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Review of the Literature on Temporal Resolution in Listeners with Cochlear Hearing Impairment: A Critical Assessment of the Role of Suprathreshold Deficits

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Abstract

A critical review of studies of temporal resolution in listeners with cochlear hearing impairment is presented with the aim of assessing evidence for supra-threshold deficits. Particular attention is paid to the roles of variables—such as stimulus audibility, overall stimulus level, and subject age—that may complicate the interpretation of experimental findings in comparing the performance of hearing-impaired (HI) and normal-hearing (NH) listeners. On certain temporal tasks (e.g., gap detection), the performance of HI listeners appears to be degraded relative to that of NH listeners when compared at equal SPL. For other temporal tasks (e.g., forward masking), HI performance is degraded relative to that of NH listeners when compared at equal sensation level. A relatively small group of studies exists, however, in which the effects of stimulus audibility and level (and occasionally subject age) have been controlled through the use of noise-masked simulation of hearing loss in NH listeners. For some temporal tasks (including gap detection, gap-duration discrimination, and detection of brief tones in modulated noise), the performance of HI listeners is well reproduced in the results of noise-masked NH listeners. For other tasks (i.e., temporal integration), noise-masked hearing-loss simulations do not reproduce the results of HI listeners. In three additional areas of temporal processing (duration discrimination, detection of temporal modulation in noise, and various temporal-masking paradigms), further studies employing control of stimulus audibility and level, as well as age, are necessary for a more complete understanding of the role of supra-thresholds deficits in the temporal-processing abilities of HI listeners.

Keywords

cochlear hearing loss; supra-threshold effects; audibility; noise-masked simulation of hearing impairment; temporal resolution

I. Introduction

Hearing impairments can produce two types of deficits that degrade the perception of auditory signals. The first type arises from a reduction in audibility due to elevated detection thresholds. Auditory perception can suffer from an audibility deficit whenever signals are partially or completely inaudible. The second type of deficit is defined as the loss in auditory abilities

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beyond those due to elevated detection thresholds. Such supra-threshold deficits might be manifested, for example, as poorer-than-normal frequency selectivity or temporal resolution for signals that are clearly audible.

An important question in the study of hearing impairment is to what extent each of these two types of deficits -- audibility and supra-threshold -- accounts for the observed psychoacoustic performance of hearing-impaired listeners. An improved understanding of the role of supra-threshold deficits would contribute to the effort to advance models of hearing impairment that link behavioral measures to physiological mechanisms. A better characterization of the role of supra-threshold deficits in speech reception, in particular, could lead to improved signal processing for hearing aids and more appropriate aural rehabilitation generally.

The question of the roles of threshold and supra-threshold deficits can be addressed for any type of hearing loss, including losses of cochlear, conductive, and retrocochlear origin. The work reviewed in this paper, however, is restricted to studies of listeners with cochlear hearing impairment. Cochlear hearing impairment represents the primary type of loss for which hearing aids are sought. Furthermore, cochlear loss is also marked by reduced dynamic range (or, equivalently, loudness recruitment), which makes compensation with amplification difficult. Conductive hearing loss, by comparison to cochlear loss, is simpler to understand; it is also more amenable to both surgical treatment and hearing aid rehabilitation. Retrocochlear hearing losses, which most-frequently result either from eighth-nerve tumors or auditory neuropathy (Sininger and Starr, 2001; Rance, 2005), constitute an important category of impairments that differ in important respects from cochlear loss and that should be addressed separately. For these reasons, the focus of the current review is on research conducted with cochlear hearing loss.

A large number of research studies have been aimed at assessing the roles of audibility and supra-threshold deficits in the performance of listeners with cochlear hearing impairment. These studies have examined a wide range of tasks, conditions, and listener characteristics. However, the many studies that have been reported thus far have not resulted in a clear consensus view. In fact, conclusions in the literature regarding the role of supra-threshold deficits range from ‘no role’ to ‘very important,’ if not ‘the dominant factor’ in some conditions. Our goal in this paper, examining temporal resolution, is to provide a complete and critical review of the literature on the role of supra-threshold deficits accompanying cochlear hearing impairments. Several issues, discussed in the following sections, have complicated the interpretation of many past studies. By re-examining the literature with an eye on these issues we hope to reach a clearer understanding of existing studies and point out areas where future efforts might be fruitfully directed.

A. Stimulus Level and Audibility as Confounding Factors

Psychoacoustic performance comparisons between normal-hearing (NH) and hearing-impaired (HI) listeners are intrinsically complicated by the difference in absolute thresholds. This complication, if not controlled, can result in an experimental confound between suprathreshold deficits as a factor and either stimulus level or stimulus audibility.

In choosing stimulus levels for comparisons between NH and HI listeners, experimenters have frequently elected to present signals at either an equal sound-pressure level (SPL) for all listeners or at equal sensation level (SL), which is signal level re absolute threshold. Figure 1 illustrates these different conditions for a stimulus that is a band of noise between 0.5 and 4 kHz, presented at a moderate level. Such a noise stimulus has been used in some of the studies of temporal resolution described later. Figure 1(a) plots absolute thresholds (minimum audible pressure, ANSI S3.6-2004) for NH listeners along with the spectrum of the noise stimulus. Figure 1(b) plots hypothetical HI thresholds with the same noise spectrum. In this equal-SPL case the stimulus levels are the same for NH and HI listeners but, because of the differences in absolute thresholds between the listeners, the stimulus has greater audibility for the NH listener. Whereas much of the stimulus spectrum is audible to the NH listener (i.e., it lies above the absolute threshold curve), the frequency components in the regions below 0.3 kHz and above 2 kHz are inaudible to the HI listener. In addition, in the mid-frequency region where the stimulus is audible for the HI listener, the signal-to-threshold ratio is much less than it is for the NH listeners. HI performance with this stimulus should be expected to be degraded by reduced audibility, in addition to any suprathreshold deficits. With such equal-SPL stimuli, however, it will not be possible to interpret observed performance degradations for the HI listeners as resulting solely from suprathreshold deficits because of the clear difference in audibility.

Figure 1(c) plots the same HI thresholds but with the noise spectrum shaped so that each band is presented at equal SL, exceeding threshold to the same degree as it does for the NH listener in Figure 1(a). In this case, because HI thresholds are higher than NH thresholds and hearing loss is usually not constant with frequency, the overall stimulus presentation level is greater for the HI listener and the spectral shape is altered. As a result, in this equal-SL case, comparisons of NH and HI performance made to estimate suprathreshold deficits with this stimulus will be confounded by the frequency-dependent differences in sound-pressure level between groups.

Figure 1 shows only two examples out of many possible stimulus configurations for making NH-HI comparisons. One could also, if dynamic range allows, amplify the unshaped stimulus and present it to both groups at an equal SPL that is sufficiently high that audibility is not limited in any frequency region for the HI listeners. Alternatively, one could achieve an equal-SL condition by shaping and reducing the overall level of the stimulus for the NH listeners to match the audibility of the stimulus spectrum experienced by the HI listener in Fig. 1(b). Whatever stimulus conditions are used, however, if thresholds differ between the groups there will inevitably be a difference in either signal level or audibility, or some combination of the two.

Stimulus audibility is, of course, of prime importance for any psychoacoustic task. To the extent that NH-HI comparisons are confounded by audibility differences the results will be difficult to interpret in terms of supra-threshold deficits.

Stimulus level is known to be a critical variable in some types of psychoacoustic measurements of temporal-resolution ability. In some tasks, performance (for NH listeners, at least) improves with an increase in stimulus level until asymptotic performance is achieved. An example of this pattern of performance can be seen for the detection of gaps in broadband noise (Florentine and Buus, 1984). In other tasks, performance may be independent of level (once threshold of detection for the signals is exceeded), as appears to be the case in measurements of temporal modulation transfer functions (Bacon and Gleitman, 1992) The results of studies comparing NH and HI listeners with level confounded on such a task may be plausibly argued to be valid assessments of supra-threshold deficits.

B. Experimental Controls for Stimulus Level and Audibility

The problems of controlling for level and audibility can be reduced with narrowband stimuli by testing under a range of conditions that include equal-SPL, equal-SL, and possibly other conditions. If a clear superiority of NH over HI performance is consistently seen with a wide range of stimulus level configurations that control for level and/or audibility, it can be argued that the results point to an underlying suprathreshold deficit. However, with broadband stimuli the frequency-dependencies of the stimulus spectrum and of the NH and HI thresholds complicate such manipulations.

The Simulation Paradigm—The problems with making valid NH-HI comparisons have led to the use of what can be called ‘the simulation paradigm,’ which is illustrated in Figure 2. Stimulus signals are presented identically to both HI and NH listeners, with the signals to the NH listener pre-processed by a hearing-loss simulation. In general, one can incorporate any presumed characteristic of hearing loss into the simulation and test it against actual HI performance. If a hypothesized characteristic of hearing impairment can be simulated in signal processing, it can be tested experimentally via comparisons to HI listener performance. Observed discrepancies can be analyzed and the simulation can be modified to lead to improved simulation methods.

One particular class of simulation, which incorporates both threshold elevation and recruitment, has been used in several studies to address the question of supra-threshold deficits (e.g., Buus and Florentine, 1989; Dubno and Schaefer, 1992). Equating NH and HI thresholds results in equal-SPL stimuli also being presented at equal SL, thus removing the confound simultaneously from both audibility and level. At the same time the simulation of recruitment produces a growth in loudness for NH that is similar to that seen with HI listeners. A further result of the recruitment simulation is that the auditory systems of both the NH and HI listeners are stimulated with the same high-level signals (beyond the level where full recruitment is reached). With confounds eliminated, superior performance of NH over HI listeners can then be ascribed to supra-threshold deficits associated with the hearing impairment.

Noise masking has been the method used most frequently for simultaneously elevating thresholds and inducing loudness recruitment for NH listeners. The use of spectrally-shaped masking noise (e.g., see Buus and Florentine, 1989) allows very accurate matching to many individual audiometric configurations (Dubno and Schaefer, 1992) and it results in a reduction in dynamic range (or loudness recruitment) similar to that observed in cochlear hearing loss (Steinberg and Gardner, 1937; Stevens and Guiaro, 1967). The noise masking simulation method, however, has limitations.

One limitation is that in order to avoid loudness discomfort from the masking noise required for threshold elevation, the technique is limited to hearing loss less than roughly 70 dB HL. Another issue is that remote masking (Bilger and Hirsh, 1956) can complicate the matching of abrupt high-frequency losses with steeply high-pass-filtered noise. [Another class of techniques for simulating hearing loss, based on the use of automatic-gain control (Villchur, 1973, 1974), may be used for simulating larger amounts of hearing loss. Such methods have not been applied to studies of temporal resolution, however, and thus are not discussed further here.]

It has been questioned whether the noise masking technique accurately represents the neurophysiological response in the impaired auditory system (e.g. Dubno and Schaefer, 1992; Phillips, 1987). Although this difference in peripheral response is unavoidable, it should be noted that the time intervals when that difference is greatest will be those where no acoustic cues are being transmitted, because of either hearing loss in the impaired ear or masking noise in the normal ear. For inaudible stimuli, the impaired ear would have no response while the normal ear would respond to the masking noise. In contrast, peripheral responses during intervals of audible stimulation can be expected to be much more similar for NH and HI ears because they are being driven by similar stimuli. This difference in peripheral response to inaudible stimuli has to be weighed against the benefit of the technique in allowing stimuli to be presented at sound pressure levels, and with frequency-dependent audibility, that are matched for NH and HI listeners.

There are other more specific issues that arise with the use of the noise-masking simulation, such as whether it duplicates such psychoacoustic effects as the additivity of masking, off-frequency listening, and spread of masking. In addition, there is the question of whether the presence of the simulation noise has a degrading cognitive effect on the NH listeners. There are likewise a range of issues associated with other hearing loss simulation methods that have been employed less frequently than noise masking, such as automatic-gain control (Lum and Braida, 2000) and spectral smearing (Baer and Moore, 1993). These issues must be considered when interpreting experimental results.

C. Age as a Confounding Factor

The intended experimental factors in research studies are often either knowingly or unavoidably confounded by factors (e.g., gender of the subjects) that are disregarded as being inconsequential. For many years listener age was not widely viewed as an important factor in studies of hearing impairment. Because of the much higher incidence of hearing impairment in older people, and also because of the greater availability of both elderly retirees to serve as HI listeners and college students as NH listeners, many studies of supra-threshold deficits in the literature have confounded hearing loss with age. However, as a result of intensive study of aging over the last twenty years, we now are aware of a variety of changes in sensory and/or cognitive processing that can occur with age (e.g., see review by Fozard and Gordon-Salant, 2001). Thus, age must now be regarded as an important confounding factor in comparisons of NH and HI listeners. Although there are also many studies that have not shown age effects on certain auditory tasks, the evidence indicating auditory deterioration with age should make us very cautious when examining studies of hearing impairment with large age differences between NH and HI listeners.

D. Study Selection Criteria

In order to critically assess the evidence of supra-threshold deficits of temporal resolution provided by studies in the literature, we selected studies according to the following criteria:

1. hearing losses confirmed to be of cochlear origin;
2. testing done monaurally with an earphone (excluding studies involving binaural hearing, spatial effects, and hearing aids); and
3. the data on which HI and NH listeners were compared were the results of objectively-scored tests (excluding results of rating scales, questionnaires, and subjective adjustments).

Care will be taken to point out experimental confounds (involving hearing impairment and age as well as audibility and level) and the limitations on interpretations that those require. By following these guidelines we hope to present an overview of the literature that reflects the quality of the experimental evidence on supra-threshold deficits in temporal resolution of listeners with cochlear hearing loss.

II. Review of Studies of Temporal Resolution with Hearing-Impaired Listeners

The remainder of this paper is concerned with a review of the literature in the area of temporal resolution in listeners with cochlear hearing impairment. Important cues to the perception of speech, music, and environmental sounds are carried in the temporal fluctuations of the waveforms associated with such signals. Temporal cues are conveyed both in the long-term properties of the temporal envelope (providing information about prosodic aspects of speech, for example) as well as in short-term fluctuations (which may provide information about segmental speech properties, such as manner of consonant articulation or consonant voicing). Additionally, temporal processing ability may be related to the ability to understand speech in background noise when listeners can take advantage of momentary changes in speech-to-noise ratio to improve reception. Thus, the ability to detect and discriminate temporal properties of acoustic waveforms plays a basic role in the recognition of speech and other environmental sounds both in quiet and in noise by listeners with sensorineural loss.

The temporal-resolving power of the auditory system of NH and HI listeners has been probed using a variety of psychoacoustic tasks. Measurements of temporal resolution can be classified into a number of major categories, each of which assesses a different aspect of temporal processing: (A) detection of gaps in tones and noise; (B) discrimination of gap duration and signal duration; (C) detection of signals as a function of duration (i.e., temporal integration); (D) detection of tones in temporally modulated noise; (E) detection of temporal modulation in noise; (F) detection of signals in various temporal masking paradigms. That these tasks access different processing mechanisms within the auditory system is evident from the different patterns of results observed for HI relative to NH listeners across the different categories of experiments reviewed below.

Our review of studies of temporal-resolution is organized by the categories of psychoacoustic tasks described above. Within each category of experiments, we begin the review with a summary of those studies in which audibility, sound level, and age effects are well-controlled (when such studies exist). These studies provide a benchmark against which results obtained in other studies (employing less strict control of these variables) can be compared and evaluated.

A. Detection of Gaps in Tones and Noise

In a gap-detection task, the listener is required to discriminate between a reference signal which is continuous throughout the presentation intervals and a comparison signal containing a silent interval (gap). The experiment is typically conducted using a two- or three-alternative forced-choice adaptive procedure. The subject's task on each trial is to select the interval containing the signal with the silent gap. The duration of the gap is typically varied adaptively. A threshold is determined representing the minimal gap duration that can be detected for some defined level of performance (e.g., 50%, 70%). Experimental parameters include signal type (typically pure tones or bursts of noise with varying spectral characteristics), signal duration (defined as the duration of the reference signal; the portion of the comparison signal before the gap is often referred to as the “leading marker” and the portion of the signal following the gap is often referred to as the “trailing marker”), and location of the gap relative to signal onset (the default location is in the center of the signal such that the durations of the leading and trailing markers are equal). Various means are used to reduce the possibility of spurious cues arising from spectral splatter: the leading and trailing markers are gated off and on with gradual rise-fall times; narrow-band signals are typically presented in the background of low-level continuous noise with a spectral notch in the region of the signal; and the reference signal itself may be constructed from leading and trailing markers that are gated on and off with the same rise-fall times as used in the comparison stimulus (to control for spectral splatter cues that may be introduced by the gating operation).

