Its location is more than likely peripheral, with critical bandwidths probably corresponding to 1 to 2 mm distances along the human cochlear partition (Scharf, 1970). Thus, the critical band presents itself as a fundamental concept in the frequency-analysis capability of the cochlea, the physiological aspects of which are discussed in Chapter 4.

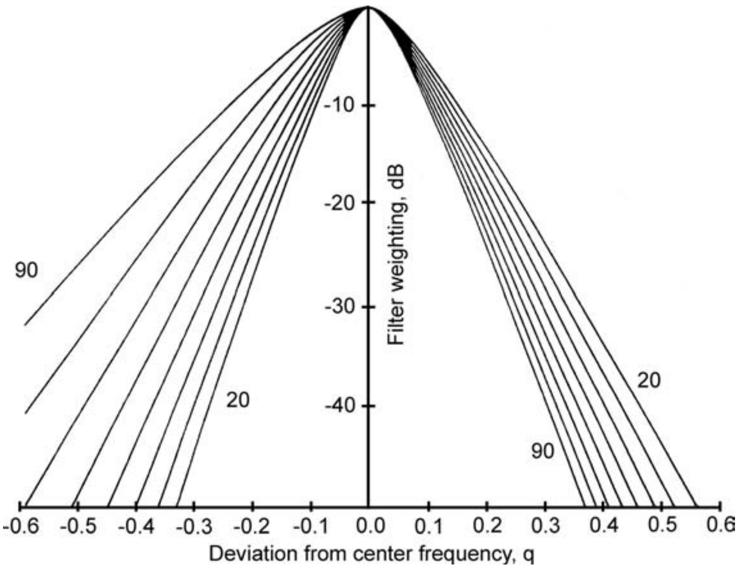

Figure 10.8 Shape and bandwidth (ERB) of the auditory filter expressed in terms of increasing level in 10 dB steps from 20 to 90 dB SPL/ERB. (Note the opposite directions in which the left- and right-hand slope change as level increases from 20 to 90 dB. The left-hand slope shown on these filters determines the high frequency aspect of the excitation pattern.) *Source*: From Moore and Glasberg (1987), with permission of *Hear Res*.

Detailed reviews of the critical band concept may be found in the work of Scharf (1970) and Bilger (1976).

The idea of the internal filter originally embodied in the critical band concept, particularly in its conceptualization as a rectangular filter around the center frequency (Fletcher, 1940), has been modified and updated by numerous investigators (Patterson, 1974, 1976; Houtgast, 1977; Weber, 1977; Moore and Glassberg, 1981, 1987; Patterson et al., 1982; Shailer and Moore, 1983; Fidell et al., 1983; Glasberg et al., 1984a, 1984b). Figure 10.8 shows the shapes of the auditory filter over a wide range of intensities, as derived in a paper by Moore and Glasberg (1987). The curves were based on raw data from young, normal hearing subjects from variety of studies.[1] The figure reveals that the filter becomes increasingly more asymmetric with increasing level. The major aspect of this asymmetry is that the slope of the low-frequency (left-hand) branch of the filter decreases with increasing level. This widening of the left-hand branch of the filter that corresponds to the phenomenon of upward spread of masking has been discussed earlier in this chapter. We saw the reason is that the left-hand branch of this filter determines the high-frequency aspect of the excitation pattern.

With an idea of the shape of the auditory filter, we may ask how it is related to frequency and to the critical band (cf. Fig. 10.7). To do this, we need to summarize the nature of the filters in some valid and convenient way. This can be done by using what is called the **equivalent rectangular bandwidth (ERB)** of the filter. An ERB is simply the rectangular filter that passes the same amount of power as would pass through the filter we are trying to specify. Thus, if a white noise is directed to the inputs of a filter of any given configuration and also through its ERB, then the power at their outputs (passed through them) would be the same. Using this approach, Moore and Glasberg (1983b) have shown how the auditory filter changes with frequency. Figure 10.9 shows the ERB of the auditory filter as a function of its center frequency. Here we see that the width of the auditory filter widens as frequency increases, and also that this relationship is quite consistent across several studies. Also shown in the figure is an equivalent line based upon the classical critical band. [The latter was derived using a formula by Zwicker and Terhardt (1980).] Observe that the more recent measurements of auditory filter width are slightly narrower but generally parallel with the older ones based upon classical critical band data. The parallel relationship breaks down below about 500 Hz, where unlike the earlier critical band data, the newer observations suggest that the auditory filter continues to be a function of frequency. One should refer to Patterson and Moore (1986), whose extensive discussion of this topic includes arguments addressing the discrepancy below 500 Hz in the light of differences in processing efficiency.

We have already seen that beats and combination tones can adversely affect tone-on-tone masking measurements. Now that we have an idea of the auditory filter, we may consider another factor that can confound masking (among other) experiments.

[1] The auditory filter tends to widen with age (Patterson and Moore, 1986). See Patterson et al. (1982) for other findings, and Gelfand (2001) for a general discussion of factors relating to aging and hearing impairment.

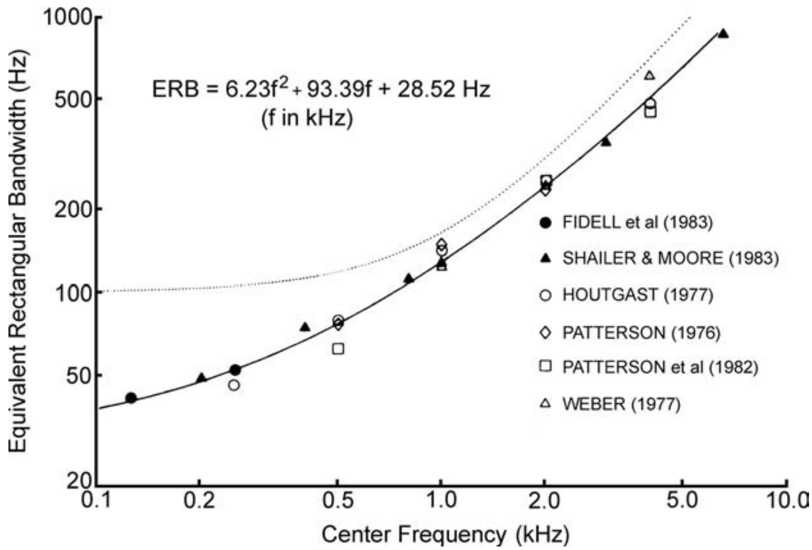

Figure 10.9 The solid line shows the width of the auditory filter (in terms of ERB) as a function of center frequency based on the data of various studies. The dotted line summarizes the same relationship for classical critical band data. *Source*: From Moore and Glasberg (1983b), with permission of *J. Acoust. Soc. Am.*

This phenomenon is **off-frequency listening** (Patterson, 1976; Patterson and Moore, 1986). Recall from the previous discussion the notion of a continuum of overlapping auditory filters. We typically presume that the subject is listening to some tone "through" the auditory filter, which is centered at that test frequency. However, the subject might also "shift" to another auditory filter, which includes the test frequency but is not centered there. The example in Fig. 10.10 shows why this might happen. The vertical line depicts a tone of some frequency, and the bell curve portrays the auditory filter centered around this tone. The square represents a low-pass noise masker. Look first at Fig. 10.10a. Notice that part of the masker falls within the auditory filter (shaded area). If the tone were presented *without* the noise, then the signal-to-noise (S/N) ratio coming out of this auditory filter would be very high. Hence, the subject would detect the tone. When the *noise is presented* along with the tone, then the portion of the noise falling inside of this auditory filter causes the S/N ratio to be diminished. This, in turn, reduces the chances that the subject will detect the tone.

