
Psychoacoustics and Aging: Implications for Everyday Listening

Psychoacoustique et vieillissement : les répercussions sur l'écoute dans la vie quotidienne

by • par

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ABSTRACT

Elderly listeners often find it difficult to identify and locate sound sources, and understand speech, in everyday listening situations. Age-related changes that occur in the anatomy, biomechanics, and physiology of the cochlea could be responsible for many of these difficulties. A review of recent findings (primarily based on animal models) suggests that cochlear degeneration in aging subjects, in addition to elevating thresholds, may also adversely affect the temporal and spectral resolution of the auditory system. As well, behavioural measures of hearing in the elderly are consistent with both a loss of temporal resolution and a broadening of the auditory filter. In the early stages of presbycusis these changes may be so subtle that elderly listeners may experience little if any difficulty in processing speech in a quiet environment. However, as the environment becomes noisier and the speech faster, even rather subtle deficits can result in poorer speech recognition and comprehension on the part of elderly listeners.

ABRÉGÉ

Les personnes âgées ont souvent du mal à repérer la source du son et à comprendre la parole dans le quotidien. Les changements anatomiques, biomécaniques et physiologiques de la cochlée qui sont attribuables à l'âge pourraient être la cause de leurs difficultés. Une analyse des constatations récentes (surtout à partir de modèles animaliers) donne à penser qu'en plus d'élever les seuils auditifs, la dégénérescence de la cochlée chez les sujets âgés peut nuire à la résolution tant temporelle que spectrale du système auditif. En outre, les mesures du comportement de l'audition chez les personnes âgées sont compatibles à la fois avec la perte de la résolution temporelle et un élargissement du filtre auditif. Aux premiers stades de la presbycusis, les changements sont parfois si subtils que les personnes âgées ont très peu de mal à traiter la parole dans un environnement silencieux. Cependant, la discrimination et la compréhension de la parole seront d'autant plus ardues que le bruit ambiant est fort et la parole, rapide, même chez les personnes âgées dont la déficience auditive sera très légère.

KEY WORDS

presbycusis • hearing • hearing loss • aging • temporal processing

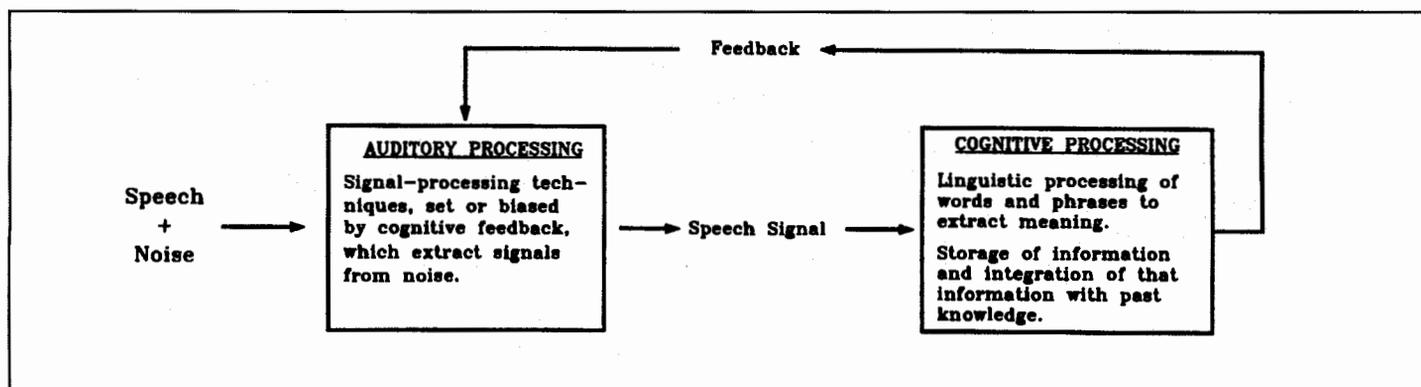
Elderly listeners, including those who have normal audiometric thresholds, often find that it is difficult to hear things in the ordinary situations typical of everyday life. For example, they may fail to hear faint sounds, especially in noisy backgrounds; they may not be able to locate a heard sound (is the telephone ring coming from the kitchen, or is it coming from the television program?); or they might find it difficult to identify, locate, and understand a person talking in a restaurant or at the dinner table. Moreover, these hearing difficulties become more apparent and more debilitating when the listening environment is more complex.