The major studies reviewed in Sections A-1 and A-2 below, concerned with gap-detection thresholds of listeners with sensorineural hearing impairment, are summarized in Table 1. (Please note that Table 1 does not include the studies concerned with the effects of age in subjects with clinically normal hearing that are discussed briefly in the last paragraph of Section A-2.)

A-1. Studies with Controls of Audibility and Level—Florentine and Buus (1984) and Buus and Florentine (1985) studied the detection of gaps in broadband noise using three groups of subjects that included (a) six NH listeners (aged 20-50 years), (b) seven HI listeners (aged 20-57 years), and (c) two NH listeners with noise-masked simulations of hearing loss (selected from the group of six NH listeners, but whose ages were unspecified). The HI listeners were classified into four groups described by the following audiometric configurations and pure-tone averages (PTA; the average of thresholds in dB HL across the frequencies 500, 1000, and 2000 Hz): bowl-shaped loss (one subject; characterized by greater loss in the mid-frequency range than at 250 and 8000 Hz; PTA= 62 dB HL), flat loss (two subjects; PTA=46 dB HL), mildly-sloping high-frequency loss (two subjects; PTA=29 dB HL), and steeply-sloping high-frequency loss (two subjects; PTA=32 dB HL). For the latter three types of losses defined above, spectrally-shaped masking noise was used to simulate the hearing loss in the same two NH subjects through elevation of their pure-tone thresholds to match the desired loss within ±3 dB in the audiometric range of 250 to 8000 Hz. For the HI listener with a unilateral bowl-shaped loss, the noise-masked simulation was performed on the normal ear of this same listener in addition to one of the NH subjects.

The ability to detect a gap in a 500-msec burst of broadband noise was examined as a function of overall level for signals that encompassed a range from 20 to 90 dB SPL. The gap was inserted at 50 msec relative to the onset of the noise burst and was produced with 1-msec rise/fall times. The gap-detection results of Florentine and Buus (1984) are replotted in Figure 3 for NH listeners (solid curves, representing averages over six subjects), HI listeners (filled and unfilled circles), and for noise-masked simulations of those hearing losses averaged across two NH ears (X symbols).

For NH listeners, gap-detection thresholds decreased from 25 msec at 20 dB SPL (presumably just above detection threshold for the broadband noise) to an asymptotic value of roughly 3 msec for levels in the range of 50 to 90 dB SPL. For HI listeners, absolute thresholds for the noise signals were elevated by 25 to 45 dB relative to NH thresholds. The function relating gap-detection threshold to stimulus level demonstrates a pattern of gap-detection thresholds in the range of roughly 30-50 msec for stimulus levels near absolute threshold, accompanied by a rapid decrease in gap-detection threshold with increasing level of the broadband noise stimulus. Minimum gap-detection threshold values were typically achieved at 80-85 dB SPL (and ranged from roughly 4 to 8 msec across subjects). For the data shown in panels (a) and (b) of Figure 3 for steeply-sloping and bowl-shaped losses, respectively, the performance of the individual HI listeners was generally well reproduced in the listeners with simulated hearing loss both in the dependence of gap-detection thresholds on stimulus level and in the actual gap-detection threshold values. In panel (c) depicting mildly-sloping losses, the data of the HI listener depicted by unfilled symbols showed asymptotic values of gap-detection thresholds that were elevated compared to those of the simulated-loss listeners and NH listeners. The data of the other HI listener (filled symbols), however, were closely matched to those of the simulated-loss listeners. The results of the flat-loss subjects (panel (d) of Figure 3) showed an unusual pattern in which the gap detection thresholds of the simulated-loss subjects were larger than those of the HI listeners for stimulus levels below 80 dB SPL but were smaller than the HI values at higher stimulus levels.

Buss, Hall, Grose, and Hatch (1998) measured gap detection in narrow bands of noise (as well as gap-duration discrimination; see Section B-2 below) in seven HI listeners with steeply-sloping high-frequency losses (mean age of 47 years) and in three NH listeners with simulated high-frequency losses (mean age of 31 years). The audiograms of the HI listeners were examined to determine the “edge” frequency of the hearing loss, i.e., the frequency below which thresholds were relatively normal in dB HL and above which hearing loss increased with frequency to some maximum value of hearing loss. Two representative high-frequency losses were simulated in the NH listeners through the use of filtered background noise. Both losses were created with an “edge” frequency of roughly 500 Hz but differed in the upper frequency where a maximum loss of 60 dB HL was achieved (which was 1000 Hz in one simulated loss and 2000 Hz in the other). Gap-detection thresholds were measured using 100-Hz bands of noise centered at frequencies that included values just below the “edge” frequency and four additional values between the “edge” frequency and the frequency with maximum loss. Gaps were inserted 200 msec after the onset of a noise burst whose total duration was always 400 msec. Measurements were made at 30 dB SL for both groups as well as at 80 dB SPL for the NH listeners and at 85 or 90 dB SPL for the HI listeners. For the equal SL condition, the gap-detection thresholds of the HI listeners were significantly higher than those of the simulated-loss NH group. For measurements made at the higher presentation level (80 to 90 dB SPL), however, gap-detection thresholds ranged from 25 to 40 msec across all subjects and indicated no significant differences between groups of NH and HI listeners or as a function of the frequency of the narrowband noise stimuli.

The results of Florentine and Buus (1984) and the high-presentation level data of Buss et al. (1998) demonstrate that the effects of hearing loss on gap-detection threshold can be explained for the most part on the basis of audibility. In the Florentine and Buus data, the pattern of gap-detection thresholds in HI listeners as a function of stimulus level was generally reproduced by a hearing-loss simulation in NH listeners that equated audibility between the two groups. In the Buss et al. (1998) data, the gap-detection thresholds of the HI listeners were equivalent to those of the NH listeners with simulated loss at presentation levels greater than 80 dB SPL.

A-2. Other Studies Comparing Normal-Hearing and Hearing-Impaired Listeners—Other studies of gap-detection resolution, reviewed below, fall into two general categories: studies in which the performance of HI listeners is compared to that of NH listeners at equivalent values of sensation level or sound-pressure level (age-matched subjects were employed in some of these studies but not in others) and studies which attempt to separate the effects of aging and hearing impairment.

Fitzgibbons and Wightman (1982) examined gap detection in a group of five NH listeners (mean age of 27 years) and a group of five HI listeners (mean age of 28 years with bilaterally symmetric losses that increased gradually from 40 to 65 dB HL across the frequency range of 250 to 4000 Hz). Gap-detection thresholds were measured for three octave bands of noise in HI listeners at a level of roughly 85 dB SPL (corresponding to roughly 30 dB SL in these subjects) and in NH listeners at levels of 85 dB SPL (50 dB SL) and 65 dB SPL (30 dB SL, equivalent to the SL tested in the HI listeners). Gaps were inserted into 410-msec bursts of leading and trailing noise with a 20-msec rise/fall time. For both groups of subjects, gap-detection threshold decreased as the center frequency of the noise band increased. The gap-detection thresholds of the NH listeners were higher at 65 compared to 85 dB SPL and were more similar to those of the HI listeners when compared at equivalent SL. For the 800-1600 Hz band of noise, for example, the mean gap-detection threshold at 30 dB SL was 12.6 msec for the HI listeners compared to 9.5 msec for the NH listeners.

De Filippo and Snell (1986) compared the gap-detection ability of five NH and five age-matched HI listeners (all between the ages of 19 and 25 years) with relatively flat sensorineural loss using 50-Hz bands of noise centered at 250, 500, and 1000 Hz and presented at 5, 15, and 25 dB SL. Gaps were inserted into 400-msec bursts of leading and trailing noise markers. NH listeners were also tested at 78 dB SPL (corresponding to the signal level needed for 5-dB SL in the HI group). Gap-detection thresholds decreased with an increase in SL for both groups (consistent with the data of Florentine and Buus, 1984) and were similar for both groups at 5 dB SL (roughly 105-110 msec). At 25 dB SL, thresholds for the HI listeners averaged 42 msec compared to 25 msec for the NH group. A comparison at equal SPL of 78 dB indicated lower gap-detection thresholds for the NH compared to the HI listeners...Strong frequency-dependent effects were not observed in the data for either group of subjects, contrary to the results of other studies (e.g., Fitzgibbons and Wightman, 1982; Glasberg, Moore, and Bacon, 1987).

Glasberg et al. (1987) examined gap detection in bandpass noise centered at 500, 1000, and 2000 Hz with bandwidth equal to one-half of center frequency. Eight listeners with bilateral sensorineural hearing loss (age range of 18 to 69 years) and nine listeners with unilateral loss (a normal and impaired ear) (age range of 42 to 72 years) were tested. Stimuli were presented to the impaired ears at 84 dB SPL and to the normal ears of the subjects with unilateral loss at 84 dB SPL as well as at a lower level selected to equate sensation level with the impaired ear. Gap-detection thresholds (measured using 410-msec bursts of leading and trailing noise markers) in the impaired ears were similar for subjects with unilateral and bilateral loss. In the unilateral-loss subjects, gap-detection thresholds for the normal and impaired ear of a given subject were more similar for comparisons made at equal SL than at equal SPL. For equal SL comparisons at a center frequency of 1000 Hz, for example, the mean gap-detection thresholds for the impaired groups ranged from 10.7 to 12.4 msec compared to 11.5 msec for the normal ears. A trend for a decrease in threshold with an increase in the center frequency of the noise band was observed for both normal and impaired ears. A tendency was also observed for an increase in gap-detection threshold with absolute threshold. At any given level of absolute threshold, however, there was a substantial spread in gap-detection threshold (e.g., for absolute thresholds in the range of 65-70 dB SPL, gap-detection thresholds ranged from roughly 10 to 34 msec). Moore and Glasberg (1988) reported additional results on seven unilateral-loss subjects (ranging in age from 45 to 72 years) using pure-tone as well as narrow-band noise markers. For both types of stimuli, the gap-detection thresholds of the impaired ear were quite similar to those of the NH ear when compared at equal SL. Additional sinusoidal gap-detection results were reported by Moore, Glasberg, Donaldson, McPherson, and Plack (1989) for a 1000 Hz tone at a level of 80 dB SPL. Gap-detection thresholds for four HI listeners (audiometric thresholds of 45 to 65 dB HL at 1000 Hz) were roughly 1.0 to 2.0 times that of the two NH listeners (which averaged roughly 3 msec).

Grose, Eddins, and Hall (1989) examined gap detection in noise as a function of bandwidth in six subjects with normal hearing (age 22-30 years) and eight subjects with impaired hearing (age 21-49 years with a maximum loss of 55 dB HL for frequencies at and below 2000 Hz, 70 dB HL at 4000 Hz, and 100 dB HL at 8000 Hz). Filtered bands of noise of varying widths were created using two different high-frequency cut-off values: 600 Hz (with bandwidths in the range of 25 to 600 Hz) and 2200 Hz (with bandwidths in the range of 50 to 1600 Hz). Gaps were inserted 500 msec after the onset of a noise burst whose total duration was always 1 sec. Stimuli were presented at a spectrum level of 60 dB SPL/Hz for all conditions and subjects. For both groups of subjects, gap detection thresholds decreased as the bandwidth of the noise increased for both cutoff frequencies. Gap-detection thresholds for the HI listeners were typically elevated compared to those of the NH listeners, but were more similar to those of the NH subjects at wider than narrower bandwidths within each of the cutoff frequencies. This result was hypothesized to be due to larger differences in sensation level between the two listening groups for narrow-bandwidth signals, as can arise when the narrow-band signal is located within a region of greater loss in subjects with sloping audiograms. Specifically, a high correlation was observed between the HI listeners’ absolute thresholds at 2000 Hz and the magnitude of the gap-detection threshold for the 50-Hz-bandwidth condition with a high-pass cutoff of 2200 Hz.

Hall, Grose, Buss, and Hatch (1998) examined gap detection as a function of the bandwidth of bandpass noise in a group of 25 NH subjects (mean age of 30 years) and a group of 21 HI subjects (mean age of 49 years) with a wide variety of audiometric configurations and degrees of hearing loss. The center frequency of the bandpass noise (whose bandwidth was 50, 400, or 1000 Hz) took on values in the region of 1000 to 3000 Hz selected on an individual basis for the HI listeners depending on audiometric threshold. NH listeners were tested with bandwidths of 50, 400, and 1000 Hz at a center frequency of 1000 Hz. Stimuli were presented at 95 dB SPL (or at a lower level if in the region of discomfort) for NH and HI listeners and also within the region of loudness recruitment in the HI subjects. Gaps were inserted 500 msec after the onset of the noise burst, whose total duration was always 1 sec. On average, the mean gap-detection thresholds of the HI group (73.5, 27.2, and 14.5 msec for bandwidths of 50, 400, and 1000 Hz, respectively) were larger than those of the NH group (61.8, 16.8, and 11.6 msec, respectively). A wide range of performance was observed among the HI group. The gap-detection thresholds of more than half of the HI listeners fell within the range of normal values, while those of other listeners were 2 or 3 times larger than normal. No effects were found for stimulus levels in the region of loudness recruitment.

Grose and Hall (1996b) examined gap detection in 10 NH (age range of 20-39 years) and 12 HI (age range of 39-57 years) listeners with relatively flat mild-to-moderate hearing losses. Gap-detection ability was studied in sequences of 75-msec pure-tone bursts as a function of frequency (using sets of four tones from each of two spectral regions: a low-frequency region that encompassed the range of 472 to 561 Hz and a high-frequency region of 2699 to 3174 Hz) and number of tonebursts (2 to 16) in a given sequence. For the reference stimulus, the tones in a given sequence were abutted (that is the interval between any two consecutive tones in the sequence was 0 msec). In the test stimulus, a variable gap was introduced between the 1st and 2nd tones of a 2-tone stimulus or between the 8th and 9th tones of a 16-tone sequence. All tones were presented at a level of 80 dB SPL to both groups of listeners. A minimal gap-detection threshold of roughly 8 msec was observed in both groups of listeners for 2-tone sequences of similar-frequency tones. For both groups, thresholds increased for a wider frequency difference between leading and trailing markers in the 2-tone sequence: to 34 msec for NH and 68 msec for HI listeners. The highest thresholds were observed in a condition which alternated an 8-tone series of high-frequency tones with an 8-tone series of low-frequency tones (where thresholds averaged roughly 100 msec for NH and 110 msec for HI listeners for the detection of a gap inserted in the center of the sequence). Alternations of high and low frequency tones, which may have allowed the listeners to improve their performance through the perception of two separate auditory streams, yielded thresholds of roughly 20 msec for NH and 25 msec for HI listeners.

Moore, Peters, and Glasberg (1992) examined gap-detection thresholds for sinusoidal markers as a function of signal level in two groups of age-matched elderly listeners: 11 elderly subjects (mean age of 76.3 years) with normal hearing (defined as 25 dB HL or better below 2000 Hz with some subjects demonstrating substantial loss at higher frequencies) and 15 elderly subjects (mean age of 75.9 years) with moderate-to-severe high-frequency hearing loss. The stimuli were 450-msec tones at six frequencies in the range of 100 to 2000 Hz presented at levels in the range of 25 to 85 dB SPL. The HI listeners were tested only at frequency/level combinations that were audible to them. The performance of the two groups of elderly subjects was compared to that of a group of 11 young NH subjects (mean age of 27 years) tested in similar experimental conditions by Moore, Peters, and Glasberg (1993). A clear pattern was observed for all three groups of listeners indicating a decrease in gap-detection threshold with an increase in both stimulus frequency and level. Asymptotic values of gap-detection threshold were lower for the young NH group (achieved at roughly 55 dB SPL and consistent with the NH data of Florentine and Buus, 1984) than for either group of elderly subjects (who required higher signal levels to reach asymptote). Generally, the performance of both elderly groups was similar and inferior to that of the young group, suggesting that age rather than hearing status is the dominant factor in determining performance. For a given stimulus frequency, substantial overlap was observed for gap-detection thresholds from young and elderly subjects; however, the highest thresholds were obtained in elderly listeners.