All of this supposes that the only way to listen to the tone is through the auditory filter centered at that tone's frequency. However, the dashed curve in Fig. 10.10b shows that a sizable proportion of this test tone is also passed by a neighboring auditory filter, which itself is centered at a slightly higher frequency. Moreover, a much smaller part of the masking noise is passed by this neighboring filter. Hence, that the S/N ratio between the test tone and the masking noise is increased when the subject listens "through" this shifted auditory filter. Consequently, the likelihood that the tone will be detected is improved due to such off-frequency listening.

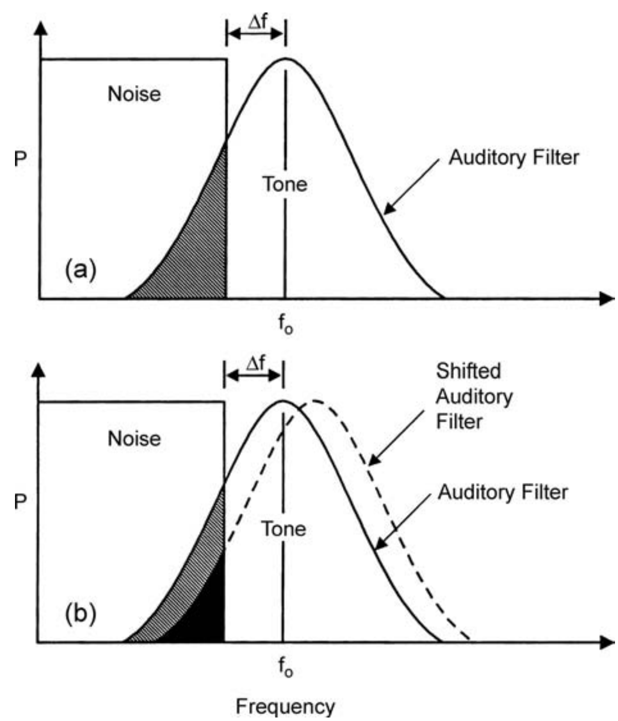

Figure 10.10 In both graphs, the solid curve represents the auditory filter centered at the test tone and the square at the left portrays a lower frequency masking noise. Off-frequency listening occurs when the subject shifts to another auditory filter (indicated by the dashed curve in graph b) in order to detect the presence of a test signal. *Source*: Adapted from Patterson (1976), with permission of *J. Acoust. Soc. Am.*

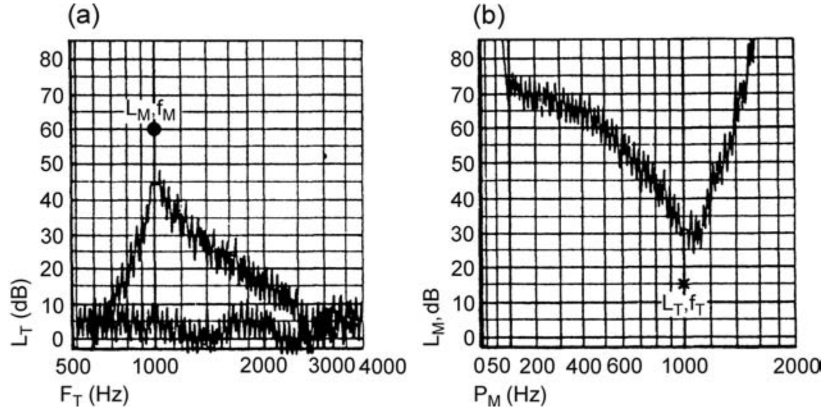

Figure 10.11 (a) Thresholds of sweeping-frequency *test* tones (LT, dB) as a function of frequency (of the test tones, FT, Hz) in quiet (*lower tracing*) and in the presence of a fixed masker (*upper tracing*). The filled circle shows the level and frequency of the fixed masker (60 dB, 1000 Hz; LM, FM). (b) These tracings show the levels of sweeping-frequency *masker* tones (LM, dB) needed to just mask the fixed test tone of 1000 Hz at 15 dB (LT, FT). *Source*: From Zwicker and Schorn (1978), with permission of *Audiology.*

An effective approach to minimize the confounding effects of off-frequency listening is to present the signals involved in an experiment (such as the test tone and masker tone) along with additional noise(s) which will mask out the frequencies above and below the range of interest (O'Loughlin and Moore, 1981).

PSYCHOACOUSTIC TUNING CURVES

So far, we have described masking in terms of the level of the tone (or other signal), which has been masked. Thus, the masking patterns in Fig. 10.2 expressed the amount of masking produced for various test tones as a function of frequency by a given masker (at some fixed level). That is, "30 dB of masking" on one of these graphs means that the masker caused the threshold of the test signal to be increased by 30 dB above its unmasked threshold. If this experiment were done using the Bekesy tracking method (Chap. 7), the "raw" results might look something like the left panel in Fig. 10.11. Here, the lower tracing shows the threshold of the test signal, which is a tone sweeping in frequency from 500 to 4000 Hz. The upper tracing shows the masked threshold tracing in the presence of a fixed masker (which is a 1000-Hz tone at 60 dB). Subtracting the lower (unmasked) tracing from the upper (masked) threshold tracing would result in a familiar masking pattern similar to those in Fig. 10.2.

Another way to look at masking was initiated by Chistovich (1957), Small (1959), and Zwicker (1974). This approach essentially asks the question, what levels of the masker are needed to mask the test signal? Now, the test tone (signal) is kept at a fixed level and frequency, and the level of the *masker* tone is adjusted until it just masks the test tone. This is done at many different frequencies of the masker, resulting in a curve very different from the familiar masking audiogram seen above.

This approach is easily understood by referring to the right panel of Fig. 10.11. (A careful look at this graph will reveal differences from the left panel not only in the tracing but also in the captions for the x- and y-axes.) The tonal signal (i.e., the signal being masked) is a 1000-Hz tone at 15 dB (indicated by the *X*). Now it is the *masker* tone, which sweeps across the frequency range, and the subject uses the Bekesy tracking method to keep the masker at a level that will just mask the fixed test tone. The resulting diagram shows the level of the masker needed to keep the test tone just masked as a function of the masker frequency.