Because pure-tone audiometry cannot readily predict the nature and extent of these difficulties (Bergman, 1980; Duquesnoy, 1983; Plomp, 1986), we have to do more than assess hearing acuity in quiet. We have to identify the age-related changes in the auditory system that make it difficult for an elderly person to listen to and comprehend speech in a noisy environment. Because the ability to communicate is so impor-

tant to any individual, and because the speech understanding process engages most, if not all, of an individual listener's auditory processing skills, we will focus most of our attention in this paper on efforts to identify the age-related changes in auditory processing that lead to speech understanding difficulties in the elderly.

Figure 1 presents a simplified model of the processing system for speech. The input to the system consists of a speech signal immersed in a noisy background. In the first stage, the peripheral auditory system applies a number of signal-processing techniques to the input to extract the signal from the background noise so that a "clean" speech signal is available for higher-order, cognitive processing. At the cognitive level, the words and phrases in the speech signal are processed linguistically and integrated with past knowledge to extract meaning, and the processed information is stored for future use. In addition, there are feedback loops such that information processed and/or stored at the cognitive level can, in turn, affect more peripheral levels

Figure 1. A simplified model of the processes involved in speech understanding.



of processing. For example, feedback from more central levels could affect the tuning or biasing of these peripheral mechanisms. Clearly, age-related changes in peripheral processing, such as a loss of temporal synchrony, an elevation in masked thresholds, or an increase in the bandwidth of the auditory filter, could result in difficulties in understanding speech. Just as clearly, age-related changes in cognitive abilities, such as the ability to switch attention from one talker to another, would lead to difficulties in comprehension. Little is known about the isolated effects of such perceptual and cognitive losses on comprehension. Virtually nothing is known about their combined effects, even though these might be considerable.

While a complete understanding of the speech comprehension difficulties experienced by the elderly would require an integrative approach combining both peripheral and cognitive (central) measures, it seems reasonable, as a first step, to begin our investigation by looking for age-related changes in peripheral processing. If the processing of acoustic information by peripheral structures is sufficiently compromised, the input to the cognitive system will be a distorted or masked speech signal. Even though part or all of the information lost in the early stages of auditory processing may be partially or completely recovered by higher-order "top-down" processes, the diversion of resources and effort to this recovery process may deleteriously affect other processes required for speech comprehension. For example, listeners who "mishear" a word in a sentence can often recover the word from the context provided by the sentence. To do this, however, they might have to divert some of the cognitive resources that normally would be allocated to the task of comprehension to help recover information lost during perceptual processing. This diversion of resources could then lead to less efficient linguistic and cognitive processing of speech.

Age-related changes in anatomy and physiology

Sound waves are modified both by the shape of the pinna and the conditions of the auditory canal. The transduction of sound

waves to mechanical movement depends on the efficient functioning of the tympanic membrane and middle-ear structures. The travelling wave in the inner ear will be affected by the integrity of the membranes and supporting structures in the inner-ear. The transduction of mechanical movement to neural impulses will depend on the status of the inner and outer hair cells, and the metabolic processes that support the transduction process. Finally, the quality and quantity of information supplied to the cochlear nucleus will depend on the efficient functioning of the neurons comprising the auditory portion of the 8th nerve. Age-related changes in any or all of these structures could lead to hearing difficulties in the elderly.

Marshall (1981) in a review of auditory processing in aging listeners noted that although there were anatomical changes due to aging in the outer and middle ears (loss of stiffness in the cartilaginous portion of the external auditory meatus; an increase in the prevalence of arthritis of the middle ear joints) these changes appeared to have little effect on hearing (except for a possible collapse of the ear canal when wearing earphones). As a result she concluded that, once middle-ear disorders are excluded, age-related changes in these structures do not lead to a significant conductive hearing loss in the elderly. Willott (1991), in his review of this area, is in essential agreement with Marshall. Thus, unless there is an indication of outer ear blockage or middle ear disease, it is relatively safe to assume that age-related changes in outer and middle ear structure do not produce a significant conductive hearing loss in the elderly.