The effects of age and hearing loss on gap-detection ability were examined by Roberts and Lister (2004) using groups of eight young NH listeners (age range of 20-32 years years), eight elderly listeners (53-74 years) with clinically normal hearing (i.e., individual HL less than 25 dB HL in the range of 250 to 6000 Hz and less than 35 dB HL at 8000 Hz), and eight elderly HI listeners (57-76 years) with high-frequency hearing loss (i.e., individual hearing loss in the range of 50 to 88 dB HL at 4000 Hz with similar or greater levels of loss at 6000 and 8000 Hz). Gap-detection thresholds were measured using leading and trailing markers that were 4-msec bursts of broadband noise at a level of 35 dB SL. Thresholds were similar for measurements made under monaural and diotic presentation conditions, but increased by a factor of 3 to 5 within each of the three listener groups for dichotic presentation (where the leading marker was presented to the right ear and the trailing marker to the left ear). For monaural and diotic conditions, there was no significant difference in thresholds among the three groups of listeners despite a pattern that showed lowest mean thresholds for the young NH listeners (mean of roughly 2.6 msec), intermediate values for the older NH listeners (4.7 msec), and highest values for the older HI listeners (5.8 msec). Lister and Roberts (2005) measured gap-detection thresholds for diotic and dichotic presentation using 400-msec bursts of one-quarter octave bands of noise centered at 1000, 2000, and 3000 Hz under conditions of spectrally symmetric and asymmetric leading and trailing markers. The performance of the two elderly groups was generally similar and inferior to that of the young NH subjects and was more strongly affected by frequency disparity and dichotic presentation.

In general, studies that have compared the performance of age-matched NH and HI listeners have found that gap-detection thresholds tend to be more similar for comparisons made at equal SL than at equal SPL. Because gap-detection thresholds are known to decrease with an increase in stimulus level until some asymptotic value is achieved, it is fair to make comparisons between subjects for stimulus levels within the asymptotic region. Comparisons made for equal SL stimuli may be more likely to meet this goal than those made for equal SPL stimuli (depending on the particular stimulus level selected in studies where performance is examined at one or two levels). Across studies and conditions, the ratio of the average HI to NH gap-detection thresholds at equivalent SL ranged from 1.0 to 1.7. The results of Roberts and Lister (2004) and Lister and Roberts (2005) emphasize the importance of matching the age of NH and HI listeners in gap-detection tasks in that the performance of NH and HI elderly listeners was similar and inferior to that of young NH listeners.

A number of recent studies have explored the effect of age on gap-detection ability by comparing the performance of groups of young and elderly subjects with clinically normal hearing in the audiometric range of 250 to 8000 Hz. Gap-detection thresholds appear not to be greatly affected by age when stimulus complexity is minimized through the use of long-duration tonal markers presented at comfortably loud listening levels (e.g., see Schneider and Hamstra, 1999). Under conditions of more complex stimulus markers, however, the thresholds of elderly listeners with clinically normal hearing may be greater by a factor of 2 to 4 compared with those of young NH listeners. For example, larger gap-detection thresholds in elderly compared to younger subjects have been observed in studies employing brief tone bursts (e.g., see Schneider, Pichora-Fuller, Kowalchuk, and Lamb, 1994; Schneider and Hamstra,1999; Snell and Frisina, 2000; Heinrich and Schneider, 2006), various types of noises (e.g., see Snell, 1997; Snell, Mapes, Hickman, and Frisina, 2002), non-central location of gap relative to leading and trailing stimulus markers (e.g., see He, Horwitz, Dubno, and Mills, 1999; Snell and Hu, 1999; Snell et al., 2002), spectral asymmetry of the leading and trailing markers (e.g., Pichora-Fuller, Schneider, Benson, Hamstra, and Storzer, 2006; Heinrich and Schneider, 2006), and low sensation-level signals (Strouse, Ashmead, Ohde, and Grantham, 1998). The differential performance in gap-detection thresholds between young and elderly listeners with similar hearing levels accentuates the need to control for age when examining the effects of hearing loss.

A-3. Summary—Gap-detection performance is highly dependent on signal level. Gap-detection thresholds decrease rapidly for the first 20 to 30 dB SL and reach an asymptotic value at levels greater than 30 dB SL. The results of Florentine and Buus (1984) indicate that the performance observed with HI listeners with several types of hearing loss was well-reproduced by noise-masked simulation of hearing loss both in level-dependent effects and in the magnitude of the gap-detection thresholds for long-duration bursts of broadband noise. Buss et al. (1989) also demonstrated similar gap-detection thresholds for HI listeners and simulated-loss listeners with steeply-sloping high-frequency loss. In other studies that have compared the performance of age-matched HI and NH listeners (Fitzgibbons and Wightman, 1982; De Filippo and Snell, 1986) or the normal and impaired ears of listeners with unilateral hearing loss (Glasberg et al., 1987; Moore and Glasberg, 1988), gap-detection thresholds are more similar for comparisons made at equal SL than at equal SPL. The ratio of average HI/NH gap-detection thresholds at equivalent SL falls into a range of roughly 1.0 to 1.7 across studies and conditions. Large individual differences have also been observed in the data of HI listeners, with many of their thresholds falling within the ranges observed for NH listeners (Glasberg et al., 1987; Hall et al., 1998).

The effects of age appear to be fairly small in most experiments that have employed longer-duration tonal markers. Poorer gap-detection performance with aging has been noted for more complex stimulus conditions that include the use of brief marker durations, the use of noise compared to tones, the placement of gaps near the ends rather than in the center of the leading or trailing markers, and the use of spectral asymmetries in leading and trailing markers. In discussing the effects of age independent of hearing loss on certain temporal gap-detection tasks, it should also be noted that a confound exists between age and high-frequency hearing thresholds. Even those elderly subjects who are described as having “clinically” normal hearing typically exhibit effects of presbycusis as evidenced by elevated hearing thresholds for frequencies above 2000 Hz. The use of noise-masking in young NH listeners to simulate the audibility of clinically normal elderly subjects would provide an additional check on the role of age apart from hearing status on temporal gap-detection ability.

B. Duration Discrimination

A duration-discrimination task employs a reference signal at some fixed duration which must be discriminated from a comparison signal whose duration is different from that of the reference signal. The reference signal may be a tonal or noise stimulus or may be a gap inserted into a tonal or noise stimulus. Experiments are typically conducted using a 2-, 3, or 4-alternative forced-choice procedure in which the duration of the comparison signal (or gap within the comparison signal) is varied adaptively to estimate the size of the duration difference required to achieve a given level of performance.

The studies reviewed in Sections B-1 and B-2 below are summarized in Table 2.

B-1. Studies Examining Effects of Hearing Loss and Age—Fitzgibbons and Gordon-Salant (1994; 1995; 2001; 2004) have conducted a series of studies examining the effects of age and hearing loss on the ability to discriminate the duration of pure tones and silent intervals. These experiments employed groups of subjects matched both for hearing loss (young versus elderly) and for age (NH versus HI). Fitzgibbons and Gordon-Salant (1994) measured the difference limen (DL) for tonal duration and gap duration in four groups of subjects controlled for age and hearing loss: 10 young NH (age 20-40 years), 10 elderly NH (age 65-76 years), 10 elderly HI with mild-to-moderate sloping loss (age 65-76 years), and 10 young HI (age 20-40 years) listeners with losses similar to those of the elderly group. Duration DLs were measured for 250-msec reference tones at 500 Hz and 4000 Hz and for reference gaps of 250 msec and 6.4 msec inserted between 250-msec leading and trailing markers of 500-Hz and 4000-Hz tones (including conditions with same-frequency and different-frequency markers). All signals were presented at a level of 85 dB SPL which resulted in a minimum SL of 25-30 dB at 4000 Hz for the HI subjects. Mean thresholds for each of the four groups of subjects for 250-msec reference tonal and gap signals indicate a trend for similar performance as a function of age regardless of hearing status. An exception to this trend occurred for the condition of duration discrimination of the 500-Hz tone where the performance of the two elderly groups and the young HI group was similar and inferior to that of the young NH group. Averaged across conditions employing tonal and gap signals with 500 Hz and 4000 Hz markers, the difference limens (DLs) for the two groups of young subjects were similar (averaging 48 msec) and superior to those of the two elderly groups (whose DLs averaged roughly 70 msec for corresponding conditions). For the 6.4-msec reference gaps, an age effect was observed in the data of the NH subjects (where the mean DL of the young group averaged roughly 12 msec across conditions compared to roughly 25 msec for the elderly group) but not in the data of the HI subjects (where DLs of the young and elderly groups were similar and averaged roughly 20 msec).

Fitzgibbons and Gordon-Salant (1995) examined tonal duration discrimination and gap-duration discrimination in four groups of subjects controlled for age and hearing loss (consisting of 10 subjects within each group, demonstrating the same characteristics as the subject groups described above for Fitzgibbons and Gordon-Salant, 1994). DLs for tonal duration discrimination were measured using a 250-msec 4000-Hz pure tone presented in isolation or embedded in a sequence of five 250-msec tone bursts whose frequencies were selected from a third-octave region around 4000 Hz. DLs for gap-duration discrimination were measured using a 250-msec reference gap that was inserted either into a 4000-Hz tone with 250-msec leading and trailing markers, or into a sequence of four 250-msec tones selected from a third-octave region around 4000 Hz The sequential tone complexes were constructed with different levels of complexity based on the use of fixed versus randomly selected frequencies of the non-target (or “masking”) tones within a sequence. Stimuli were presented at 85 dB SPL, providing SL of 25-30 dB at 4000 Hz for the HI listeners. In nearly all the conditions studied, the performance of the NH and HI elderly subjects was similar and inferior to that of the two younger groups (with the exception of tonal duration discrimination in isolation, where all four groups had similar DLs). For tonal duration discrimination, the DLs of the elderly subjects were nearly twice as large in the sequences compared to isolated tones (roughly 100 msec versus 50 msec, respectively), whereas the DLs of the younger subject groups were the same for both types of stimuli. For gap-duration discrimination, the DLs of the elderly NH and HI listeners were larger than those of the young NH and HI listeners on all conditions and each of the four subject groups performed significantly worse in the tonal sequences than in isolation.

Fitzgibbons and Gordon-Salant (2001) examined the ability to discriminate the inter-onset interval (IOI; that is, the sum of the burst duration and the inter-stimulus interval) of five 50-msec bursts of 4000-Hz tones. Reference IOIs were studied in the range of 100 to 600 msec. Experimental conditions were created where all four IOIs in the sequence were adjusted equally or where the duration of only one IOI was adjusted (with varying degrees of uncertainty regarding the target interval). The four groups of subjects consisted of 15 younger NH listeners (age 18-40 years), 13 older NH listeners (age 65-76 years), 10 younger HI listeners (with mild-to-moderate high-frequency loss), and 14 older HI listeners (with mild-to-moderate high-frequency loss). Stimuli were presented at levels of 85 to 90 dB SPL for all listeners (providing SL of at least 25 to 30 dB in HI listeners). The relative DL (where the DL is expressed as a percentage of the reference IOI) decreased with IOI and leveled off for IOIs above 200 msec. Relative DL was roughly 4% for both groups of young subjects and 6% for both groups of elderly subjects (demonstrating a significant effect of age but not hearing loss). The elderly subjects were more adversely affected by the task where only one IOI was adjusted. Fitzgibbons and Gordon-Salant (2004) also examined IOI discrimination for conditions similar to Fitzgibbons and Gordon-Salant (2001), but with increased complexity in terms of uncertainty in frequency of the tones in the sequence and in terms of the value of IOI to be discriminated in the single-interval task. Again, performance was similar for the two groups of young subjects (regardless of hearing status) and superior to that of the two groups of elderly subjects (who had similar performance). Both age groups were more adversely affected by temporal compared to spectral complexity in the stimuli; however, the elderly groups showed a greater percentage increase in DL as a function of temporal complexity than did the younger subjects.

On average, these studies indicate that duration and gap-duration discrimination thresholds are determined primarily on the basis of subject age rather than hearing loss. That is, the performance of NH and HI elderly subjects tended to be similar and inferior to that of the NH and HI younger subjects who performed similarly to each other. Specific conditions were observed, however, where this general pattern of results did not hold. Instead, the performance of the young NH listeners was superior to that of the other three groups of subjects (young HI and elderly NH and HI) for conditions of duration discrimination with a 500-Hz tone and gap-duration discrimination with a reference gap of 6.4 msec (Fitzgibbons and Gordon-Salant, 2004).

B-2. Other Studies Conducted with Hearing-Impaired Listeners—Buss et al. (1998), whose results for gap detection were described in Sec. A-1, also reported data on a gap-duration discrimination task conducted with three of their HI listeners and three noise-masked NH listeners with simulated high-frequency loss. (Details concerning the test frequencies, stimulus levels, and subjects are described previously in Sec. A-1.) For the gap-duration discrimination test, the standard stimulus consisted of an 80-msec gap inserted into a 400-msec leading marker and a 400-msec trailing marker of 100-Hz narrowband noise. Gap-duration discrimination thresholds averaged roughly 50 msec across conditions and subjects. No significant effects were observed for subject group, presentation level, or center frequency of the narrow-band noise.

Bochner, Snell, and MacKenzie (1988) examined duration discrimination and gap discrimination using tonal complexes and speech stimuli in three NH listeners (age range of 27-36 years) and seven HI listeners (age range of 19-24 years) with a flat audiometric configuration (hearing loss of 75 to 85 dB HL at 500, 1000, and 2000 Hz and unspecified for frequencies outside this range). The tonal stimuli were 3-component harmonic complexes of 500, 1000, and 2000 Hz tones which were used for measuring (1) duration discrimination at nine reference values of tonal duration between 25 and 500 msec and (2) gap discrimination for six reference gaps in the range of 25 to 150 msec bounded by a 150-msec leading marker and a 50-msec trailing marker. The speech stimuli were CVC syllables with six different vowels and with a final voiceless stop. For the duration-discrimination task, glottal cycles were repeated to increase the duration of the comparison stimulus. For gap discrimination, segments of silence were inserted into the closure portion of the final stop consonant. All stimuli were presented at levels of 60 dB SPL for the NH listeners (i.e, 40-50 dB SL) and at 100 or 110 dB SPL for the HI listeners (resulting in SL in the range of 15-35 dB SL). Results for duration discrimination with the tonal complexes indicated that the relative DL decreased with an increase in the duration of the standard, and improved from 20% to 10% in NH listeners and from 60% to 15% in the HI listeners as the tonal duration increased from 25 to 500 msec. For speech stimuli, relative DLs for the duration-discrimination task were roughly 15% for NH listeners and 20-30% for HI listeners. Gap-duration discrimination results were similar for speech and tonal complexes and for both groups of listeners, indicating a decrease in relative DL as reference gap size increased (DL decreased from roughly 100-120% to 20-30% as gap size increased from 25 to 175 msec).

Abel, Krever, and Alberti (1990) measured the ability to discriminate the duration of one-third octave bands of noise centered at 500 Hz or 4000 Hz in two 15-subject groups of HI listeners (a mild-to-moderate-loss group with mean age of 55 years and a severe-loss group with mean age of 61 years) and in two 15-subject groups of NH listeners (a young group with mean age of 24 years and an older group with mean age of 48 years). Performance was measured for two base durations of 20 and 200 msec at a presentation level of 70 dB SPL or 40 dB SL, whichever was greater. Results for the two HI groups and the group of older NH listeners were similar and indicated significantly larger DLs than those obtained in the younger NH listeners for both signal durations and center frequencies. For the noise band centered at 500 Hz, the DLs of the young NH group averaged roughly 15 and 55 msec at durations of 20 and 200 msec, respectively, compared to DLs averaging roughly 30 and 80 msec, respectively, across the three groups of older NH and HI listeners. For the 1000-Hz center frequency, the DLs of the young NH group averaged roughly 12 and 25 msec for base durations of 20 and 200 msec, respectively, compared to average DLs across the three older groups of 25 and 75 msec, respectively. This pattern of results is similar to that obtained by Fitzgibbons and Gordon-Salant (1994) for tone-duration discrimination employing a 250-msec reference duration at 500 Hz and for tone- and gap-duration discrimination with 6.4-msec reference signals.

Lister, Koehnke, and Besing (2000) examined the effect of spectral disparity between the leading and trailing markers in a gap-duration discrimination task for a group of six NH listeners (age range of 22-51; mean age of 36 years) and a group of six listeners with bilateral symmetric hearing loss (age range of 21-71; mean of 53 years). Stimuli were eight quarter-octave bands of noise with center frequencies in the range of 500 to 7000 Hz. The leading marker was always the band with center frequency of 2000 Hz and the trailing marker was selected from the eight possible values of center frequency. Signals were presented binaurally at a level of 70 dB SPL for NH listeners and at 70 dB SPL or 30 dB SL (whichever was greater) for HI listeners. Gap-duration discrimination thresholds (which were not significantly different for HI and NH subjects) increased as the frequency difference between the leading and trailer markers increased, were more affected by low-frequency compared to high-frequency trailers, and increased from 10 msec for same-frequency markers to 40 msec for the 500-Hz trailer. Effects of age, however, were present in the data regardless of hearing status. Older subjects (i.e., 40 years of age and older) were more affected by spectral disparity than were younger subjects (i.e., below the age of 40). Lister, Besing, and Koehnke (2002) examined performance on a similar set of experimental conditions as a function of age in three groups of subjects [screened for 25 dB HL or better in the frequency range 250 to 6000 Hz and 30 dB HL or better at 8000 Hz]: six young (18-30 years), six middle-aged (40-52), and six older (62-74) listeners. Signals were presented at 35 dB SL re threshold at 2000 Hz. Performance of subjects in the older group was significantly worse than that of the younger group, showing a greater deterioration in performance with spectral disparity.