It should be apparent to the reader that this tracing bears a striking resemblance to the auditory neuron tuning curves seen in earlier chapters. It is thus called a **psychoacoustic** (or **psychophysical) tuning curve (PTC)**. Psychophysical tuning curves provide a very good representation of the ear's frequency selectivity. This occurs based on the notion that we are sampling the output of just one auditory filter when a very low signal is used. As the masker gets closer and closer to the frequency of the test signal, less and less level will be required to mask it, and hence the function of masker level needed to just mask the tone provides a picture of the filter.

However, one must avoid the temptation to think of the PTC as the psychoacoustic analogy of an individual neural tuning curve. It is clear that much more than a single neuron is being sampled, and that PTCs are wider than neural tuning curves. Moreover, the earlier discussions dealing with the implications of beats, combination tones, and off-frequency listening in masking are particularly applicable to PTCs. For example, PTCs become wider when off-frequency listening is minimized by the use of notched noise (Moore et al., 1984). A notched noise is simply a band-reject noise (see Chap. 1) in which the band being rejected is centered where we are making our measurement. Therefore, the notched noise masks the frequency regions above and below the one of interest, so that off-frequency listening is reduced.

Figure 10.12 shows two sets of individual PTCs at four test-tone frequencies (500–4000 Hz) from a more recent

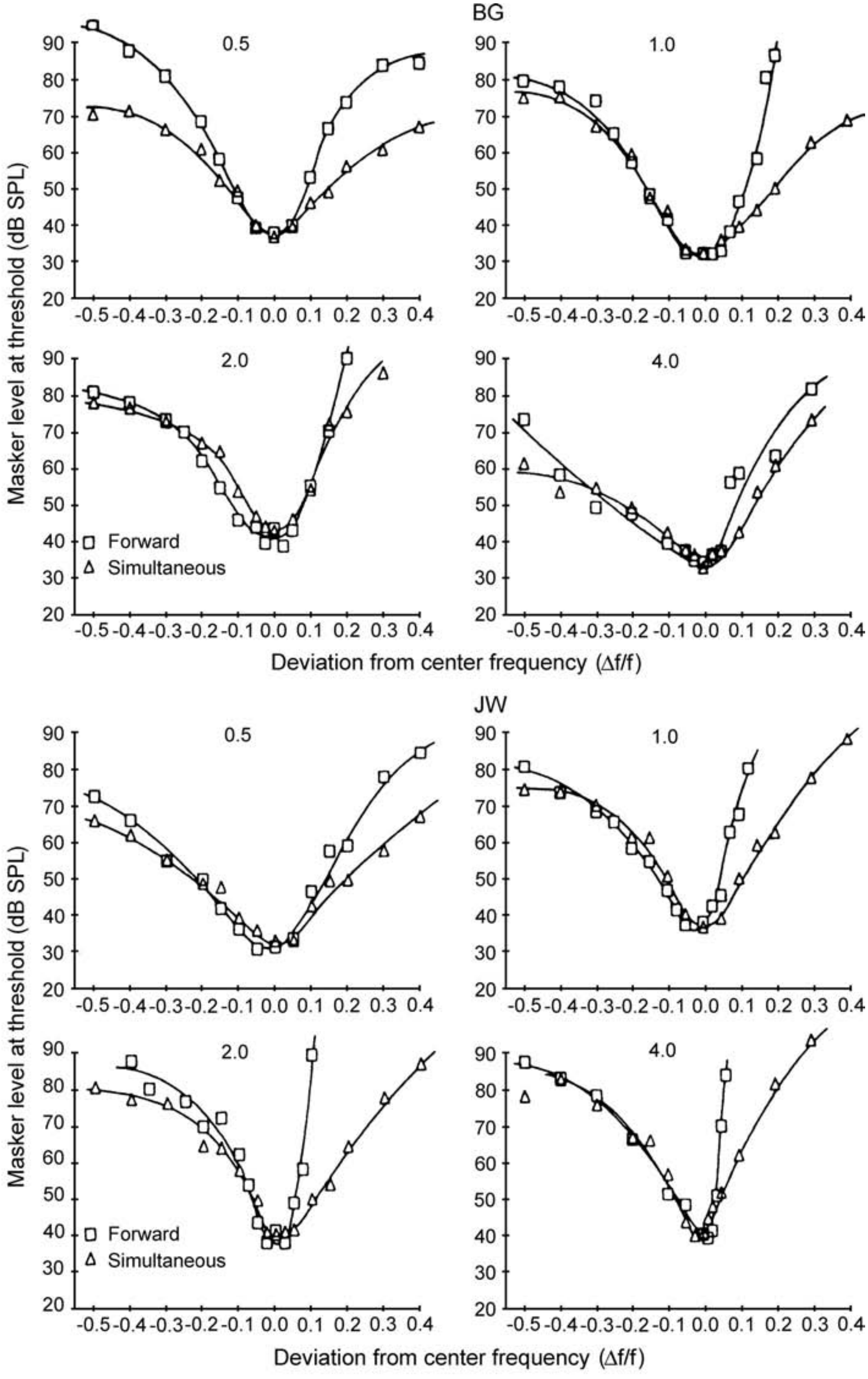

Figure 10.12 Individual psychoacoustic tuning curves at 500, 1000, 2000, and 4000 Hz for two listeners. Triangles are simultaneous masking data and squares are forward masking data. Notice that the forward masking PTCs show sharper tuning. *Source*: From Moore et al. (1984), with permission of *J. Acoust. Soc. Am.*

experiment. These PTCs were obtained by using simultaneous masking (triangles) versus forward masking (squares). As the figure shows, PTCs generated under forward masking conditions generally show sharper tuning than those described for simultaneous masking conditions (e.g., Houtgast, 1972; Duifhuis, 1976; Wightman et al., 1977; Weber, 1983; Lufti, 1984; Moore et al., 1984). These differences go beyond the current scope, but the interested reader will find several informative discussions on this topic (e.g., Weber, 1983; Jesteadt and Norton, 1985; Patterson and Moore, 1986; Lufti, 1988).

COMODULATION MASKING RELEASE

Recall that only a certain critical bandwidth of noise around a signal tone is involved in the masking of that tone: The masked threshold of the signal will not be changed by widening the noise bandwidth beyond the CB or adding one or more other bands outside of the CB. However, a different situation occurs when the masking noise is amplitude modulated, as illustrated by the following example.