Schuknecht (1964, 1974), in considering the pathologies of the inner ear, employed 4 categories: (a) sensory presbycusis (pathologies of the organ of Corti), (b) neural presbycusis (pathologies of the spiral ganglion cells and their processes), (c) mechanical presbycusis (pathologies of the basilar membrane and other structures involved in cochlear mechanics), and (d) strial presbycusis (pathologies of the stria vascularis). Willott (1991) added vascular presbycusis (pathologies of the vascular system of the inner ear) to this list. (A more general term for

this type of presbycusis might be metabolic presbycusis which would take into account any metabolic changes that might affect the status of the inner ear.) Finally, Willott argues that a sixth category (sensorineural presbycusis) should be added to the list because sensory and neural pathologies often occur together. Because Willott (1991) has provided an excellent review of both human and animal studies relating to these six categories, we will first review Willott's (1991) generalisations and interpretations. Then, in order to relate changes in aging auditory structures to behaviour, and to control for such factors as a history of noise exposure, we will consider a particular animal model.

Willott (1991) notes that a number of studies have reported degenerative changes in the organ of Corti of aging people. These include hair cell loss which is most severe in the basal region of the cochlea. The pattern of hair cell loss, however, differs between outer and inner hair cells. While inner hair cell loss is concentrated in the basal region, outer hair cell loss is more widely distributed, with the outer rows being most severely affected. The relationship between hair cell loss and audiometric threshold, however, is uncertain. A number of studies (e.g., Bredberg, 1968; Belal, 1975) have shown that substantial hair cell loss may occur in aging individuals with only a small effect on audiometric thresholds at the frequencies usually tested (< or equal to 8 kHz). Moreover, it is likely that outer and inner hair cell loss have different functional implications for hearing. Current models of hearing consider inner hair cells as being vibration detectors which transduce vibratory energy into neural energy by initiating activity in the primary auditory neurons. A total loss of inner hair cells in a particular region therefore would result in a total loss of hearing in that region. On the other hand, a number of studies of the biomechanics of the cochlear partition suggest that the outer hair cells control basilar membrane gain by contracting to change the mechanical properties of the membrane in such a way as to increase vibration amplitude (see Dulon & Schacht, 1992, for a review). A total loss of outer hair cells therefore would not be expected to eliminate hearing in that region, but may very well attenuate the resulting signal and eliminate many of the nonlinear mechanisms that enhance signal detection and processing.

As is the case for inner hair cell loss, there is also an age-related loss of ganglion cells which is typically greatest near the base of the cochlea. Ganglion cell loss has been observed in the absence of hair cell loss and vice versa, so that hair cell loss is neither a necessary or sufficient condition for ganglion cell degeneration. It is interesting to note that audiometric thresholds can remain relatively normal in the presence of either extensive hair cell loss or spiral ganglion degeneration. Thus, elderly individuals with relatively normal audiograms may nevertheless be experiencing a significant amount of sensory, neural, or sensorineural degeneration. The fact that they have rela-

tively good pure-tone audiograms, however, does not mean that their hearing is normal. Indeed, the effect of these degenerative changes may not become evident until the auditory systems of these individuals are stressed by being forced to listen to speech and other signals in noisy environments.

Although a number of studies have found degeneration of the spiral ligament (e.g., Allam, 1970; Johnsson & Hawkins, 1972; Wright & Schuknecht, 1972), which attaches both the basilar and Reissner's membrane to the bony labyrinth, and a thickening and calcification of the basilar membrane (e.g., Nadol, 1979), it is not yet clear to what extent these changes affect the mechanical properties of the inner ear. However, it must be the case that anything that affects the mechanical properties of the inner ear must also affect some aspect of hearing. In addition to the degenerative tissue changes that might affect basilar membrane mechanics, it is also important to note that the mechanics of the basilar membrane are directly modified by the action of the outer hair cells. Thus, outer hair cell loss, or any changes in metabolic processes that affect the functioning of the outer hair cells, will alter the mechanical properties of the membrane. If, for example, proper outer hair cell functioning depended on the maintenance of a healthy endocochlear potential, the degeneration of the metabolic system that maintains this potential will indirectly affect cochlear mechanics. Because outer hair cell loss appears to be ubiquitous with age, it would be premature to rule out a biomechanical basis for presbycusis.

The most heavily envasculated structure in the inner ear is the stria vascularis. Degenerative changes in the lateral wall that ultimately limit the blood flow to this system might affect the metabolic processes that maintain the various cochlear potentials (Pauler, Schuknecht, & White, 1988). Disruption of these potentials, therefore, can be deleterious for hearing (Konishi, Butler, Fernandez, 1961; Schulte & Schmiedt, 1992; Sewell, 1984). Strial pathology has been noted in older individuals which can include degeneration of all three layers of the stria vascularis and loss of capillaries. Capillary loss has also been noted in the spiral ligament. Losses that are severe enough to interfere with metabolic processes should result in hearing problems.