Grose, Hall, and Buss (2001) examined the effects of spectral disparity between leading and trailing tonal markers and the introduction of random variation in the duration of the markers on gap-duration discrimination. Standard gaps of 35 msec or 250 msec were inserted into a leading marker with mean duration of 50 msec or 300 msec and trailing marker with mean duration of 300 msec. Subjects included a group of seven NH listeners (mean age of 50 years) and a group of nine listeners with bilaterally symmetric mild-to-moderate hearing loss (mean age of 49 years; PTA in the range of 30 to 63 dB HL). Stimuli were presented at 85 dB SPL to all listeners under both monaural and dichotic listening conditions. No effect of hearing loss was present in the data. For both groups of subjects, thresholds were higher for the longer leading-marker duration, increased with frequency difference between markers, and were worse under dichotic compared to monaural presentation.

Grose, Hall, and Buss (2004) examined the ability to discriminate the duration of pure tones, frequency-modulated (FM) tones, and narrow-band noises in seven NH listeners (mean age of 50 years) and nine HI listeners (mean age of 49 years; PTA in the range of 30 to 63 dB HL). In measurements obtained with a fixed-frequency paradigm, a frequency of 1035 Hz was used for the pure tone, the carrier frequency of the FM tone, and the center frequency of a 40-Hz band of noise. In measurements with a roving-frequency paradigm, the frequency of the stimuli was randomly selected from interval-to-interval from a set of 13 frequencies in the range of 432 to 2180 Hz. The duration of the reference stimuli was 250 msec and signals were presented at a level of 80 dB SPL. Duration-discrimination thresholds were larger for roving-frequency versus fixed-frequency conditions and were higher for narrowband noise signals than for pure tones and FM tones. There was no significant difference, however, between results for NH (mean DL across conditions of 76 msec) and HI (mean DL across conditions of 91 msec) listeners. The relative DLs were in the range of 0.24 to 0.35 across listeners and conditions, consistent with results obtained by Abel et al. (1990) and Fitzgibbons and Gordon-Salant (1994).

In the area of gap-duration discrimination, the thresholds of HI listeners were not significantly different from those of NH listeners with a noise-masked simulation of hearing loss (Buss et al., 1998). Other studies (using various types of stimulus level comparisons across groups) have also reported similar gap-duration discrimination thresholds for HI and NH listeners (Lister et al., 2001; Grose et al., 2001, 2004). In the area of duration discrimination, thresholds reported for HI listeners were similar to those of age-matched NH listeners listening at equivalent SPL or SL levels (Abel et al., 1990) but were higher by a factor of roughly 1.5 to 2.0 in one study where age was not controlled across groups (Bochner et al., 1988).

B-3. Summary—Comparisons across groups of NH and HI listeners matched for age (including both young and elderly groupings) indicate mixed results regarding the effects of either hearing impairment or age on duration and gap-duration discrimination. Concerning the effects of hearing loss, the results of several studies indicate that the performance of NH and HI listeners is similar when subjects are matched roughly for age (e.g., the 250-msec gap duration discrimination task of Fitzgibbons and Gordon-Salant, 1994; Fitzgibbons and Gordon-Salant, 1995; Bochner et al., 1988; Grose et al., 2001). In other conditions, however, the results indicate poorer performance in HI listeners relative to that of age-matched NH listeners (e.g., the 6.4-msec gap duration discrimination data from the young listeners of Fitzgibbons and Gordon-Salant, 1994). Likewise, various patterns of results have been observed as a function of age. Whereas some studies have shown decreased performance with age in subjects with both clinically normal and impaired hearing (e.g., Lister et al., 2000, 2002), other studies have observed decreased performance as a function of both age and hearing loss compared to the performance of young NH listeners (e.g., Abel et al., 1990). Results using hearing-loss simulation in this area, limited to those reported by Buss et al. (1998) for gap-duration discrimination, indicate similar performance for HI and noise-masked NH listeners. Further studies are necessary to control for the effects of audibility and level, in addition to age, in comparing the performance of NH and HI listeners on duration and gap-duration discrimination tasks.

C. Temporal Integration

Studies of temporal integration involve threshold measurement of tones (in quiet or in a background noise) as a function of signal duration. For NH listeners, thresholds decrease by roughly 3 dB/doubling of duration in the range from about 10 to 200 msec and remain constant above 200 msec (e.g., Plomp and Bouman, 1959; Watson and Gengel, 1969). The difference in dB between the threshold of a short-duration signal (e.g., on the order of 3 to 30 msec) and that of a long-duration signal (e.g., on the order of 200 to 500 msec) is often used as a measure of temporal integration.

A summary of the studies reviewed in Section C-1 below is provided in Table 3.

C-1. Studies with Controls of Audibility and Level—Several studies have found that listeners with sensorineural hearing loss exhibit less temporal integration than listeners with normal hearing.(e.g., see Gengel and Watson, 1971; Gengel, 1972; Chung, 1981; Tyler, Fernandes, and Wood, 1980). To determine if the higher signal levels at threshold for HI compared to NH listeners may be responsible for reduced amounts of temporal integration, Gengel (1972) measured thresholds as a function of duration in four NH listeners (ages unspecified) in the presence of a background noise of 87 dB SPL. Average masked thresholds for 500-msec tones were 64 dB SPL at 500 Hz, 66 dB SPL at 2000 Hz, and 73 dB SPL at 4000 Hz, comparable to the long-duration quiet thresholds of the HI listeners tested by Gengel and Watson (1971). The amount of temporal integration (defined as the difference in dB between thresholds for 10-msec and 500-msec signals) averaged roughly 15 dB at 500 Hz, 10 dB at 2000 Hz, and 8.5 dB at 4000 Hz and was very similar to that observed for NH listeners in quiet. These values of temporal integration were substantially larger than those observed in the HI listeners tested by Gengel and Watson (1971). Thus, it appears that elevated threshold levels *per se* are not responsible for the reduced amounts of temporal integration observed in sensorineural hearing loss.

Fastl (1977) used masking noise to simulate the threshold elevation observed in one HI listener whose loss was limited to a narrow region around 3000 Hz. The simulation, conducted on one NH listener, was well-matched to the thresholds of the HI listener at frequencies of 3000 Hz and above; below 3000 Hz, the simulated loss produced thresholds that were roughly 10 dB higher than those of the actual HI listener. Tone detection was measured as a function of duration in the range of 3 to 300 msec for pure-tone signals of 1000, 2500, 3000, 3500, and 7000 Hz. At 3000 Hz, the HI listener had roughly the same threshold of 45 dB SPL at each duration tested (indicating 0-dB temporal integration), whereas the noise-masked NH subject had a threshold difference of 25 dB between the 3 msec and 300 msec tones. At frequencies where less hearing loss was present, the amount of temporal integration was roughly similar for the HI listener and the noise-masked NH listeners.

Further study of noise-masked simulations of hearing loss in temporal integration was carried out by Florentine, Fastl, and Buus (1988). Absolute thresholds were measured at 250, 1000, and 4000 Hz for durations in the range of 2 to 500 msec in three groups of subjects: five NH listeners (age 20-42 years), six HI listeners (20-62 years), and two NH listeners with noise-masked simulations of hearing loss (selected from the original NH group). The hearing losses included flat losses (three subjects) and both mildly (two subjects) and steeply (one subject) sloping high-frequency losses. Spectrally-shaped masking noise was employed to match the thresholds of two NH listeners to each of the three types of hearing loss for 500-msec tones. The results of the study are summarized in Figure 4, re-plotted from Florentine et al. (1988), showing data for subjects with flat (top row), mildly sloping (middle row), and steeply sloping losses (bottom row). Results for NH listeners in quiet (shown by the solid black lines in the plots) indicate that the amount of temporal integration between 2 msec and 500 msec was roughly 12 dB at 250 Hz (column one), 15 dB at 1000 Hz (column two), and 18 dB at 4000 Hz (column three). In frequency regions where hearing loss is present, the HI listeners (denoted by filled and unfilled circles) demonstrated less temporal integration (i.e., a maximum of roughly 10-dB of integration) than NH listeners. Reduced temporal integration is observed in the listeners with flat losses of roughly 40-60 dB HL at all frequencies tested (see top row of Figure 4) and at frequencies above 250 or 1000 Hz in the listeners with sloping losses (middle and bottom rows). Temporal-integration functions for NH listeners with noise-simulated hearing loss (X symbols connected by dashed lines) were similar to those obtained in quiet. Thus, for simulated thresholds matched to the actual impairments for 500-msec tones, the listeners with hearing impairment do not show as much of an increase in threshold as duration is decreased as do NH listeners either in quiet or in the presence of spectrally-shaped noise.

Oxenham, Moore, and Vickers (1997) studied the detection of a 6500-Hz tone as a function of duration in the presence of a 400-msec bandpass-filtered noise in four NH (age 25-34 years) and four HI listeners (age 61-81 years with hearing loss between 40-60 dB at the test frequency). The 2000-12000 Hz masker was presented at spectrum levels of −10, 20, and 50 dB SPL/Hz for NH subjects and 30, 40, and 50 dB SPL/Hz for HI subjects. For all listeners, the slope of the temporal-integration function was steeper from 2 to 10 msec than from 20-200 msec. The slopes of the HI subjects were generally more similar to those of the NH subjects in the short-duration region of the function than in the long-duration region (where less integration was observed in the HI listeners). An effect of noise level was observed for NH listeners (where steeper integration functions primarily in the short-duration region were obtained in the mid-level noise compared to the lower and higher levels) but not for HI listeners.

The results of the papers discussed above are in good agreement regarding the temporal-integration functions of HI listeners compared to NH listeners both in quiet and in masking noise. The amount of temporal integration observed in NH listeners is the same for tones in quiet and in background noise and is greater than that observed in HI listeners. Thus, noise-masked simulations of hearing impairment are incapable of modeling the temporal-integration results observed in HI listeners. It should be noted, however, that possible confounding effects of age may be present in the results of the studies reported here (see Table 3).

C-2. Summary—Noise-masked simulations of hearing loss with NH listeners have not reproduced the decreased amounts of temporal integration observed in HI listeners. If noise-masked thresholds are equated to those of HI listeners for long-duration tones, then the absolute thresholds of the impaired listeners are lower at short durations than those of the noise-masked NH listeners. On the other hand, if noise-masked thresholds are equated to those of HI listeners at short durations, then the long-duration thresholds of the impaired listeners are higher than those of noise-masked NH listeners. Possible confounding effects of age, however, may be present in these data. These differences in temporal integration between listeners with real versus noise-masked simulations of hearing loss have important implications for auditory tasks involving the detection or discrimination of brief tonal signals (e.g., as in a forward-masking paradigm). The presentation level in dB SPL will necessarily differ between the HI listeners and their noise-masked counterparts due to differences in temporal integration, with the simulated-loss listeners requiring greater signal intensity to achieve a given SL for a short-duration tonal pulse.

D. Masked Thresholds in Temporally Modulated Noise

The three studies reviewed in this section are summarized in Table 4.

As a measure of temporal-resolution ability, Zwicker and Schorn (1982) examined the difference in thresholds for long-duration tones presented in a background of continuous versus interrupted noise. The assumption behind this technique is that the amount of release from masking observed in interrupted noise is related to the temporal-resolving power of the auditory system. Zwicker and Schorn (1982) measured thresholds of 600-msec pure tones (500, 1500, and 4000 Hz) in quiet and for two types of filtered background noise: continuous and square-wave-modulated at 14 Hz. For testing at 500 Hz, the masker consisted of a 500-Hz lowpass band of noise; at 1500 and 4000 Hz, the maskers were octave bands of noise centered at the test frequencies. The noise was set to an overall level in dB SPL that was 40 dB above the pure-tone threshold in quiet for a given frequency. Subject groups included 40 NH listeners (age range of 17 to 57 years) and listeners with various types of cochlear hearing loss (whose ages were not reported), including 20 listeners with noise-induced loss, 15 listeners with Meniere's Disease, 9 listeners with ototoxic losses, and 11 listeners with sudden hearing loss. In addition, four NH listeners (ages unspecified) were also tested with a simulated hearing loss created by the addition of continuous masking noise to elevate thresholds at the test frequency to 35 or 55 dB SPL (degrees of hearing loss that were included in the range of losses exhibited by the HI listeners). For NH listeners, the threshold difference between steady-state and modulated noise was roughly 15 to 20 dB at each of the three test frequencies. In HI listeners, the magnitude of this threshold difference, which decreased with an increase in hearing loss, was typically in the range of 5 to 10 dB when threshold in quiet exceeded 50 dB SPL. In listeners with simulated hearing loss, however, the release of masking was not reduced and was observed to be roughly 15 to 25 dB across test frequencies.

Humes (1990) measured thresholds for short-duration tones in the presence of modulated background noise in three groups of subjects: ten listeners with NH (ages 17-32 years), five listeners with bilaterally symmetric high-frequency hearing loss (ages 22-67 years), and ten listeners with noise-masked simulation of hearing loss (ages 17-32 years). Thresholds of 4.6-msec tone bursts at 500, 1400, and 4000 Hz were measured in the envelope maximum (peak) and minimum (trough) of a 100% sinusoidally amplitude-modulated (SAM) speech-shaped noise as a function of frequency of modulation in the range of 2.5 to 20 Hz. The noise was presented at a level of 70 dB SPL for all conditions and subjects. Data from Humes (1990) are replotted in Figure 5, where results for the three listener groups are shown at 500 Hz (top panel), 1400 Hz (middle panel), and 4000 Hz (bottom panel). Data points for thresholds in the acoustic peaks are represented by filled symbols and acoustic troughs by unfilled symbols. At each of the three test frequencies, the results for NH listeners (circles) indicate that thresholds in the peaks were independent of modulation rate while those in the troughs increased with modulation rate. Thus, the difference between peak and trough thresholds was greatest at the lowest modulation rate (roughly 30-40 dB difference across test frequencies) and least at the highest modulation rate (roughly 15-dB difference). For HI listeners (diamonds), a trend similar to that of the NH listeners was observed at 500 and 1400 Hz although the magnitude of the difference between peak and trough thresholds (25 dB at low modulation rates and 10 dB at high modulation rates) was less than that observed for NH listeners. At 4000 Hz, the HI thresholds were the same for peak and trough conditions and for all modulation rates and appear to be governed by absolute threshold. That is, the thresholds in noise were roughly equivalent to thresholds in quiet suggesting that the components of the noise in the region of 4000 Hz were inaudible to the HI listeners. The data of the noise-masked NH listeners (squares) were quite similar to those of the HI listeners at each of the three test frequencies. The largest discrepancy between the noise-masked simulations and the HI listeners was for the 500-Hz signal at the two lowest modulation rates, where the trough thresholds were roughly 9-dB lower for the noise-masked subjects.

Halling and Humes (2000) measured pure-tone thresholds at 500, 1000, and 2000 Hz in the presence of a steady-state or modulated broadband noise at 75 dBC. Modulation was introduced using 100% SAM at 7 modulation frequencies in the range of 0.5 to 32 Hz. The subjects included 8 young NH listeners (mean age of 23 years), 8 elderly NH listeners (mean age of 72 years, with 20 dB HL or better in the range of 250 to 4000 Hz and 8000-Hz thresholds in the range of 15 to 75 dB HL), and 8 elderly HI listeners (mean age of 73 years, whose hearing losses were primarily various configurations of high-frequency loss). The results were summarized by averaging across the masked thresholds obtained in the various modulated noises and subtracting this average threshold from that obtained in the steady-state noise. The resulting “release of masking” was slightly greater for the young NH compared to the elderly NH listeners and substantially larger for the elderly NH compared to the elderly HI listeners.

Using a model based on additivity of masking to predict masked thresholds of HI and noise-masked NH listeners, Humes, Espinoza-Varas, and Watson (1988) compared their predictions to the data reported by Zwicker and Schorn (1982). The predictions provided a close match to the masked thresholds of the noise-masked NH listeners obtained in both continuous and modulated noise but not to those of the HI listeners, particularly in the modulated-noise background. When the model of Humes et al. (1988) was subsequently employed to predict the results of Humes (1990) and Halling and Humes (1998), however, the data for noise-masked NH listeners and HI listeners were reasonably well fit by the model. Unlike the data reported by Zwicker and Schorn (1982), the results of the two later studies suggest that audibility effects are capable of explaining the differences between NH and HI listeners in detection of tones in amplitude-modulated noise. These contradictory results may be due in part to methodological differences. Zwicker and Schorn (1982), for example, measured thresholds of long-duration tones in a background of modulated noise using a Bekesy tracking procedure. Humes (1990), on the other hand, used an adaptive forced-choice procedure to measure thresholds of short-duration signals that were positioned either in the peaks or in the valleys of a SAM modulated noise.