It will be convenient for the noise band centered on the test tone to be called the *on-signal band*, and for any other bands of noise to be called *flanking* or *off-frequency bands*. We will begin by masking a pure tone signal by an on-signal band of noise that is being amplitude modulated, as illustrated by the waveform in the panel labeled "on-signal band alone" in upper portion of Fig. 10.13. The graph in the lower part of the figure shows that the masked threshold of the signal is 50 dB in presence of this amplitude modulated on-signal noise. We will now add another band of noise that is outside of the CB of the test tone. The off-signal band will be amplitude modulated in exactly the same way as the on-signal band, as illustrated in the panel labeled "comodulated bands" in Fig. 10.13. These two noise bands are said to be *comodulated bands* because the envelopes of their modulated waveforms follow the same pattern over time even though they contain different frequencies. We do not expect any change in masking with the comodulated bands because adding the off-frequency band is outside of the signal's critical band. However, we find that the masked threshold of the signal actually becomes better (lower) for the comodulated bands compared to what it was for just the on-signal band alone. This improvement is called **comodulation masking release (CMR)** (Hall, Haggard, and Fernandes, 1984). In the hypothetical example of Fig. 10.13, the masked threshold of the tone improved from 50 dB in the presence of just the on-signal band (left bar) to 39 dB for the comodulated bands (middle bar), amounting to a CMR of 11 dB. Notice that the masked threshold does not improve (right bar) if the on-signal and off-signal noise bands are *not* comodulated (panel labeled

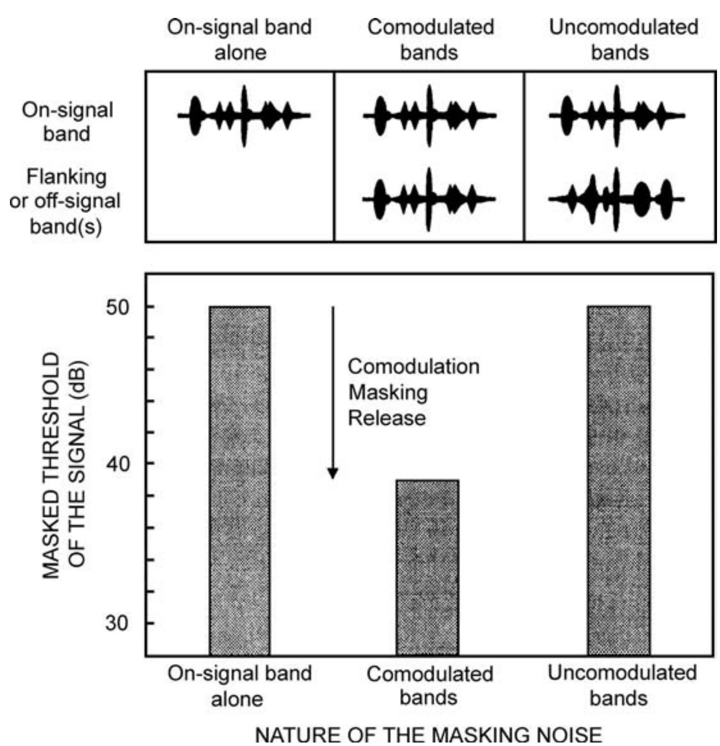

Figure 10.13 Hypothetical modulated noise band waveform envelopes (*above*) and masked threshold results (*below*) illustrating comodulation masking release. See text.

"uncomodulated bands"). Comodulation masking release also occurs for complex signals (made up of, e.g., 804, 1200, 1747, and 2503 Hz) even if there is some spectral overlap between the signal and the masker (Grose, Hall, Buss, and Hatch, 2005)

Comodulation masking release reveals that the auditory system is able to capitalize upon information provided across critical band filters, although a cohesive model explaining CMR is not yet apparent. One type of explanation suggests that the information provided by the off-signal band(s) helps the subject know when the troughs or "dips" occur in the modulating noise. Listening for the signal during these dips would result in a lower threshold (less masking) compared to times when the noise level is higher. Another type of model suggests that the auditory system compares the modulation patterns derived from the outputs of auditory filters in different frequency regions. This pattern would be similar for the filters that do not contain a signal but would be modified for the filter that contains a signal. Detecting a disparity between the outputs of the filters would thus indicate the presence of a signal. The interested student should see the informative review by Moore (1990) and the many contemporary discussions of CMR parameters, models, and related effects (e.g., Buus, 1985; Hatch et al., 1995; Hall and Grose, 1990; Moore et al., 1990; Hicks and Bacon, 1995; Bacon et al., 1997; Grose et al., 2005).

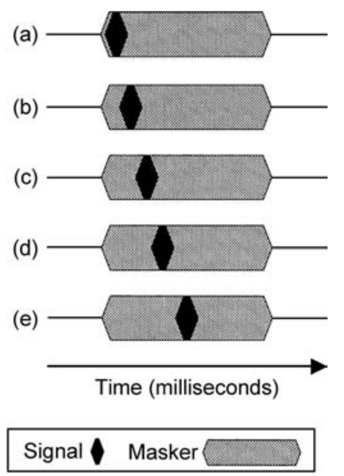

Figure 10.14 Timing relationships between a masker and brief signal. The signal onset is within a few milliseconds of the masker onset in the first frame and occurs at increasing delays in the subsequent frames. The signal is presented in the temporal middle of the masker in the last frame.

OVERSHOOT

The masked threshold of a brief signal can be affected by the temporal arrangement of the signal and a masking noise. The typical experiment involves a very brief signal and a longer duration masker, with various timing relationships between them. For example, the signal onset might be presented within a few milliseconds of the masker onset (as in Fig. 10.14a), in the middle of the masker (Fig. 10.14b), or the signal onset might trail the masker onset by various delays between these extremes (as in Fig. 10.14c to d). Compared to the amount of masking that takes place when the signal is in the middle of the masker, as much as 10 to 15 dB more masking takes place when the signal onset occurs at or within a few milliseconds of the masker onset. In other words, a brief signal is subjected to a much larger threshold shift at the leading edge of a masker compared to when it is placed in the temporal middle of the masker. This phenomenon was originally described by Elliott (1965) and Zwicker (1965a, 1965b) and is known as **overshoot**.

The amount of masking overshoot decreases as the signal delay gets longer, usually becoming nil by the time the delay reaches about 200 ms (e.g., Elliott, 1969; Zwicker, 1965a; Fastl, 1976). Masking overshoot is maximized for signals with high frequencies (above 2000 Hz) and short durations (under 30 ms) (e.g., Elliott, 1967, 1969; Zwicker, 1965a; Fastl, 1976; Bacon and Takahashi, 1992; Carlyon and White, 1992), and when the masker has a very wide bandwidth, much broader than the critical band (e.g., Zwicker, 1965b; Bacon and Smith, 1991). In addition, overshoot becomes greater as the masker increases from low to moderate levels, but it declines again as the masker continues to increase toward high levels (Bacon, 1990).