This brief summary of age-related changes in the anatomy and physiology of the human cochlea indicates that there are many points at which pathological change might affect hearing. In many of these human studies it was difficult to control for related factors that might affect hearing, such as a history of exposure to ototoxic drugs and/or noise. Thus, it is sometimes difficult to identify the factors that are responsible for the observed pathology. There are, however, certain changes that appear to be ubiquitous. The first is a loss of both inner and outer hair cells, with inner hair cell loss being greater in the basal portion of the cochlea and outer hair cell loss occurring throughout the cochlea. Because the outer hair cells modulate the mechanical properties of the membrane, their loss can be expected to affect

hearing. Because the inner hair cells transduce vibration into neural impulses, their loss might also be expected to affect hearing. In addition, degenerative changes in intracochlear vascularization occur, which appear after the first decade of life and progressively worsen with age. Although a direct linkage between age-related histopathology in the vascular system and hearing problems has not yet been established in humans, an adequate blood supply must be crucial for the metabolic processes that are essential for the maintenance of cochlear structures and electrical potentials. Because both hair cell loss and vascular degeneration begin early and continue throughout life, they constitute good candidates for the peripheral basis of presbycusis.

However, adequate evaluation of the effects of such age-related changes requires an animal model so that factors such as noise exposure can be controlled and the relationship between pathological changes and the behaviour of the system determined. Again Willott (1991) provides a good description of the animal models that have been employed and the results obtained from them. Rather than repeat what he has said we will focus on a single animal model (the Mongolian gerbil) that has been studied by researchers (J. H. Mills, R. A. Schmiedt, & B. A. Schulte) at the Medical University of South Carolina because of the extensive data that has been collected by this group on age-related changes in both the anatomy and electrophysiology of these animals.

To control for the cumulative effects of noise exposure on auditory processing, Mills, Schmiedt, Schulte and their associates have raised gerbils in both quiet and noisy environments. Gerbils raised in quiet were born and raised in a colony where the mean noise level was approximate 35 dBA with very minimal exposure to noise above 49 dBA. Gerbils raised in noise were born and raised in the quiet environment before being exposed to a continuously present 85 dBA bandlimited noise from eight months of age for a period of between 1 and 2 years. The average age of the animals when they were removed from the colony for terminal physiological studies was about 36 months.

A number of anatomical and physiological changes were noted in the aged cochleas of the quiet-reared animals. Although quiet-reared animals showed very little if any loss of inner hair cells, outer hair cell loss was quite common, and most extensive in the apex of the cochlea (see Schmiedt & Schulte, 1992, for a review). Hellstrom and Schmiedt (1990) found no significant changes in the cochlear microphonic (CM) potential in aged, quiet-reared gerbils. Because the CM potential is thought to be related to membrane movement, this suggests that the mechanical properties of the basilar membrane are relatively unaffected by aging in spite of the outer hair cell loss which might also be expected to affect basilar membrane mechanics and the CM.

Schulte and Schmiedt (1992) assessed stria function in aged gerbils by immunostaining for the enzyme Na,K-ATPase, which is known to play a prominent role in generating the endocochlear potential (Thalmann, Marcus, & Thalmann, 1981; Marcus, 1986; Salt, Melichar, & Thalmann, 1987). Cochleas from older animals showed an extensive loss of immunostaining for Na,K-ATPase in the apical turn that tended to extend into the middle turn of the ears of many of the older animals.

Schulte and Schmiedt (1992) also found a strong correlation between the endocochlear potential and the volume of immunostained stria vascularis. Although they were unable to directly correlate threshold shift with either stria atrophy or with endocochlear potential (EP), other investigators have found a correspondence between acutely depressed EPs and decreased compound action potentials (e.g., Konishi et al., 1961; Sewell, 1984). However, they did note that the degeneration of stria functioning must be extensive in order to produce a significant reduction in EP.