E. Temporal Modulation Detection

The ability to detect temporal modulation has been studied in HI listeners through measurements of temporal-modulation transfer functions (TMTFs) and modulation-detection interference (MDI). The studies reviewed in this area are summarized in Table 5 in the order in which they are discussed in Sections II-E-1 (TMTF) and II-E-2 (MDI).

E-1. TMTFs in Listeners with Hearing Impairment—In these studies, temporal resolution is examined through measurements of the minimal amount of SAM necessary for a listener to discriminate between a modulated and an unmodulated noise. The temporal modulation transfer function (TMTF) is derived from a plot of modulation threshold as a function of the frequency of modulation. Modulation thresholds are expressed in dB and are calculated as 20 log m, where m is the index of modulation.

Bacon and colleagues (Bacon and Viemeister, 1985; Bacon and Gleitman, 1992) have compared results obtained on NH and HI listeners for equal sound-pressure and sensation levels and have examined the effect of reduced bandwidth in NH listeners. Bacon and Viemeister (1985) measured temporal modulation transfer functions in four listeners with normal hearing (mean age of 24 years) and six listeners with high-frequency, flat, and bowl-shaped hearing loss (ranging in age from 19 to 68 years). Threshold of modulation was measured for a continuous broadband noise carrier as a function of modulation rate in the range of 2 to 1024 Hz. Signals were presented at a spectrum level of 30 dB SPL/Hz for NH listeners and at 5, 15, 30, and 40 dB SPL/Hz for HI listeners. For NH subjects, sensitivity to amplitude modulation was constant (with modulation thresholds of roughly -25 dB) for modulation rates in the range of 2 to 10 Hz, decreased by 3 dB at 50 Hz, and decreased at a rate of 4-5 dB/octave in the range of 50-1024 Hz. For the HI listeners, sensitivity improved with signal level; however, the general shape of the TMTF was similar across levels and similar to that of the NH listeners. For one of the HI listeners, modulation thresholds obtained at a spectrum level of 30 dB SPL/Hz were nearly identical to those of the NH listeners. For the remaining HI subjects, modulation-threshold sensitivity at the noise level of 30 or 40 dB SPL/Hz was 2.5 to 7 dB worse than that of the NH listeners. Modulation thresholds of the NH listeners were also tested for a modulated lowpass filtered noise at 1600 Hz (in combination with a high-pass filtered masker at 1600 Hz) as a function of modulation rate and spectrum level. Results obtained in this reduced-bandwidth condition indicated reduced overall sensitivity similar to that observed in the HI listeners. Moore, Shailer, and Schooneveldt (1992) also measured TMTFs in a narrow-bandwidth signal (a one-octave band of noise centered at 2000 Hz) and observed similar performance between the normal and impaired ears of three subjects with unilateral hearing loss at equal SPL and at equal SL. The performance of three subjects with bilateral hearing loss (tested in the ear with better audiometric thresholds) was also similar to that obtained in the normal ears of the unilateral-loss subjects.

Bacon and Gleitman (1992) measured modulation detection of a SAM broadband noise carrier as a function of spectrum level in five listeners with normal hearing (age range of 22-29 years) and eight listeners with relatively flat hearing loss in the region of 500 to 2000 Hz (age range of 11 to 63 years and PTA range of 18 to 45 dB HL). For NH listeners, the shape of the TMTF was insensitive to level and the functions generally overlapped except for reduced thresholds at the lowest level tested (-10 dB SPL/Hz spectrum level). Effects of level were also generally small within any given HI listener, where at most a 4-dB reduction in threshold was observed at the lowest level tested. The performance of the HI and NH listeners was compared at equal overall levels (where 7 of 8 HI listeners fell within the normal range) and at equal sensation level (which indicated overlapping performance at 30 dB SL and more sensitive thresholds for HI listeners at 20 dB SL).

Several other studies have reported a decline in modulation-detection thresholds for HI listeners with an increase in modulation rate. Formby (1987) measured TMTF in the normal and impaired ears of six subjects (ranging in age from 27-56 years) with unilateral hearing loss resulting from Meniere's Disease, exhibiting generally flat losses of 40-60 dB in the region from 250 to 4000 Hz in the impaired ear. A broadband noise carrier with SAM at frequencies in the range of 10 to 1000 Hz was presented at 30 dB SPL in the good ear and at a level in the poor ear that was matched in loudness to that of the good ear. In general, the impaired-ear results were similar to normal data at rates below 200 Hz. For modulation frequencies above 200 Hz, the thresholds for the impaired ears grew worse more rapidly than was observed in normal ears. Lamore, Verweij, and Brocaar (1984) measured TMTFs in 32 severely-hearing impaired subjects (ages 12-20 years) and 10 NH subjects (both students and adults) using a broadband noise carrier at 10 dB SL as a function of modulation rate in the range of 2 to 500 Hz. The results indicated substantial overlap between the thresholds of the HI and NH subjects accompanied by greater variability in the HI data. Mean results of the HI subjects were most similar to the NH data at a modulation rate of 10 Hz and were less sensitive at rates above and below 10 Hz.

Moore and Glasberg (2001) measured TMTFs using sinusoidal (rather than noise) carriers in four listeners with normal hearing (age 23-54 years) and three listeners with mild-to-moderate cochlear loss (age 70-84 years). Modulation-detection thresholds were measured for three carrier frequencies (1000, 2000, and 5000 Hz) at each of seven modulation frequencies (ranging from 10 to 640 Hz) at a level of 80 dB SPL and 30 dB SPL for NH subjects and at a level of either 80 or 90 dB SPL for HI subjects. Performance of the HI subjects was similar to that obtained for the NH subjects at 30 dB SPL, indicating relatively flat thresholds as a function of modulation frequency. The TMTFs of the NH subjects at 80 dB SPL, however, showed a rapid improvement at modulation rates above 80 Hz. This pattern of results was attributed to the availability of spectral cues in the sidebands at high presentation levels for NH listeners.

Grant, Summers, and Leek (1998) examined modulation-rate detection and discrimination in four NH listeners (age 38-52 years) and eight HI listeners with moderately sloping high-frequency hearing loss (age 58-76 years) with PTA of 30-60 dB HL. The stimuli consisted of broadband noise that was modulated by a square wave with a frequency of 80, 160, or 320 Hz presented at a spectrum level of 40 dB SPL/Hz. Experiments included both modulation detection (where the standard stimulus was unmodulated noise) and modulation discrimination (where the standard stimulus was modulated noise at one of three different rates and three different depths of modulation). For modulation detection, the thresholds of the HI subjects at the higher rates of modulation were worse than those of the NH subjects at these same rates. This poorer performance was related in part to low audibility of spectral components in the noise at frequencies above 3000 Hz based on a comparison of the HI tone-detection thresholds with the peak spectrum level of the modulated noise signals. For modulation discrimination, the thresholds of the HI listeners were generally worse than those of the NH listeners by a factor of roughly 3. No correlation was observed between performance on the detection and discrimination tasks for either group of subjects.

For the most part, the studies reviewed here suggest that the shape of the TMTF as well as the magnitude of modulation detection thresholds are similar for NH and HI listeners for comparisons made with carrier stimuli at equal SPL or equal SL (Bacon and Viemeister, 1985; Moore et al., 1992; Bacon and Gleitman, 1992). In cases where discrepancies have been observed in the performance of HI and NH listeners, the performance of the HI listeners has been found to deteriorate more rapidly than normal with an increase in modulation rate (Formby, 1987; Lamore et al., 1984; Grant et al., 1998). Age confounds were present in several of these studies (Moore and Glasberg, 2001; Grant et al., 1998); however, in a study examining modulation detection in normal-hearing listeners over an age range of 21-76 years, Takahashi and Bacon (1992) did not find a significant effect of age.

E-2. Modulation-Detection Interference in Listeners with Hearing Impairment— Modulation-detection interference (Yost and Sheft, 1989) has been examined in listeners with hearing impairment (e.g., Grose and Hall, 1994, 1996a; Bacon and Opie, 2002). In this paradigm, thresholds for the detection of amplitude modulation in a target signal are examined in isolation and in the presence of unmodulated or modulated signals in a frequency region remote from that of the target. Interference in the ability to perform the modulation-detection task typically arises in the presence of modulated (but not unmodulated) flanking signals. Grose and Hall (1994, 1996a) conducted studies of MDI in listeners with normal hearing and with impaired hearing (with fairly flat losses in the region of 500-2000 Hz and thresholds ranging from 30 to 60 dB HL in this region). Grose and Hall (1994) employed groups of 12 NH listeners (age range 18 to 45 years) and 11 HI listeners (age range of 24 to 53 years), while Grose and Hall (1996a) employed groups of ten NH listeners (age range 20 to 39 years) and ten HI listeners (age range 39 to 57 years). The stimuli were constructed with a target carrier frequency of 1000 Hz at a 10-Hz rate and a distal carrier frequency of 4000 Hz with no modulation and with 100% modulation at rates of 10 and 25 Hz. All modulated tones were presented at a level of 83 dB SPL. Results were similar for NH and HI listeners: modulation-detection thresholds were unaffected by the presence of an unmodulated flank, but increased by roughly 12 dB in the presence of modulated flanks (using modulation rates that were the same or different from the modulation rate of the target). Results for NH and HI listeners were also similar in conditions examining the effect of the frequency and depth of modulation of the flanker. Modulation-detection interference data obtained by Bacon and Opie (2002) on listeners with mild high-frequency hearing loss corroborate the results of Grose and Hall (1994, 1996a).

E-3. Summary—Comparisons of TMTFs in NH and HI listeners for signals presented at equal spectrum levels or at equal SL indicate a general similarity in performance between the two groups of listeners both in the overall shape of the TMTF and in the magnitude of the modulation thresholds (Bacon and Viemeister, 1985; Bacon and Gleitman, 1992; Moore et al., 1992). Several studies, however, have reported that the performance of HI listeners deteriorates more rapidly than that of NH listeners as modulation rate is increased (Formby, 1987; Lamore et al., 1984; Grant et al., 1998). Although none of the studies of TMTF in HI listeners have employed comparisons with noise-masked simulations of hearing loss in NH listeners, several observations suggest that audibility and level are important factors in determining performance on this task. The decreased resolution observed under conditions of decreased noise bandwidth in NH listeners (Bacon and Viemeister, 1985; Moore et al., 1992) suggests that the decreased audibility that accompanies hearing loss can have an effect on resolution. Although age was confounded with hearing loss in some studies, other work (Takahashi and Bacon, 1992) indicates that age alone does not appear to play a major role in the ability to perform a modulation-detection task. Finally, the effects of modulation-detection interference (Grose and Hall, 1994, 1996a; Opie and Bacon, 2002) appear to be comparable for HI and NH listeners.

F. Temporal Masking Paradigms

Temporal processing resolution has been assessed by examining the time course of masking in paradigms that include forward masking, comodulation release of masking, and release of masking through overshoot. The studies reviewed in these areas are summarized in Table 6 in the order in which they appear in Sections F-1, F-2, and F-3.

F-1. Forward Masking—Kidd, Mason, and Feth (1983) investigated forward masking functions in young adult subjects that included two NH listeners, four HI listeners with bilaterally symmetric high-frequency loss, and one HI listener with unilateral notched loss. Forward masking was measured as a function of masker level (in the range of 20 to 100 dB SPL) using a 20-msec probe at 3000 Hz, a 3000-Hz masker whose duration was either 35 or 300 msec, and a 10-msec delay between the offset of the masker and the onset of the probe. NH subjects were sensitive to the duration of the masker in that masked thresholds were higher for the longer compared to shorter-duration masker. HI listeners, on the other hand, demonstrated similar amounts of threshold shift for both masker durations (consistent with reduced temporal integration for detection of a 3000-Hz tone—see Section C above). When NH subjects were tested in a background of broadband noise to shift the threshold of the 20-msec probe to 60 dB SPL, thresholds for both masker durations were shifted by roughly 30 dB and the results did not simulate the lack of masker-duration effect observed for the HI listeners. Humes et al. (1988) used their additivity-of-masking model to predict the results obtained by Kidd et al. (1983) with a 300-msec masker duration. The predictions of the model provided a reasonably good fit to the data for masked-normal listeners; however, the model failed to predict the results of the HI listeners in that the observed masked thresholds were substantially greater than the predicted values at the higher masker levels.

Nelson and Freyman (1987) measured forward masking in 12 listeners with normal hearing and 16 listeners with varying amounts of sensorineural hearing loss (subject ages were not specified). The masker (a 200-msec 1000-Hz tone) preceded the probe (a 20-msec 1000-Hz tone) with durations between masker offset and probe offset in the range of 42 to 160 msec. The probe level was fixed and the level of the masker required to mask the probe tone was measured as a function of time delay for probe-tone levels in the range of 5 to 30 dB SL for both groups of listeners. Using the functions relating masker-level thresholds in dB SL to delay time, time constants were derived from exponential fits to the data. Time-constant estimates for the HI listeners ranged from roughly 1 to 2.3 times the average size of that for the NH listeners (50 msec) and were correlated with degree of hearing loss at the test frequency, indicating that the time required for recovery from the masker increases with hearing loss. For a given sensation level of the probe, however, both groups of listeners required roughly the same sensation level of the masker to just mask the probe for the extrapolated condition corresponding to a 0-msec time delay. Because the experiment was conducted with probe levels at equal SL for the two groups of listeners, the effects of presentation level and audibility were not controlled as they would be in the use of masked-noise simulation of hearing loss.

Nelson and Pavlov (1989) measured forward masking in three NH and four HI listeners (ages not specified) using procedures similar to those of Nelson and Freyman (1987). This follow-up study included two off-frequency masking conditions (at 900 and 1100 Hz) in addition to the on-frequency masker of 1000 Hz and probe presentation levels in the range of 6 to 9 dB SL. For NH listeners, temporal masking functions were shallower for the two off-frequency maskers compared to the on-frequency condition. For the HI listeners, the slopes of the masking functions were related to the degree of hearing loss at the 1000-Hz probe frequency. For two subjects with mild hearing loss at 1000 Hz (but greater loss at frequencies above and below 1000 Hz), the slopes of the masking functions were similar to those of the NH subjects. For the remaining HI subjects (whose losses at the probe frequency ranged from roughly 30 to 50 dB), the recovery from masking was similar for on and off-frequency maskers.

A recent group of papers has examined forward masking in HI listeners as a method of inferring whether the compressive function of the basilar membrane is reduced as a result of outer-hair cell loss. In these studies, temporal-masking effects are typically examined as a function of the frequency separation between the probe and masker (e.g., Nelson, Schroder, and Wojtczak, 2001; Plack, Drga, and Lopez-Poveda, 2004; Lopez-Poveda, Plac, Meddis, and Blanco, 2005; Rosengard, Oxenham, and Braida, 2005; Stainsby and Moore, 2006).

Nelson et al. (2001) employed the same procedures as described in the earlier work of Nelson and Freyman (1987) and Nelson and Pavlov (1989) but extended the range of off-frequency maskers to include low-frequency maskers in the range of 500 to 900 Hz and high-frequency maskers in the range of 1012 to 1200 Hz. Temporal-masking curves were obtained in four NH (ages unspecified) and one HI listener (with thresholds in the range of roughly 50 to 70 dB SPL across the audiometric range). The 20-msec 1000-Hz probe tone was presented at a level of 10 dB SL, the masker was always 200 msec in duration, and delay times between masker offset and probe offset were in the range of 42 to 140 msec. For the HI subject, the slopes of the temporal-masking curves were quite similar at all masker frequencies, in comparison with the NH listeners for whom masking functions were more shallow for off-frequency compared to on-frequency maskers.

Plack et al. (2004) obtained temporal-masking curves in 16 listeners with normal hearing (ranging in age from 19-37 years) and in nine listeners with mild-to-moderate hearing impairment (ages 54-68 years). Average hearing loss was 20 dB HL at 1000 Hz, 30 dB HL at 2000 Hz, and 38 dB HL at the test frequency of 4000 Hz. The study employed a 4000-Hz probe signal set at 10 dB SL with duration of 8 msec and an on-frequency or off-frequency (2200 Hz) masker with duration of 204 msec. The interval between masker offset and probe onset took on values in the range of 0 to 100 msec. For NH listeners, the difference in levels required to mask the probe signal for an off-frequency masker versus an on-frequency masker varied as a function of masker-signal interval. A maximum difference of roughly 40 to 55 dB was observed for a 10-msec interval compared to a convergence of masker levels at the same value for intervals in the vicinity of 60 to 80 msec. For HI listeners, the difference between on- and off-frequency masker levels at the 10-msec interval tended to vary with degree of hearing loss at the probe frequency. This difference decreased systematically from roughly 40 dB for a listener with an audiometric threshold of 10 dB SPL at 4000 Hz to roughly 5 to 10 dB for listeners with thresholds near 50 dB SPL. Additionally, the slopes of the off-frequency masking functions in the HI listeners tended to be shallower than those of the NH listeners.