The different amounts of overshoot produced by narrow versus broad band maskers has been addressed by Scharf, Reeves, and Giovanetti (2008), who proposed that overshoot is caused (or at least affected) by the listener's ability to focus on the test frequency at the onset of the noise. This is disrupted by the wide range of frequencies in a broadband masker, but is focused by the narrow band masker because its spectrum is close to the signal frequency. Consistent with their explanation, they found that narrow band maskers caused little if any overshoot when the test tone always had the *same* frequency (stimulus *certainty*), as in the typical overshoot experiment. In contrast, narrow maskers produced more overshoot when the test frequency was *changed randomly* between trials (stimulus *uncertainty*). The opposite effect occurred with wide band maskers, in which case stimulus uncertainty produced less overshoot.

Although the precise origin of overshoot is not definitively known, the most common explanation is based on adaptation in auditory neurons (e.g., Green, 1969; Champlin and McFadden, 1989; Bacon, 1990; McFadden and Champlin, 1990; Bacon and Healy, 2000). Recall from Chapter 5 that the initial response of an auditory neuron involves a high discharge rate, which declines over a period of roughly about 10 to 20 ms. The neural response produced by the masker would thus be greatest at its leading edge and would weaker thereafter. As a result, more masking would be produced at the beginning of the masker than in the middle of it. Other hypotheses suggest that the basis for masking overshoot may be related to processes associated with the basilar membrane input–output function (von Klitzing and Kohlrausch, 1994; Strickland, 2001; Bacon and Savel, 2004), or a disruption in the listener's ability to attend to the signal frequency (Scharf et al., 2008).

Masking overshoot can also occur when the signal is very close to the offset of the masker, although it is considerably smaller than the onset effect (e.g., Elliott, 1969; Bacon and Viemeister, 1985; Bacon and Moore, 1986; Bacon et al., 1989; Formby et al., 2000). A peripheral origin for offset overshoot is unlikely because the increased spike rate seen at the onset of auditory neuron firing patterns does not also occur at offset. Hence, overshoot at masker offset has been attributed to central processes (e.g., Bacon and Viemeister, 1985; Bacon and Moore, 1986).

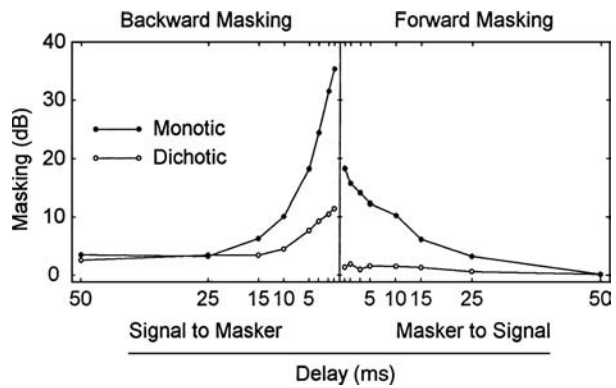

Figure 10.16 Temporal masking in decibels as a function of the interval between signal and masker. (Signal: 10 ms, 1000 Hz tone bursts; masker: 50 ms broadband noise bursts at 70 dB SPL.) *Source*: Adapted from Elliott (1962a), with permission of *J. Acoust. Soc. Am.*

TEMPORAL MASKING

So far, we have been considering situations in which the masker and test signal occur simultaneously. Let us now examine masking that occurs when the test signal and masker do not overlap in time, referred to as **temporal** or **nonsimultaneous masking**. This phenomenon may be understood with reference to the diagrams in Fig. 10.15, which show the basic arrangements used in masking experiments. In Fig. 10.15a, the signal is presented and terminated, and then the masker is presented after a brief time delay following signal offset. Masking occurs in spite of the fact that the signal and masker are not presented together. This arrangement is called **backward masking** or **pre-masking** because the masker is preceded by the signal, that is, the masking effect occurs backward in time (as shown by the arrow in the figure). **Forward masking** or **post-masking** is just the opposite (Fig. 10.15b). Here, the masker is presented first, and then the signal is turned on after an interval following masker offset. As the arrow shows, the masking of the signal now occurs forward in time.

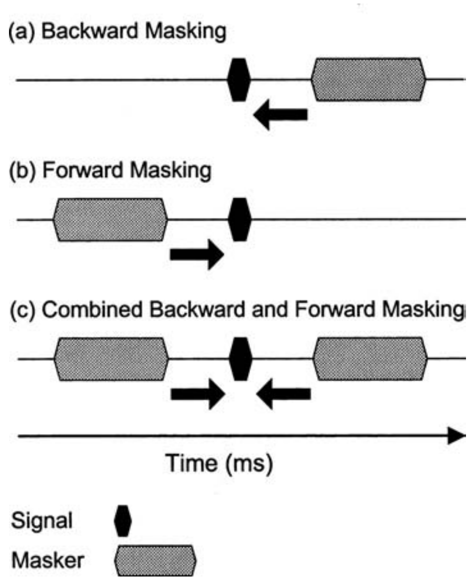

Figure 10.15 Temporal masking paradigms: (a) in backward masking the masker follows the signal, (b) in forward masking the masker precedes the signal, and (c) combined forward and backward masking. The heavy arrows show the direction of the masking effect.

The amount of masking of the test signal produced under backward, forward, or combined forward/backward masking conditions is determined while various parameters of the probe and masker are manipulated. These parameters may be the time interval between signal and masker, masker level, masker duration, etc.

Figure 10.16 shows some examples of temporal masking data from Elliott's (1962a) classic paper. The ordinate is the amount of masking produced by 50-ms noise bursts presented at 70 dB SPL for a test signal of 1000 Hz lasting 10 ms. The abscissa is the time interval between masker and test signal for the backward and forward masking paradigms. Finally, the solid lines show the amount of masking produced when the masker and signal are presented to the same ear (monotically), and the dotted lines reveal the masking that results when the noise goes to one ear and the signal goes to the other (dichotic masking). Notice that considerably more masking occurs monotically than dichotically.

The amount of temporal masking is related to the time gap between the signal and the masker. More masking occurs when the signal and masker are closer in time, and less masking occurs as the time gap between them widens. However, the backward and forward masking functions are not mirror images of each other. As the figure shows, Elliott found greater threshold shifts for backward masking than for forward masking. Similar findings were reported by some investigators (Lynn and Small, 1977; Pastore et al., 1980), but others found the opposite to occur (Wilson and Carhart, 1971).