Gratton and Schulte (1995) showed that capillary loss and stria atrophy were associated in the cochleas of quiet-reared gerbils. This suggested that loss of stria function, and its associated decrease in the EP, may result from changes in the vascularization of the lateral wall of the cochlea. According to their results capillary degeneration begins at an early age in the low-frequency region, and becomes quite extensive in older animals. Gratton and Schulte also noted that loss of vascularization precedes atrophy of the stria cell layers. They interpret their data as suggesting that over time there is a narrowing of the capillary lumen which is not accompanied by a loss of stria cells. However, progressive shrinkage in the capillary diameter eventually restricts the blood supply, leading to capillary loss, stria degeneration, and eventual reduction in the endocochlear potential. There are large individual differences with respect to the rate at which such degeneration takes place.

These studies indicate that the microanatomy of the cochlea changes with age even in the absence of environmental stressors. Moreover, these changes are associated with, and perhaps cause, changes in the endocochlear potential. Given these intracochlear changes, it becomes important to determine how these changes affect primary auditory neurons.

Activity in the 8th auditory nerve can be assessed either through individual fibre recordings or by recording the compound action potential (CAP) generated by the whole nerve. Hellstrom and Schmiedt (1990) measured compound action potentials in aged, quiet-reared gerbils using round-window electrodes. On average, threshold CAPs were elevated for aged animals; however, a large amount of variability was observed across the aged animals, with some having thresholds close to those of the young animals while others experienced severe losses. Hellstrom and Schmiedt (1990) also measured the amplitude of



the CAP as a function of stimulus intensity for young and aged animals. The slope of the function relating CAP to stimulus intensity (dB SPL) was much lower in the older animals as was the maximum CAP achieved by the older animals. Hellstrom and Schmiedt (1990) noted that it is unlikely that the decrease in maximum CAP is caused by (a) a decrease in the amplitude of individual spikes, or (b) a difference in the spread of excitation along the basilar membrane between young and aged animals. They noted that there is some evidence supporting the notion that the decrease is due to a loss of spiral ganglion cells and/or a loss in synchrony in nerve firing. A decrease in the number of functioning ganglion cells would mean that the CAP was summed over fewer units. Because the maximum CAP will be higher if the units are firing in synchrony, an increase in the variability of the latency of the first action potential in the individual fibres will cause the peak amplitude of the CAP to be less. The question of loss of synchrony will be discussed later.

Schmiedt, Mills, and Adams (1990) measured tuning curves and two-tone suppression in young and quiet-reared aged animals. Thresholds at the characteristic frequency (CF) of the tuning curves for older animals were elevated relative to younger animals. However, the widths of the tuning curves for young and old animals were nearly equivalent at high SPLs. Figure 2 presents idealised versions of the types of tuning curves observed in young and aged animals. (The tuning curve for the older animal is depicted as having a higher frequency than that of the younger animal for purposes of clarity. No systematic age

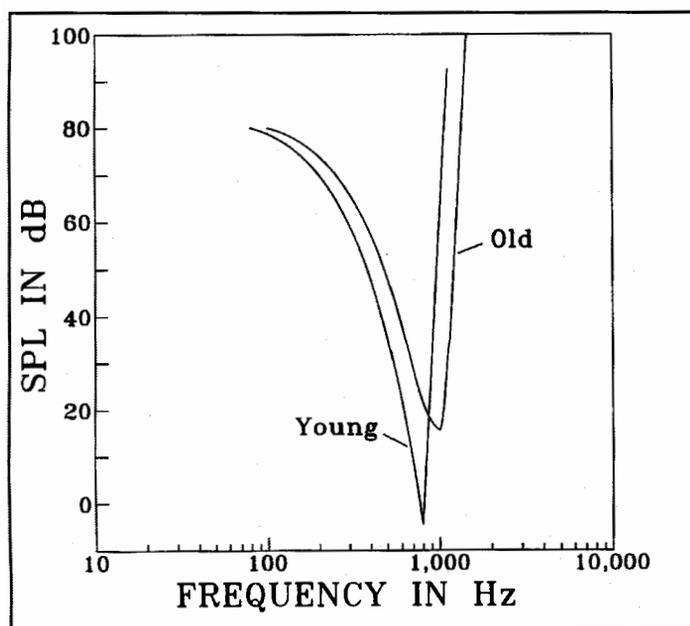
differences were observed with respect to the proportion of neurons tuned to various frequencies.) Clearly, the frequency selectivity of the unit from the older animal is reduced for pure tones near its CF threshold relative to the young animal. For example, consider the response of each hypothetical animal to pure tones presented within 10 dB of each animal's CF threshold. The younger animal would respond to pure tones between 722 and 823 Hz whereas the older animal would respond over a much larger frequency range (between 739 and 1085). Hence, the tuning of individual animals for low-intensity stimulation is reduced with age.