Lopez-Poveda et al. (2005) extended the research of Plack et al. (2004) on HI listeners to include a wider range of probe (500, 1000, 2000, 4000, and 8000 Hz) and masker frequencies (0.5, 0.6, 0.7, 0.9, 1.05, 1.1, and 1.2 times the probe frequency). The three HI listeners (age range of 24 to 70 years) included two subjects with relatively flat absolute thresholds of roughly 30 to 50 dB SPL in the range of 250 to 3000 Hz and gradually increasing loss at higher frequencies and one subject with a loss that increased gradually with frequency (30 dB SPL at 250 Hz increasing to 80 dB SPL at 10000 Hz). The probe signal was set at a level of 10 or 14 dB SL depending on the listener, had a duration of 10 msec, and was presented at intervals in the range of 10 to 100 msec relative to offset of a 110-msec forward masker. The slopes of the temporal-masking functions of the HI listeners were typically more shallow (by a factor of 1.5 to 4) than those observed in three NH listeners tested under the same conditions (Lopez-Poveda, Plack, and Meddis, 2003) for both on- and off-frequency maskers at each of the probe frequencies.

Rosengard et al. (2005) measured temporal-masking functions in five listeners with normal hearing (age range of 18 to 32 years) and five listeners with hearing loss characterized by relatively flat audiometric thresholds in the range of 250 to 8000 Hz (PTAs ranged from 40 to 70 dB HL across subjects whose age range spanned 27 to 74 years). Forward masking was measured at signal frequencies (f_s) of 1000, 2000, and 4000 Hz with an on-frequency masker and with an off-frequency masker that was $0.55f_{s.}$ The probe frequency was presented at 10 dB SL for NH listeners and at 5 dB SL for HI listeners; the signals and maskers were gated on and off with a 2.5-msec ramp (for 4000-Hz conditions) or a 5-msec ramp (for 1000- and 2000-Hz conditions) and a steady-state duration of 0 msec for signals and 100 msec for maskers; and values of masker-offset time to signal-onset time were in the range of 10 to 100 msec. For the NH subjects, the slopes of the temporal masking curves were always more shallow for the off-frequency compared to the on-frequency maskers, with slope ratios of roughly 0.4 at 1000 Hz and 0.14 at 2000 and 4000 Hz. The slopes of the off-frequency and on-frequency maskers were generally more similar in the HI listeners but the ratio of the slopes exhibited a fairly large range across subjects (from 0.6 to 1.2 at 1000 Hz; 0.4 to .7 at 2000 Hz; and 0.2 to 1.7 at 4000 Hz). Similar to the results of Plack et al. (2004) and Lopez-Poveda et al. (2005), the off-frequency masking functions of the HI listeners tended to be shallower than the corresponding functions of the NH listeners (although this may have been due in part to the limit of 102.5 dB SPL that was set for masker levels; see Stainsby and Moore, 2006).

Stainsby and Moore (2006) conducted tests of forward masking in three listeners with bilateral hearing loss (age 52-88 years) that was roughly flat in the region of 250 to 4000 Hz (PTAs in the range of roughly 45-65 dB HL) and increased at higher frequencies. Probe signals at 500, 1000, 2000, 4000, and 6000 Hz were 10-msec in duration and presented at 10 dB SL. At each probe frequency, masking functions were obtained for five maskers (200 msec in duration) with frequency defined as 0.5, 0.8, 1.0, 1.15, and 1.3 times the probe frequency at delays between masker offset and probe onset in the range of 0 to 75 msec. The trends in the data, which were similar for the three HI listeners, indicated that: (1) masking functions were well fit by straight lines; (2) for a given probe frequency the slopes of the lines were similar across masker frequency; and (3) slopes decreased with increasing probe frequency.

The results of the studies reviewed here (with the exception of Kidd et al., 1983) are based on the use of probe signals at fixed levels of 5 to 30 dB SL in listeners with normal and impaired hearing. Comparisons of temporal-masking functions between NH and HI listeners at comparable probe SLs generally indicate larger time constants and more shallow slopes for HI compared to NH listeners (Nelson and Freyman, 1987; Plack et al., 2005; Lopez-Poveda et al., 2005). Whereas NH listeners exhibited shallower slopes for off- compared to on-frequency maskers, slopes of the functions for HI listeners were similar across masker frequencies (Rosengard et al., 2005; Stainsby and Moore, 2006). In the one study employing hearing-loss simulation, Kidd et al. (1983) examined the effect of the duration of the forward masker on the detectability of the probe signal in noise-masked NH listeners as well as in NH and HI listeners. The lack of a duration effect observed in the HI listeners was not reproduced in the noise-masked NH listeners, likely due to differences in temporal integration between NH and HI listeners (see Section C).

F-2. Comodulation Masking Release—In studies of comodulation masking release, the threshold of a tonal signal is examined as a function of the delay between the signal and flanking noise bands in remote spectral regions. Comodulation of the flanking noise bands is accomplished by keeping the array of spectral component amplitudes and phases the same across noise bands. Grose and Hall (1996a) studied comodulation masking release in groups of ten NH listeners (age range 20-39 years) and ten HI listeners with mild-to-moderate flat losses (age range 39-57 years). The signal for these experiments was a 400-msec, 1125-Hz tone spectrally centered in a 600-msec noise masker that consisted of seven comodulated 20-

Hz bands of noise at the 3rd through 15th odd harmonics of 125 Hz. A total of seven masker conditions were studied with the spectrum level of the noises always set to 60 dB SPL/Hz. The baseline masking condition consisted of the 1125-Hz noise band alone. Six other conditions were derived by varying the time delay between the leading 1125-Hz noise band and the remaining noise bands with time delays employed in the range of 0 to 100 msec. Comodulation release of masking is assessed by examining the difference in threshold for the baseline condition relative to the conditions with flanking noisebands. For both subject groups, release of masking was greatest when the flanking bands were gated synchronously with the signal and was approximately zero for delays greater than 25 msec. The maximum release of masking was 15 dB for NH compared to 10 dB for HI listeners. NH listeners were also tested at a lower spectrum level of the noise bands to equate for sensation level with the HI group. Results were generally similar to those obtained at the higher sensation level. In general, HI listeners appear to be able to take advantage of cues in the comodulated noise bands to improve threshold detection, although perhaps not to the same degree as observed in NH listeners.

F-3. Overshoot—Another masking paradigm employed to examine temporal resolution involves the use of a brief target signal in the presence of a simultaneous masker whose bandwidth exceeds one critical band around the frequency of the target and whose spectrum contains components substantially lower than the frequency of the target. In this situation, the detectability of the signal can improve as the onset of the signal is delayed relative to the onset of the masker (referred to as the “overshoot” phenomenon). Bacon and Takahashi (1992) examined overshoot in four NH listeners (age 20-34 years) and five HI listeners (age 24-63 years; only one over the age of 35) hearing. The HI subjects had thresholds in the range of 0-20 dB HL at 1000 Hz and 40-60 dB HL at 4000 Hz. The signals were 10-msec tone bursts at either 1000 Hz or 4000 Hz presented in the background of a 400-msec wideband-noise masker at spectrum levels of 20, 30, or 40 dB SPL/Hz. The onset of the signal occurred at 1 msec or 195 msec after the onset of the masker. The magnitude of the overshoot, defined as the difference in thresholds obtained under the two different delays, was similar for normal and impaired listeners at 1000 Hz and ranged from roughly 0 to 15 dB across subjects. At 4000 Hz, the magnitude of overshoot for normal listeners (ranging from roughly 7 to 26 dB) exceeded that of the impaired listeners (which ranged from 0 to 10 dB). For both test frequencies and both groups of subjects, inter-subject variability was substantially larger at the 1-msec compared to the 195-msec delay. Comparisons of performance between the two groups of subjects at roughly equivalent SLs indicated that overshoot remained lower in the impaired group. Strickland and Krishnan (2005) reported that, for eight listeners with mild-to-moderate high-frequency hearing loss (age range of 30 to 73 years), the amount of overshoot at a given test frequency (3000, 4000, and 6000 Hz) decreased with an increase in hearing loss at the test frequency. For hearing loss in the range of 20-55 dB, overshoot was measured to be 5 to 15 dB compared to 12 to 28 dB for NH listeners (using data from Strickland, 2001) for equal-SPL signals in the range of 50-95 dB SPL.

F-4. Summary—The role of audibility in explaining temporal-masking effects in HI listeners has not been thoroughly investigated through the use of noise-masked simulations in NH listeners. In the area of forward masking, there is some evidence (Kidd et al., 1983) that the presence of a background noise to elevate the thresholds of NH listeners does not produce the same effects of masker duration in NH as in HI listeners; however, a systematic study employing age-controlled comparisons between real and simulated HI listeners has yet to be performed. Comparisons of temporal masking functions for NH and HI listeners to date have been made primarily with the use of equal SL probe signals, thus resulting in overall higher levels of presentation in dB SPL for the HI listeners. The differences observed between the temporal-masking functions of HI and NH listeners (including shallower slopes of HI listeners for on-frequency maskers and no change in slope between on- and off-frequency maskers for

HI listeners) may therefore be related in part to differences in level. In the area of comodulation release of masking, the performance of HI listeners was similar to that of NH listeners for stimuli presented at equivalent overall levels in dB SPL. Finally, the results of overshoot experiments indicate that the size of the overshoot effect is less for HI compared to NH listeners for stimuli in the region of the hearing loss presented at equivalent levels of dB SPL or SL.

G. Overall Summary and Conclusions

In the area of temporal processing by HI listeners, certain abilities appear to be degraded when compared to the performance of NH listeners at equal SPL (e.g., as observed in certain studies of gap detection such as De Filippo and Snell, 1986 and Glasberg et al., 1987 and in studies of the release of masking in temporally fluctuating noise such as Halling and Humes, 2000). Other temporal abilities of HI listeners appear to be degraded when compared to those of NH listeners at equal SL (e.g., as in the forward masking studies cited in Table 6 which employ stimulus probes at equal SL across the two groups of subjects). A relatively small group of studies has been conducted, however, in which the effects of audibility and level have been controlled in comparing the performance of HI and NH listeners through the use of noise-masked simulation of hearing loss. The results of such studies are available in four areas of temporal processing: gap detection, gap-duration discrimination, temporal integration, and tone detection in modulated noise.

The performance of HI listeners is well-matched by that of noise-masked NH listeners with simulated loss for the detection of gaps in noise (Florentine and Buus, 1984; Buss et al., 1998) and for gap-duration discrimination in narrow-band noise (Buss et al., 1998). Different patterns of results were obtained in the two existing studies of masked thresholds in temporally modulated noise employing noise-masked simulations of hearing loss. Although Humes (1990) obtained a good match for the magnitude of the release in masking observed in the detection of brief tones in the peaks and valleys of modulated noise by HI and noise-masked NH listeners, Zwicker and Schorn (1982) found less release of masking for HI compared to noise-masked NH listeners for the detection of long-duration tones in continuous versus interrupted noise. Finally, the reduced amounts of temporal integration observed in listeners with moderate to severe hearing impairment are not reproduced by noise-masked simulations in NH listeners (Fastl, 1977; Florentine et al., 1988), for whom the same amounts of temporal integration are observed in quiet and in noise.

Studies controlling for audibility, level, and age have yet to be conducted in the areas of duration discrimination, detection of temporal modulation in noise, and tonal detection under various temporal-masking paradigms. In the area of duration discrimination, further studies are needed to answer questions that still remain regarding the role of age, hearing loss, and stimulus level in determining performance on this task. Despite the lack of a controlled study in the area of temporal-modulation detection in noise, current results in this area suggest that the performance of HI listeners is roughly comparable to that of NH listeners for signals presented at moderate to high sensation levels and for filtered noise stimuli that roughly simulate the effects of high-frequency hearing loss. For tonal detection in various temporal masking paradigms, the performance of HI listeners for signals presented at equal dB SPL is roughly equivalent to that of NH listeners in studies of the comodulation release of masking and shows reduced effects in studies of the overshoot phenomenon. In studies which have compared the performance of NH and HI listeners in forward-masking paradigms, levels of the target stimuli have generally been established in terms of equivalent dB SL for both types of listeners and results are thus confounded by large differences in signal levels. Further studies in these three areas employing simulations of hearing loss are necessary for a more complete understanding of the effects of hearing loss on temporal-processing ability.

In considering the clinical implications of the temporal-processing abilities of hearing-impaired listeners, we can conclude that the most serious consequences exist for those types of tasks that show evidence of supra-threshold deficits apart from the effects of audibility. Such evidence comes from studies which show degraded performance of HI listeners relative to NH listeners on tasks which are relatively independent of level of stimulation and in studies where the effects of level and audibility have been controlled through the use of hearing-loss simulation. Certain temporal abilities of HI listeners appear to be fairly similar to those of NH listeners when compared under either of these two situations, including the tasks of gap detection and discrimination, duration discrimination, tonal detection in temporally fluctuating noise, and temporal-modulation detection. Such audibility-related effects presumably can be overcome through the use of hearing aids that provide (compression) amplification to restore speech signals to comfortable supra-threshold levels throughout a wide spectral range. The failure of listeners with cochlear hearing impairment to integrate acoustic signals over time to the same degree as normal-hearing listeners, on the other hand, may have a variety of consequences in the perception of running discourse either in quiet or in a noisy background. For example, the lengthening of a speech segment may not lead to improved detection over a shorter segment, and the effects of masking by preceding and following segments as well as by background noise may be more pronounced in HI than in NH listeners. Release of masking for tones in temporally modulated noise may be related to a listener's ability to achieve improved reception of speech in a temporally fluctuating versus continuous background noise. Although release of masking is similar for HI and noise-masked NH listeners (see Figure 5), the size of the effect is larger than in NH listeners due to increased absolute thresholds and a decreased dynamic range, thus leading to a smaller potential advantage for speech reception in a temporally fluctuating noise background. A final clinical implication of the research reviewed here concerns the interactions between age and hearing loss in determining performance on various temporal-related tasks. For some tasks, performance appears to be dominated primarily by age independent of hearing status (e.g., Fitzgibbons and Gordon-Salant, 1994,1995,2001,2004). Thus both factors must be taken into consideration in predicting clinical outcomes with hearing aid use.

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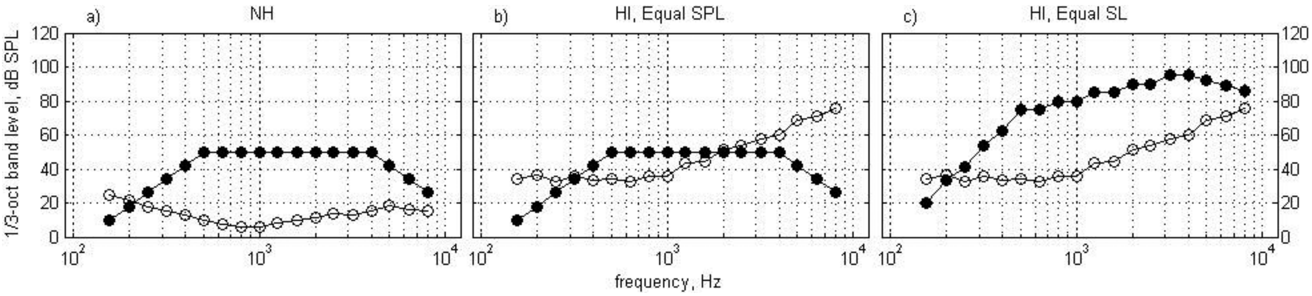

Figure 1.

(a) Absolute thresholds for NH listeners (open circles, from ANSI S3.6-2004) along with the spectrum of a bandpass noise stimulus (filled circles) presented at a level of 50 dB SPL per third-octave band in the passband. (b) Open circles plot absolute thresholds for a hypothetical HI listener with a loss that increases from 10 dB HL at low frequencies to 60 dB HL at 8 kHz. The noise spectrum is the same as in (a), indicating the ‘Equal SPL’ condition. (c) The same HI thresholds from (b) are plotted but here the noise spectrum has been shaped to achieve ‘Equal SL’, where the noise level re threshold in each band is the same as for the NH listener in (a).