Backward masking decreases dramatically as the delay between the signal and masker increases from about 15 to 20 ms, and then continues to decrease very slightly as the interval

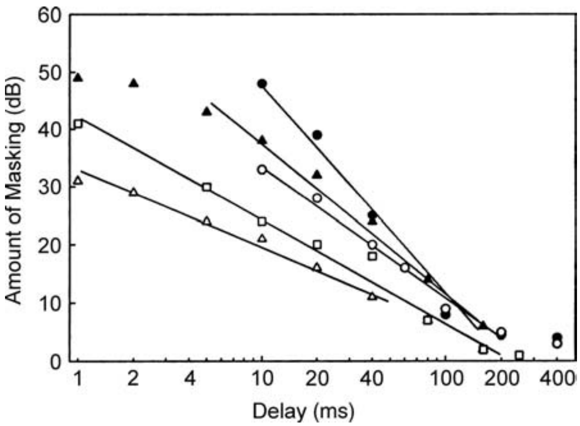

Figure 10.17 Examples of the more or less linear decrease of forward masking with the logarithm of the delay between the masker and the signal. *Source*: Based on data for various forward masking conditions from Wilson and Carhart (1971; *squares*), Smiarowski and Carhart (1975; *triangles*), and Weber and Moore (1981; *circles*).

is lengthened further. Forward masking also decreases with increasing delays, but more gradually. It declines linearly with the logarithm of the masker-signal delay (Fig. 10.17) and exists for intervals as long as about 200 ms depending on the study (e.g., Wilson and Carhart, 1971; Smiarowski and Carhart, 1975; Fastl, 1976, 1977, 1979; Widin and Viemeister, 1979; Weber and Moore, 1981; Jesteadt et al., 1982).

The amount of temporal masking increases as the level of the masker is increased, but not in the linear manner seen for simultaneous masking (Elliott, 1962a; Babkoff and Sutton, 1968; Jesteadt et al., 1981). Rather, with temporal masking, increasing the masker level by 10 dB may result in an additional threshold shift on the order of only about 3 dB.

The duration of the masker influences the amount of forward masking, but this does not appear to occur for backward masking (Elliott, 1967). The amount of forward masking increases as the masker duration gets longer up to about 200 ms (Zwicker, 1984; Kidd and Feth, 1982).

As we might expect, temporal masking is influenced by the frequency relationship between the signal and the masker (e.g., Wright, 1964; Elliott, 1967) just as we have seen for simultaneous masking. In other words, more masking occurs when the signal and masker are close together in frequency than when they are far apart. Formby et al. (2000) found that a 2500-Hz noise band produced temporal masking for a 500-Hz signal, demonstrating that remote masking can occur under temporal masking conditions.

The combined effects of forward and backward masking may be found by placing the signal between the two maskers, as shown in Fig. 10.15c. More masking occurs when backward and forward masking are combined than would result if the individual contributions of backward and forward masking were simply added together (Pollack, 1964; Elliott, 1969; Wilson and Carhart, 1971; Robertson and Pollack, 1973; Penner, 1980; Pastore et al., 1980; Cokely and Humes, 1993; Oxenham and Moore, 1994, 1995). Such findings suggest that forward and backward masking depend upon different underlying mechanisms.

The underlying mechanisms of temporal masking are not fully resolved. Duifhuis (1973) suggested that the steep segments of the monotic temporal masking curves (Fig. 10.16) may be associated with cochlear processes, while the shallower segments at longer delays may be related to neural events. Several findings implicate some degree of central processing in temporal masking. For example, we have already seen that some degree of temporal masking occurs under dichotic conditions for forward and backward masking. In addition, masking level differences (a reduction in masking associated with binaural interactions; see Chap. 13), have been shown to occur for forward, backward, and combined forward-backing masking (e.g., Deatherage and Evans, 1969; Robertson and Pollack, 1973; Berg and Yost, 1976; Yost and Walton, 1977).

Although overlapping in time of the cochlear displacement patterns is a reasonable explanation at very short masker-signal delays, short-term neural adaptation caused by the masker is the predominant explanation of forward masking (Smith, 1977; Harris and Dallos, 1979; Kidd and Feth, 1982). However, even short-term adaptation cannot fully account for the extent of the forward masking measured in psychoacoustic experiments (Relkin and Turner, 1988; Turner et al., 1994). Moreover, forward masking also occurs in cochlear implant users even though the synapses between the hair cells and auditory neurons are bypassed in these patients (Chatterjee, 1999). Thus, the existing evidence seems to suggest that both peripheral and central processes are probably involved in forward masking.

Several lines of evidence in addition to the material describe above suggest that central processes are the principal factors in backward masking. Providing the listener with contralateral timing cues supplies information that affects the uncertainty of the task and has been shown to influence backward masking but not forward masking (Pastore and Freda, 1980; Puleo and Pastore, 1980). Moreover, performance decrements in backward masking (but not forward or simultaneous masking) have been found to be associated with disorders such as specific language impairment and dyslexia (Wright et al., 1997; Wright, 1998; Wright and Saberi, 1999; Rosen and Manganari, 2001).

CENTRAL MASKING

The typical arrangement of a masking experiment involves presenting both the masker and the test stimulus to the *same* ear. Up to now, we have been discussing this ipsilateral type of masking. Another approach is to present the masker to one ear and the test signal to the *opposite* ear. Raising the intensity of the masker will eventually cause the masker to become audible in the other ear, in which case it will mask the test stimulus (a process known as *cross-hearing* or *contralateralization* of the masker). This is actually a case of ipsilateral masking as well, because it is the amount of masker that crosses the head, so to speak, that causes the masking of the signal. However, it has been demonstrated that a masker presented to one ear can cause a threshold shift for a signal at the other ear even when the masker level is too low for it to cross over to the signal ear (Chocolle, 1957; Ingham, 1959; Sherrick and Mangabeira-Albarnaz, 1961; Dirks and Malmquist, 1964; Dirks and Norris, 1966; Zwislocki et al., 1967, 1968). This contralateral effect of the masker is most likely due to an interaction of the masker and test signal within the central nervous system, probably at the level of the superior olivary complex where bilateral representation is available (Zwislocki, 1972).

Central masking is in some ways similar to, yet in other ways quite different from, the monaural (direct, ipsilateral) masking discussed earlier. In general, the amount of threshold shift produced by central masking is far less than by monaural masking, and more central masking occurs for higher-frequency tones than for low. The amount of masking is greatest at masker onset and decays to a steady-state value within about 200 ms. Of particular interest is the frequency dependence of central masking. The greatest amount of central masking occurs when the masker and test tones are close together in frequency. This frequency dependence is shown rather clearly in Fig. 10.18, in which the masker is a 1000-Hz tone presented at a sensation level of 60 dB to the opposite ear. Note that the most masking occurs in a small range of frequencies around the masker frequency. This frequency range is quite close to the critical bandwidth. As the figure also shows, more central masking results when the masker and test tones are pulsed on and off together (curve a) rather than when the masker is continuously on and the signal is pulsed in the other ear (curve b). This is a finding common to most central masking experiments, although the amount of masking produced by a given masker level varies among studies and between subjects in the same study. Furthermore, central masking increases as the level of the masker is raised only for the pulsed masker/pulsed signal arrangement, whereas the amount of masking produced by the continuous masker/pulsed signal paradigm remains between about 1 and 2 dB regardless of masker level.