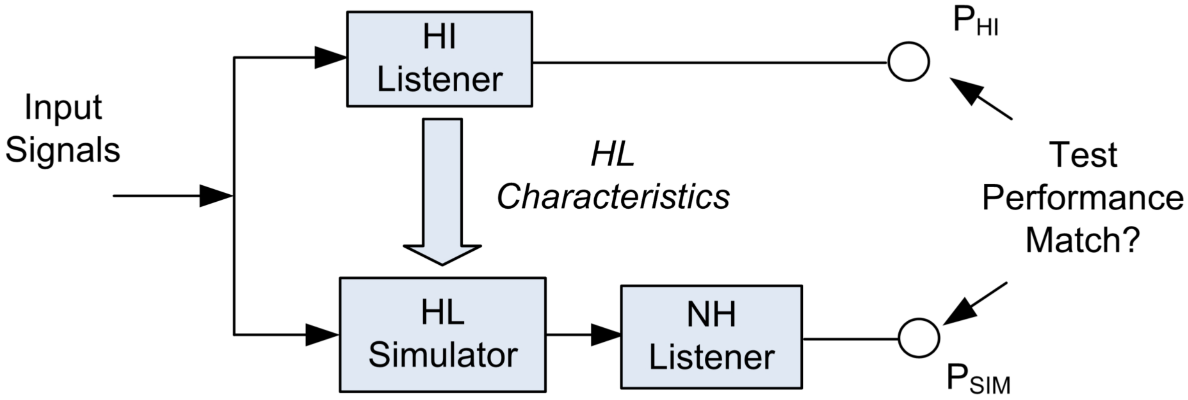

Figure 2.

Block diagram illustrating the simulation paradigm. The performance of a hearing-impaired (HI) listener on a given input signal is compared to that of a normal-hearing (NH) subject listening to that same signal passed through a hearing-loss (HL) simulation system. P_{HI} stands for the performance of the HI listener and P_{SIM} for the performance of the NH listener through the HL simulator.

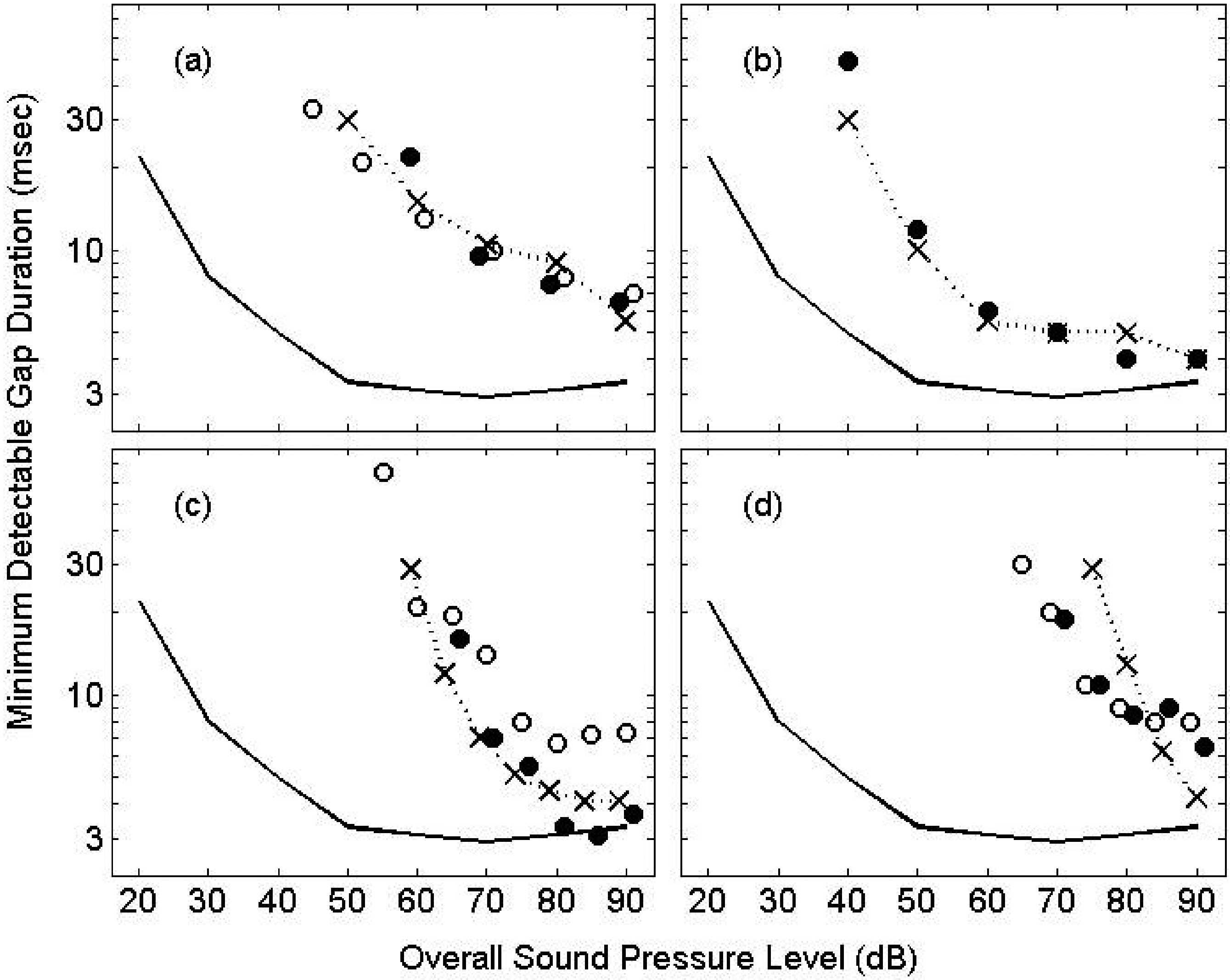

Figure 3.

Temporal gap-detection data from Florentine and Buus (1984) for NH listeners (solid curves), HI listeners (filled and unfilled circles), and noise-masked NH listeners (X symbols connected by thin lines). The minimum detectable gap duration in ms is plotted as a function of level of broadband noise stimulus in dB SPL. Results of HI listeners with steeply sloping high-frequency loss are shown in panel (a), bowl-shaped loss in panel (b), mildly sloping high-frequency loss in panel (c), and flat loss in panel (d). Filled circles represent data from the HI subject whose loss was simulated in the noise-masked NH listeners; unfilled circles represent data from another HI listener with a similar audiogram. The X symbols represent data averaged over two noise-masked subjects with simulated hearing loss.

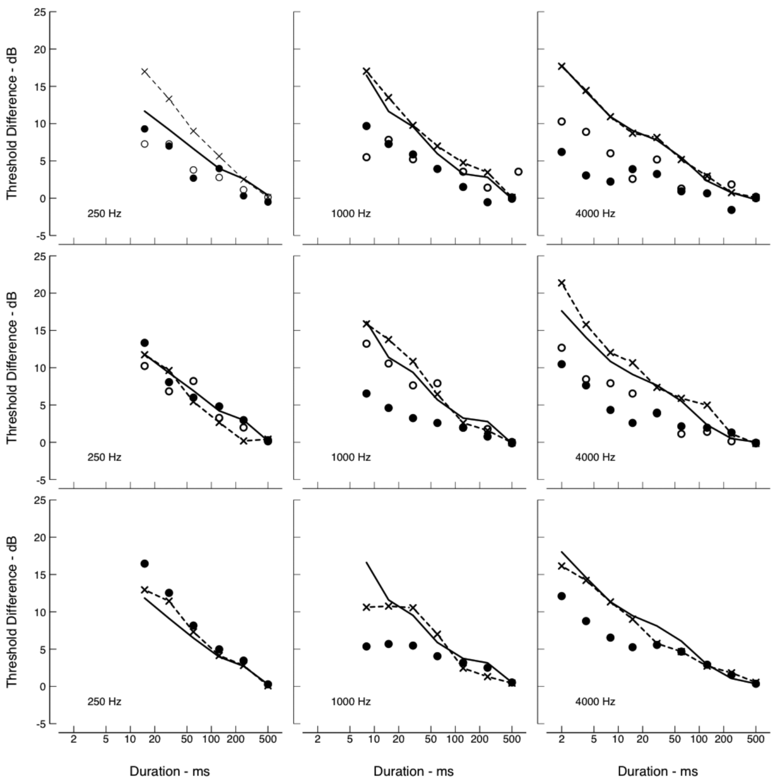

Figure 4.

Temporal integration data from Florentine et al. (1988) for NH listeners (solid curves), HI listeners (filled and unfilled circles), and noise-masked NH listeners (X symbols connected by dashed lines). Results for listeners with flat hearing loss are shown in the top row, mildly sloping high-frequency loss in the middle row, and steeply sloping high-frequency loss in the bottom row. Within each row data are plotted for 250 Hz (first column), 1000 Hz (second column), and 4000 Hz (third column). At each of the three test frequencies, the threshold obtained for a 500-msec signal was subtracted from the threshold obtained at each of the test durations. This threshold difference in dB is plotted as a function of signal duration. Filled circles represent data from the HI subject whose loss was simulated in the noise-masked NH listeners; unfilled circles represent data from another HI listener with a similar audiogram.

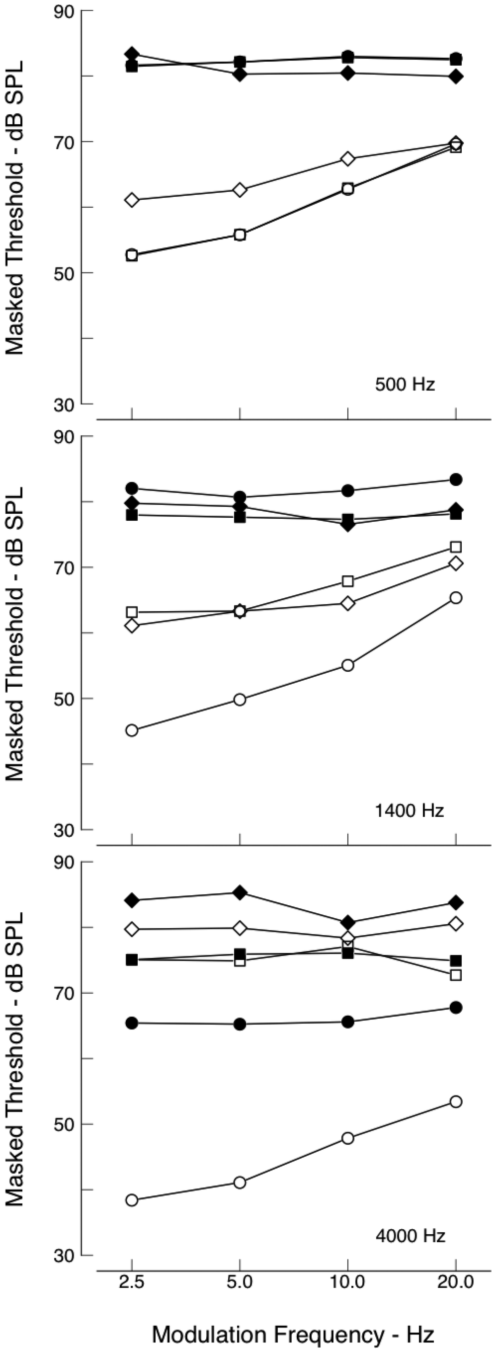

Figure 5.

Data replotted from Humes (1990) for detection of 4.6-msec probe tones in the peaks (filled symbols) and troughs (unfilled symbols) of 100% amplitude-modulated noise. Results at 500 Hz are plotted in the top panel, at 1400 Hz in the middle panel, and at 4000 Hz in the bottom panel. In each panel, masked threshold in dB SPL is plotted as a function of modulation frequency for each of three groups of listeners: NH listeners (circles), HI listeners (diamonds), and noise-masked NH listeners (squares). [Note that circles and squares overlie each other in top panel.]

Table 1

Summary of studies of gap-detection thresholds (GDTs) in listeners with sensorineural hearing loss. The major studies reviewed in this paper are listed in the first column in the order in which they are discussed in Section II-A. The second column describes the test stimuli. The third column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The fourth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The fifth column provides information about the stimulus levels that were used to make comparisons among the groups (e.g., equal SPL or equal SL). The final column summarizes key comparisons of NH and HI performance.

Study	Stimulus	Thresh. Match?	No. and Ages (Years)of Ss	Level Comparisons	Summary of Findings
Florentine & Buus (1984)	Broadband noise	NM	6NH: 20-50 7HI: 20-57	Simultaneously equal SPL and equal SL	HI GDTs generally well-produced in most NMNH listeners; exceptions in two flat-loss subjects.
Buss et al. (1998)	100-Hz noise bands	NM (approx.)	3 NH: $\bar{X}$ =31 7 HI: $\bar{X}$ =47	Simultaneously equal SPL and equal SL (approx.)	At equal SPL, GDTs were equivalent for HI and NMNH; at equal SL, HI had larger thresholds than NMNH
Fitzgibbons & Wightman (1982)	Octave noise bands	No	5 NH: $\bar{X}$ =27 5 HI: $\bar{X}$ =28	Equal SPL or equal SL	GDTs more similar for HI and NH at equal SL than at equal SPL
De Filippo & Snell (1986)	50-Hz noise bands	No	5 NH: 19-25 5 HI: 19-25	Equal SPL or equal SL	At equal SL and at equal SPL, HI had larger GDTs than NH
Glasberg et al. (1987)	Bandpass noises	No	9 NH: 42-72 8 HI: 18-69	Equal SPL or equal SL	NH data were obtained on the normal ear of HI listeners with unilateral loss; GDTs similar for bilateral and unilateral loss subjects; GDTs for NH and HI more similar at equal SL than at equal SPL
Moore & Glasberg (1988)	Pure tones; narrowband noise	No	7 NH: 45-72 7 HI: 45-72	Equal SPL and equal SL	Compared normal and impaired ears of unilateral-loss subjects; GDTs quite similar for equal SL comparisons
Moore et al. 1989	1 kHz pure tone	No	2 NH: 21 4 HI: 56-72	Equal SPL	GDTs for HI listeners were roughly 1 to 2 times larger than those of NH listeners
Hall et al. (1998)	Bandpass noise	No	25 NH: $\bar{X}$ =30 21 HI: $\bar{X}$ =49	Equal SPL	Mean GDTs of HI were roughly 1.2 to 1.7 times larger than those of NH subjects, but with considerable overlap in thresholds
Grose & Hall (1996b)	Sequences of 75-msec pure tones	No	10 NH: 20-39 12 HI: 39-57	Equal SPL	Mixed results – HI and NH GDTs were comparable in simple stimulus conditions, with HI GDTs 1.1 to 2 times larger with complex stimulus markers
Moore et al. (1992)	Pure tones	No	11 NH: $\bar{X}$ =76 11 HI : $\bar{X}$ =76	Equal SPL or equal SL	Elderly NH and HI had similar GDTs, which were larger than those of young NH listeners
Roberts & Lister (2004)	Broadband noise	No	8 NH: 20-32 8 NH: 53-74	Equal SL	No significant difference in GDTs for elderly NH, elderly HI, and young NH

Study	Stimulus	Thresh. Match?	No. and Ages (Years)of Ss	Level Comparisons	Summary of Findings
			8 HI: 57-76		
Lister & Roberts (2005)	1/4-octave noise bands	No	8 NH: 20-32 8 NH: 53-74 8 HI: 57-78	Equal SL	GDTs of elderly NH and elderly HI were similar and larger than those of young NH listeners

Table 2

Summary of studies of duration-discrimination thresholds (DDT) and gap-duration-discriminationthresholds (GDDTs) in listeners with sensorineural hearing loss. The major studies reviewed in this paper are listed in the first column in the order in which they are discussed in Section II-B. The second column gives the stimuli used. The third column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The fourth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The fifth column provides information about the stimulus levels that were used to make comparisons among the groups (e.g., equal SPL or equal SL). The final column summarizes key comparisons of NH and HI performance.

Study	**Stimulus**	**Thresh. Match?**	**No. and Ages (Years) of Ss**	**Level Comparisons**	**Summary of Findings**
Fitzgibbons & Gordon-Salant (1994)	Pure tones, gaps inserted into pure tones	No	10 NH: 20-40 10 HI: 20-40 10 NH: 65-76 10 HI: 65-76	Equal SPL	Averaged over conditions, DDTs and GDDTs were similar for young NH and HI listeners and smaller than those of elderly NH and HI listeners (who had similar performance)
Fitzgibbons & Gordon-Salant (1995)	Pure tones, gaps inserted in pure tones	No	10 NH: 20-40 10 HI: 20-40 10 NH: 65-76 10 HI: 65-76	Equal SPL	Stimulus complexity manipulated through use of sequential tone complexes with fixed or roving frequencies. DDTs and GDDTs of young NH and HI listeners were similar and smaller than those of elderly NH and HI listeners (who had similar thresholds).
Fitzgibbons & Gordon-Salant (2001)	Sequential tone bursts	No	15 NH: $\bar{X}$ =25 10 HI: $\bar{X}$ =30 13NH: $\bar{X}$ =67 14HI: $\bar{X}$ =71	Equal SPL	Relative Difference Limens (DLs) for inter-onset interval of tone bursts in 5-tone sequences showed significant effect of age but not hearing loss in groups of young and elderly subjects. Relative DL averaged 4% for young and 6% for elderly groups.
Fitzgibbons & Gordon-Salant (2004)	Sequential tone bursts	No	15 NH: $\bar{X}$ =23 10HI: $\bar{X}$ =30 11NH: $\bar{X}$ =71 15 HI: $\bar{X}$ =71	Equal SPL	Stimulus complexity increased through use of roving frequency and roving reference value of inter-onset interval of bursts in a given sequence. Performance similar for young NH and HI and superior to that of elderly NH and HI. Both groups of elderly subjects more adversely affected by temporal complexity than young NH and HI listeners.
Buss et al. (1998)	Gaps in narrowband noise	NM (approx).	3 NH: $\bar{X}$ =31 7 HI: $\bar{X}$ =47	Equal SPL and equal SL	GDDTs showed no significant differences between HI and noise-masked NH listeners or as a function of presentation level or center frequency of noise bands
Bochner et al. (1988)	3-tone harmonic complexes; gaps inserted into 3-tone complexes; CVC syllables; gaps in CVC syllables	No	3 NH: 27-36 7 HI: 19-24	60 dB SPL for NH; 100 or 110 dB SPL for HI; (Not matched for SL or SPL)	Relative DLs for duration discrimination of tonal complexes and CVC syllables were higher by a factor of roughly 1.5-2.0 for HI compared to

Study	Stimulus	Thresh. Match?	No. and Ages (Years) of Ss	Level Comparisons	Summary of Findings
					NH listeners. Relative DLs for gap-duration discrimination were similar for both groups of subjects for tonal complexes and CVC syllables.
Abel et al. (1990)	Third-octave bands of noise	No	15 NH: $\bar{X}$ =24 15 NH: $\bar{X}$ =48 15 HI: $\bar{X}$ =55 15 HI: $\bar{X}$ =61	Equal SPL or Equal SL	Results similar for two groups of older HI listeners and one group of older NH listeners, and inferior to those of a young NH group. DDTs of the older subjects were in the range of 1.2 to 2.5 times larger than those of the young subjects.
Lister et al. (2000)	Gaps in quarter-octave bands of noise	No	6 NH: 22-51 6 HI: 21-71	Equal SPL or Equal SL	No significant difference in GDDTs between HI and NH subjects; GDDTs of both groups increased as the frequency difference between leading and trailing noise markers increased. Older subjects (regardless of hearing status) more affected by spectral disparity than younger subjects (regardless of hearing status).
Grose et al. (2001)	Gaps in pure tones	No	7 NH: $\bar{X}$ =50 9 HI: $\bar{X}$ =49	Equal SPL	GDDTs were not significantly different between NH and HI groups
Grose et al. (2004)	Pure tones, FM tones, Narrowband noise	No	7 NH: $\bar{X}$ =50 9 HI: $\bar{X}$ =49	Equal SPL	Across conditions, no significant differences in DDTs between NH and HI listeners

Table 3

Summary of studies of temporal integration in listeners with hearing impairment. The major studies reviewed in the paper are listed in the first column in the order in which they are discussed in Section II-C. The second column gives the stimuli used. The third column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The fourth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The fifth column provides the stimulus durations that were tested. The final column summarizes key comparisons of NH and HI performance.

Study	**Stimulus**	**Thresh. Match?**	**No. and Ages (Years) of Ss**	**Stimulus Durations**	**Summary of Findings**
Gengel (1972)	Pure tones: 0.5, 2.0, and 4.0 kHz	NM	Unknown	10, 20, 50, 200, and 500 msec	Temporal integration averaged 15 dB at 0.5 kHz, 10 dB at 2.0 kHz, and 8.5 dB at 4.0 kHz in NM NH listeners, similar to that obtained in NH listeners in quiet and larger than amount observed in HI listeners with similar degree of threshold shift
Fastl (1977)	Pure tones: 1.0, 2.5., 3.0, 3.5, and 7.0 kHz	NM	Unknown	3, 10, 30, 100, and 300 msec	Temporal integration in NM NH listener was roughly 25 dB at all frequencies tested. HI listener had notched loss at 3.0 kHz, where temporal integration was 0.0 dB.
Florentine et al. (1988)	Pure tones: 0.25, 1.0, and 4.0 kHz	NM	5NH: 20-42 6HI: 20-62	2, 4, 8, 16, 32, 64, 128, 256, and 512 msec	Temporal integration in NH listeners and NM NH listeners was similar: 12 dB at 0.25 kHz, 15 dB at 1.0 kHz, and 18 dB at 4.0 kHz. Reduced temporal integration observed in HI listeners at frequencies in region of hearing loss
Oxenham et al. (1997)	Pure tone of 6.5 kHz in background of bandpass noise	NM	4 NH: 25-34 4 HI: 61-81	9 values between 2 and 200 msec	Slope of temporal-integration function steeper from 2-20 msec than from 20-200 msec in all listeners. Less temporal integration for HI listeners in noise compared to NH listeners in noise.

Table 4

Summary of studies of masked thresholds in temporally-modulated noise in listeners with hearing impairment. The major studies reviewed in this paper are listed in the first column the order in which they are discussed in Section II-D. The second column describes the signals and the third column describes the characteristics of the temporally-modulated noises. The fourth column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The fifth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The final column summarizes key comparisons of NH and HI performance.

Study	**Signal**	**Noise**	**Thresh. Match?**	**No. and Ages (Years) of Ss**	**Summary of Findings**
Zwicker and Schorn (1982)	600-msec pure tones of 0.5, 1.5, and 4.0 kHz	Bandpass noise; steady-state or square-wave modulated at rate of 14 Hz; overall level of 40 dB SL	NM	40 NH: 17-57 55 HI: Ages Unspecified	Threshold difference between steady-state and modulated noise was in range of 15-25 dB for NH and NM NH listeners and 5-10 dB in HI listeners whose thresholds in quiet exceeded 50 dB SPL at a particular test frequency.
Humes (1990)	4.6-msec tone bursts at 0.5, 1.4, and 4.0 kHz presented in peak or trough of noise	100% sinusoidally amplitude-modulated (SAM) speech-shaped noise with modulation frequency in range of 2.5 to 20 Hz; overall level of 70 dB SPL	NM	10 NH: 17-32 5 HI: 22-67	For NH listeners, threshold differences between detection in peaks and detection in troughs decreased as modulation rate increased: maximum difference of 30-40 dB at lowest modulation rate. Similar trend for HI listeners but maximum magnitude of threshold difference was reduced to 25 dB. Results for NMNH listeners comparable to those of HI listeners.
Halling and Humes (1998)	Pure tones of 0.5, 1.0, and 2.0 kHz	Broadband noise; steady-state or SAM at 7 modulation frequencies in range of 0.5 to 32 Hz; overall level of 70 dBC	No	8 NH: $\bar{X}$ =23 8 NH: $\bar{X}$ =72 8 HI: $\bar{X}$ =73	Release of masking defined as difference between masked threshold in steady-state noise and masked thresholds averaged across the SAM noises. Release of masking slightly greater for young NH compared to elderly NH listeners and substantially larger for elderly NH compared to elderly HI.

Table 5

Summary of studies of temporal modulation transfer functions (TMTFs) and modulation-detection interference (MDI) in listeners with sensorineural hearing loss. The major studies reviewed in this paper are listed in the first column in the order in which they are discussed in Sections II-E-1 and II-E-2. The second column describes the test stimuli. The third column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The fourth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The fifth column provides information about the stimulus levels that were used to make comparisons among the groups (e.g., equal SPL or equal SL). The final column summarizes key comparisons of NH and HI performance.

Study	**Stimulus**	**Thresh. Match?**	**No. and Ages (Years) of Ss**	**Level Comparisons**	**Summary of Findings**
Bacon and Viemeister (1985)	Broadband noise carrier	No	4 NH: $\bar{X}$ = 24 6 HI: 19-68	Equal SPL	Shape of TMTF similar for NH and HI listeners. Modulation thresholds of HI listeners at noise spectrum levels of 30 or 40 dB SPL/Hz were in the range of 0 to 7 dB worse than those of the NH listeners who were tested at a noise spectrum level of 30 dB SPL/Hz
Moore et al. (1992)	Octave band of noise centered at 2 kHz	No	3 NH: 59-76 3 HI: 59-76	Equal SPL or equal SL	TMTFs of impaired ear of listeners with unilateral hearing loss similar to that of the normal ear for equal SPL and SL comparisons; TMTFs in better ear of bilateral loss subjects also similar to normal data
Bacon and Gleitman (1992)	Broadband noise carrier	No	5 NH: 22-29 8 HI: 11-63	Equal SPL or equal SL	TMTFs of HI and NH listeners were generally equivalent for both equal SPL and equal SL comparisons
Formby (1987)	Broadband noise carrier	No	6 NH: 27-56 6 HI: 27-56	Equal Loudness	TMTFs of impaired ear of listeners with unilateral hearing loss were similar to those of normal ear for modulation rates below 200 Hz but modulation thresholds were worse than normal for modulation rates above 200 Hz
Lamore et al. (1984)	Broadband noise carrier	No	10 NH: ? 32 HI: 12-20	Equal SL	Substantial overlap between modulation detection thresholds of NH and NH listeners; greater inter-subject variability in HI results
Moore and Glasberg (2001)	Sinusoidal carriers	No	4 NH: 23-54 3 HI: 70-84	Equal SPL or equal SL	Modulation detection thresholds of HI listeners similar to NH data for roughly equal SL
Grant et al. (1998)	Broadband noise carrier	No	4 NH: 38-52 8 HI: 58-76	Equal SPL	Modulation detection thresholds of HI listeners worse than NH results at the higher rates of modulation. Modulation discrimination thresholds of HI worse than NH by a factor of 3. No correlation between detection and discrimination performance for HI or NH listeners.
Grose and Hall (1994)	Target: 1 kHz carrier; Interference: 4 kHz carrier	No	12 NH: 18-45 11 HI: 24-53	Equal SPL	Results similar for NH and HI listeners. Modulation detection thresholds at 1 kHz were unaffected by the presence of an unmodulated 4Khz tone but increased by roughly 12 dB when

Study	Stimulus	Thresh. Match?	No. and Ages (Years) of Ss	Level Comparisons	Summary of Findings
					the 4kHz tone was 100%-modulated at rates of 10 and 25 Hz.
Grose and Hall (1996a)	Same as above	No	10 NH: 20-39 10 HI: 39-57	Equal SPL	Results as described above for Grose and Hall (1994)

Table 6

Summary of studies employing temporal-masking paradigms in listeners with sensorineural hearing loss. The major studies reviewed in this paper are listed in the first column in the order in which they are discussed in Section II-F-1. The second column describes the type of temporal-masking paradigm employed. The third column describes the characteristics of the probe stimulus and the fourth column the characteristics of the masker. The fifth column (Thresh. Match?) provides information concerning the use of threshold matching to simulate hearing loss (with the noise-masking threshold-elevation procedure abbreviated as NM). The sixth column gives the number (No.) of subjects (Ss) and either the range or the mean ($\bar{X}$) of ages in years of the NH and HI groups. The final column summarizes key comparisons of NH and HI performance.

Study	Masking Paradigm	Probe Stimulus	Masker	Thresh. Match?	No. and Ages (Years) of Ss	Summary of Findings
Kidd et al. (1983)	Forward Masking	3.0 kHz; 20 msec	3.0 kHz; 35 or 300 msec; 20 to 100 dB SPL	NM	2 NH: "Young Adults" 5 HI: "Young Adults"	NH listeners had higher masked thresholds for 300 msec masker compared to 35 msec masker; HI listeners had similar amounts of threshold shift for both masker durations; NM NH listeners had 30-dB higher masked thresholds than NH listeners for both masker durations
Nelson & Freyman (1987)	Forward Masking	1.0 kHz; 20 msec; levels in range of 5 to 30 dB SL	1.0 kHz; 200 msec	No	Unknown	For NH listeners, time constant of temporal masking functions was roughly 50 msec; for HI listeners, time constant was 1.0 to 2.3 times that of NH listeners and increased with degree of hearing loss at 1.0 kHz. For a given SL of probe, SL of masker required to mask probe was similar for NH and HI listeners
Nelson & Pavlov (1989)	Forward Masking	1.0 kHz; 20 msec; levels in range of 6-9 dB SL	1.0, 0.9, and 1.1 kHz; 200 msec	No	Unknown	For NH listeners, slopes of masking functions more shallow for off-frequency compared to on-frequency maskers; for HI listeners slopes were dependent on amount of hearing loss at 1.0 kHz. Listeners with mild loss had slopes similar to NH; listeners with moderate loss showed similar slopes for off- and on-frequency maskers
Nelson et al. (2001)	Forward Masking	1.0 kHz; 20 msec; 10 dB SL	1.0 kHz; 10 other frequencies in range of 0.5- 1.2 kHz; 200 msec	No	Unknown	NH listeners exhibited shallower slopes for off-frequency maskers compared to the 1.0 kHz masker. For HI listener, slopes of masking functions were similar across masker frequencies
Plack et al. (2004)	Forward Masking	4.0 kHz; 8 msec; 10 dB SL	4.0 and 2.2 kHz; 204 msec	No	16 NH: 19-37 9 HI: 54-68	Slopes of off-frequency masking functions more shallow in HI than NH listeners. Difference in masking levels required to mask probe for on-frequency versus off-frequency masker decreased with increase in delay time for NH listeners. For HI listeners, this difference decreased with increase of hearing loss
Lopez-Poveda et al. (2004, 2005)	Forward Masking	0.5, 1.0, 2.0, 4.0, and 8.0 kHz; 10 msec; 10 or 14 dB SL	0.5, 0.6, 0.7, 0.9, 1.05, 1.1, and 1.2 times the	No	3 NH: 22-31 3 HI: 24-70	Slopes of temporal masking functions of HI listeners more shallow than those of NH listeners by a factor of 1.5 to 4 for both on- and

Study	Masking Paradigm	Probe Stimulus	Masker	Thresh. Match?	No. and Ages (Years) of Ss	Summary of Findings
			frequency of probe; 110 msec			off-frequency maskers at each of the probe frequencies.
Rosengard et al. (2005)	Forward Masking	1.0, 2.0 and 4.0 kHz; 2.5 or 5.0 msec ramp; 10 dB SL for NH; 5 dB SL for HI	1.0 and 0.55 times the frequency of probe; 100 msec	No	5 NH: 18-32 5 HI: 27-74	For NH listeners, slopes of temporal masking functions were always more shallow for off-frequency compared to on-frequency maskers; for HI listeners, slopes of on- and off-frequency maskers were more similar but were highly variable across subjects.
Stainsby & Moore (2006)	Forward Masking	0.5, 1.0, 2.0, 4.0, 6.0 kHz; 10 msec; 10 dB SL	0.5, 0.8, 1.0, 1.15, and 1.3 times the frequency of the probe; 200 msec	No	NH: none 3 HI: 52-88	For HI listeners, all temporal masking functions were well fit by straight lines; for a given probe frequency, slopes were similar across different masker frequencies; slopes decreased with increasing frequency of the probe
Grose and Hall (1996a)	Comodulation masking release	1.125 kHz; 400 msec	7 comodulated 20-Hz noisebands at odd harmonics of 125 Hz; 600 msec; equal SPL and SL	No	10 NH: 20-39 10 HI: 39-57	Maximum release of masking was 15 dB for NH and 10 dB for HI
Bacon and Takahashi (1992)	Overshoot	1.0 and 4.0 kHz; 10 msec	Wideband noise; 400 msec; 3 spectrum levels of noise	No	4NH: 20-34 5HI: 24-63	At 1 kHz, magnitude of overshoot similar for NH and HI, ranging from 0 to 15 dB across listeners; at 4 kHz, larger overshoot for NH (7 to 26 dB) than for HI (0 to 10 dB)
Strickland and Krishnan (2005)	Overshoot	3.0, 4.0, 6.0 kHz; 10 msec; equal SPL	Broadband noise; 400 msec	No	NH: None 8 HI: 30-73	Amount of overshoot decreased with increase in hearing loss at test frequency; for hearing loss of 20-55 dB, overshoot was 5-15 dB compared to overshoot of 12-28 dB for NH listeners tested by Strickland (2001) for equal-SPL signals