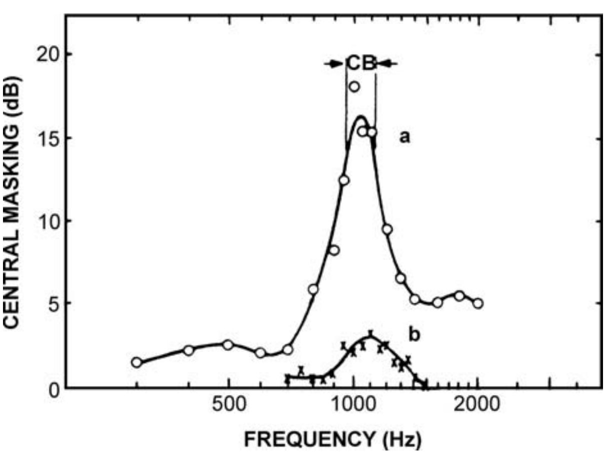

Figure 10.18 Central masking produced by a 1000-Hz tonal masker at 60 dB SL for an individual subject. Curve **a** is for a masker and a test signal pulsed on and off together; curve **b** is for a continuously on masker and a pulsed signal. *Source*: Adapted from Zwislocki et al. (1968), with permission of *J. Acoust. Soc. Am.*

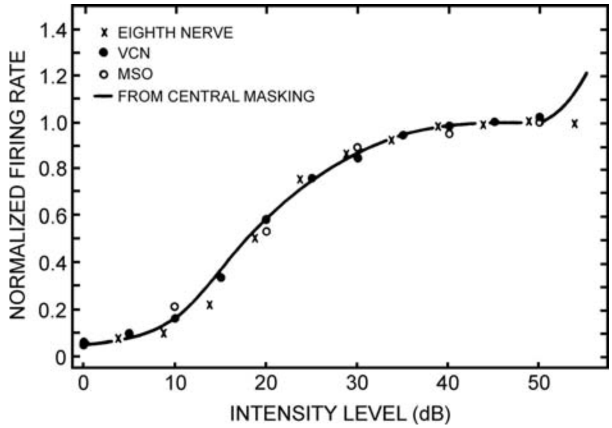

Figure 10.19 Relationship between actually obtained firing rates in the auditory (eighth cranial) nerve, ventral cochlear nucleus (VCN), and medial superior olive (MSO), and rates predicted from central masking data. *Source*: From Zwislocki, In search of physiological correlates of psychoacoustic characteristics, in: *Basic Mechanisms in Hearing* (A.R. Møller, ed.), © 1973 by Academic Press.

An excellent review of the relationships between the psychophysical and electrophysiological correlates of central masking may be found in two papers by Zwislocki (1972,1973). An example is shown in Fig. 10.19, which demonstrates the firing rates of neurons at various levels of the lower auditory nervous system (see Chaps. 5 and 6), and those predicted on the basis of central masking data. With few exceptions, the agreement shown in the figure of the intensity parameter also holds for frequency and time. Thus, central masking is shown to be related to activity in the lower auditory pathways.

INFORMATIONAL MASKING

The prior section dealt one type of central masking, in which the threshold for a signal presented to one ear is elevated by a masker in the opposite ear. This section addresses another kind of centrally mediated masking phenomenon, called informational masking. **Informational masking** refers to masking effects due to higher-level (central) processes rather than the interaction of the signal and masker in the cochlea. In this context, the term **energetic masking** is often used to describe peripheral masking effects. Informational masking effects in sound discrimination tasks are discussed in Chapter 9.

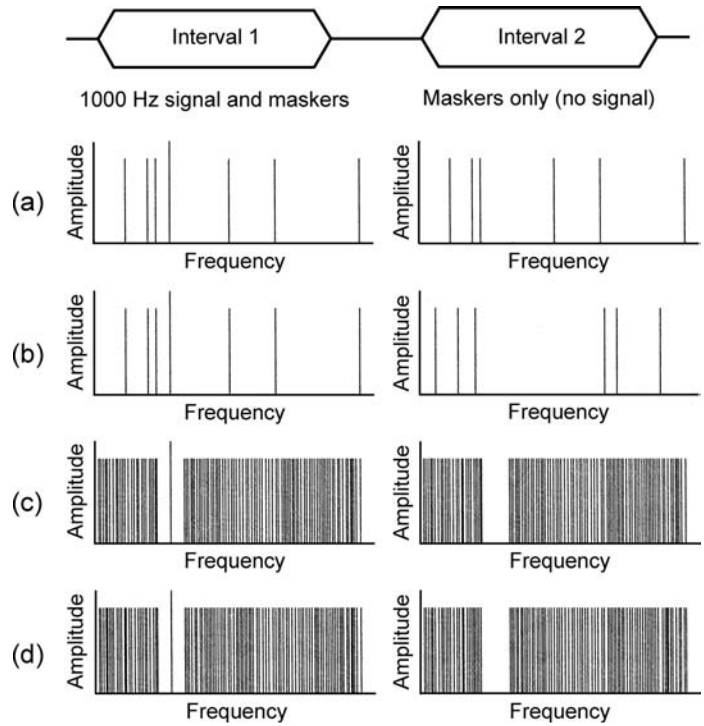

Figure 10.20 Informational masking experiments involve detecting a signal in the presence of a multiple-frequency masker. In each of these examples, the spectrum for interval 1 shows the signal and masker, and the spectrum for interval 2 shows the masker alone (no signal). The 1000-Hz signal is represented by a slightly taller line in each frame. No masker components occur within the critical band (protected range) around the signal frequency. (a) Spectra showing the same 6-component masker in both intervals. (b) Spectra showing the 6-masker components randomized between intervals. (c) Spectra showing the same 100-component masker in both intervals. (d) Spectra showing the 100 masker components randomized between intervals.

Informational masking has been studied in considerable detail (e.g., Neff and Green, 1987; Neff and Callaghan, 1988; Neff and Dethlefs, 1995; Kidd et al., 1994; Neff, 1995; Wright and Saberi, 1999; Richards et al., 2002; Arbogast, Mason, and Kidd, 2002; Gallum, Mason, and Kidd, 2005; Hall, Buss, and Grose, 2005). In the typical experiment, the listener must detect a pure tone signal in the presence of a multiple-frequency masker, although speech signals have also been used. The usual approach involves raising and lowering the signal to find its masked threshold using a two-interval forced-choice method, where one interval contains the signal and masker and the other interval contains just the masker (no signal). The subject's task is to indicate which interval contains the signal. Several examples are shown in Fig. 10.20, where the signal is a 1000-Hz pure tone. It is represented in the figure by the slightly taller line in interval 1 of each frame for illustrative purposes. The signal would actually be presented randomly in both intervals in a real experiment. The masker is a sound composed of two or more pure tone components within a certain frequency range (typically about 300–3000 Hz). The examples in the figure have maskers composed of 6 components (frames a and b) and 100 components (frames c and d). Masked thresholds are obtained separately for each masking condition (for 2-component maskers, 4-component maskers, 8-component maskers, etc.). All of the maskers have the same overall level regardless of how many components they contain or what the frequencies of the components happen to be. What is special about the informational masking situation is that the specific *frequencies of the masker components are randomized* from trial to trial. In other words, the frequencies making up the masker in one trial are different from what they are in another trial. In some conditions, the masker frequencies might also be randomized between the two intervals of the same trial.

In order to avoid or at least minimize the chances that the results might be confounded by effects due to peripheral (energetic) masking, informational masking experiments use a critical band-wide "protected region" around the signal frequency that does not contain any masker components. (Recall that in peripheral masking, a tone is masked by the part of the masker spectrum that is within a certain critical band around that tone.) All of the spectra in Fig. 10.20 have this protected range (most easily seen in frames c and d).

Figure 10.21 shows the amount of masking (for the 1000-Hz signal) produced by maskers with as few as 2 and as many as 150 components under two conditions: (1) when masker components *are* allowed to fall inside the critical band (as in the

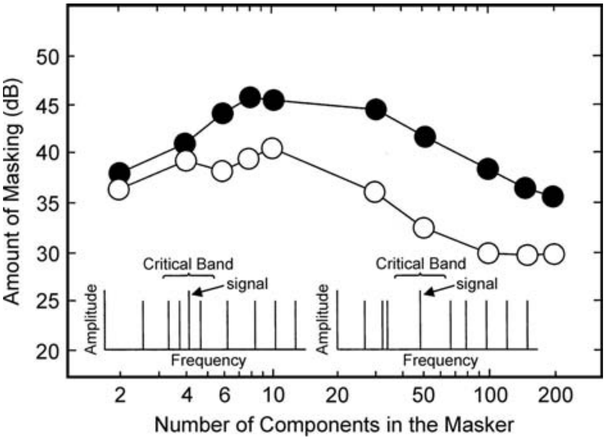

Figure 10.21 The graph shows amount of masking of a 1000-Hz signal produced by maskers with different numbers of components when masker components may fall within the critical band around the signal (*filled symbols*) compared to when none of the components are within the critical band (*open symbols*). *Source*: Adapted from Neff and Callaghan, 1988 with permission of *J. Acoust. Soc. Am. Insets*: The left spectrum shows some masker components falling *inside* the critical band around the signal. The right spectrum shows the same number of masker components, all falling *outside* the critical band.

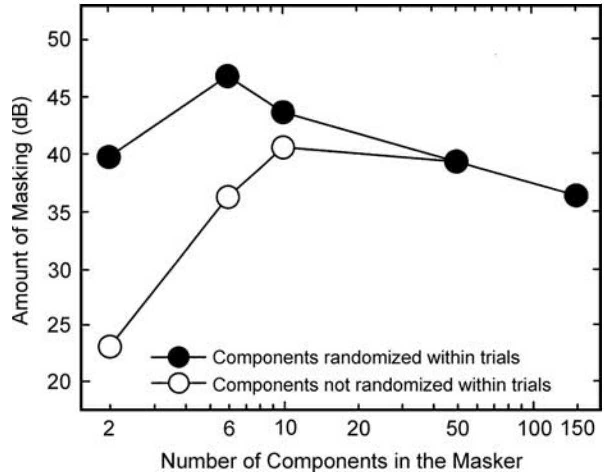

Figure 10.22 The amount of masking of a 1000-Hz signal produced by maskers with different numbers of components. Open symbols show results when the masker frequencies are the same for both intervals (as in Fig. 10.20a and c). Closed symbols show results when the masker frequencies are randomized between intervals (as in Fig. 10.20b and d). *Source*: Adapted from Neff and Callaghan (1988) with permission of *J. Acoust. Soc. Am.*

left inset), and (2) when all of the components are outside of the critical band (as in the right inset). We see that more masking occurs when some of the masker components are within the critical band (filled symbols) than when they are all outside of the critical band (open symbols). However, there is still a considerable amount of masking even when all of the masker components are outside the critical band, that is, where they are too far from the signal to cause any appreciable energetic masking. This is informational masking. It is attributed to the *uncertainty* introduced into the listening task by randomizing the masker components, thereby interfering with the ability to detect the signal even though it has not be rendered inaudible at the periphery.

The influence of the degree of masker uncertainty is illustrated in Fig. 10.22. It shows the amount of masking (for the 1000-Hz signal) produced by multitone maskers composed of various numbers of components under two degrees of uncertainty. (1) The smaller degree of uncertainty occurs when the frequencies of the masker components are randomized between trials, but are the same for both intervals within a given trial (e.g., Fig. 10.20a for a 6-component masker and Fig. 10.20c for a 100-component masker). (2) Greater uncertainty occurs when the masker components are also randomized between the two intervals within each trial (e.g., Fig. 10.20b for 6 components and Fig. 10.20c for 100 components). The salient finding is that more informational masking occurs when there is a greater degree of uncertainty (components randomized within trials, filled symbols) than when there is less uncertainty (components not randomized within trials, open symbols). We also see that informational masking is greatest when the masker contains a smaller number of components and smallest when there are a great many components.

It might seem odd that a smaller change in informational masking is produced by altering the degree of uncertainty when the masker contains a large number of components, but it makes sense with a simple visual analogy: Look at the spectra in Fig. 10.20, and notice that it is easier to see that the signal line is in interval 1 in frame a (where the few masker lines are the same for both intervals) than in frame b (where the few masker lines are different between the intervals). On the other hand, it is just as easy to see that the signal line is in interval 1 in frame d (where the many masker lines are different between the intervals) as it is in frame c (where they are the same for both intervals). It is as if a small number of masker components face the listener with a sparse and irregular background where knowing the details is very important; thus random changes in these details create a lot of uncertainty. On the other hand, a large number of components make the background more uniform so that knowing the details is relatively less important. Thus, random changes in its details do not cause as much uncertainty.

In summary, informational masking is the result of higher-level (central) processes related to uncertainty about the masker. The amount of informational masking is typically quite large, on the order of 40 to 50 dB or more, and the effect is greatest when the masker contains a relatively small number of components (generally about 20 or fewer). Before leaving this topic, it should be pointed out that informational masking is subject to a considerable amount of variability among subjects and is affected by a variety of factors (see, e.g., Neff and Callaghan, 1988; Neff and Dethlefs, 1995; Neff, 1995; Wright and Saberi, 1999; Richards et al., 2002).

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