Schmiedt et al. (1990) also measured two-tone suppression in individual units. Two-tone suppression was found in both young and old animals, suggesting that the nonlinear processes that are responsible for two-tone suppression are relatively unaffected by aging.

Boettcher, Mills, and Norton (1993) have also measured auditory brainstem responses (ABRs) in quiet-reared aged gerbils. Consistent with the results found for CAPs, the magnitude of the ABR is significantly reduced in older animals as is the slope of the function relating the amplitude of the ABR to stimulus intensity. Boettcher, Mills, Norton, and Schmiedt (1993) found that ABR latencies for aged animals with normal (relative to young) ABR thresholds were comparable to those for young animals over the low to mid frequency range, but were actually shorter at the high frequencies. Animals with elevated ABR thresholds, however, had longer latencies at all frequencies.

We have seen that the major changes in cochlear function with age include, but are not necessarily limited to: (a) loss of hair cells, (b) decreased vascularization of the stria vascularis, and (c) reduction of the endocochlear potential but not necessarily the cochlear microphonic. At the level of 8th auditory nerve activity, the major changes with age are: (a) an elevation in the thresholds of individual units at or near their CF, (b) a loss of tuning near the thresholds of individual units, (c) a threshold elevation in the compound action potential, (d) an attenuation of the growth of the CAP with stimulus intensity, and (e) a decrease in the maximum CAP. At the level of the brainstem we find: (a) an elevation in ABR thresholds, (b) a reduction in the slope of the function relating ABR amplitude to stimulus intensity, and (c) an increase in the latency of the ABR in those aged animals showing an ABR threshold elevation. As Boettcher, Mills, and Norton (1993) and Boettcher, Mills, Norton, and Schmiedt (1993) point out, the ABR results are mostly consistent with the age-related changes that are occurring in behaviour of the 8th auditory nerve (i.e., an increase in CAP threshold and a reduction in CAP amplitude and slope should produce equivalent effects in the ABR). The changes in CAP activity may be attributed to a loss of ganglion cells or to a loss of neural synchrony.

Figure 2. Hypothetical tuning curves for young and old gerbils.



Four of these changes have potentially direct consequences for age-related changes in hearing. The first and most obvious is that a significant threshold elevation would produce a hearing loss. Second, if, as suggested by Hellstrom and Schmiedt (1990), there is a loss of synchrony in neural firing, we would expect that any higher order processes strongly dependent upon neural synchrony (such as frequency discrimination, temporal discrimination, localisation, and binaural unmasking) might be adversely affected. Third, we might expect that a reduction of the slope of the function relating compound action potential to intensity would lead to a loss in intensity discrimination (e.g., Hellman & Hellman, 1990; Nizami & Schneider, 1997). Finally, if the width of the tuning curve is increased, we might expect to find a corresponding increase in the width of the behaviourally-measured auditory filter. We will now examine the extent to which age-related changes in psychophysical measures are consistent with the pattern of age-related changes in cochlear anatomy and function.

Behavioural Assessment of Age-related Changes in Hearing

Age-related changes in the anatomy, mechanics, and physiology of the auditory system ultimately will affect an individual's ability to process sounds. If the aging system can no longer respond to soft tones, if it can no longer discriminate small changes in frequency or intensity, if it can no longer effectively filter out background noises, or precisely locate a target sound, then the ability of the individual to function effectively in everyday situations will be compromised. Therefore it is important to determine what these limits are and how they change with age.

The loss of pure-tone sensitivity with age is one of the most extensively documented age-related changes in hearing. Willott (1991) has reviewed a number of studies (both cross-sectional and longitudinal) of hearing loss with age and has constructed a profile for the average individual. According to this profile there is little or no loss of sensitivity (thresholds within 5 dB of optimal) for frequencies below 1 kHz before age 50. After age 50, loss of sensitivity to frequencies < 1 kHz begins to appear and by age 70, sensitivity may be reduced by as much as 15 dB in this frequency range. Loss of sensitivity occurs much earlier and is more severe at the higher frequencies. By the 5th decade, hearing loss at high frequencies may be as much as 15-20 dB for frequencies between 3 and 8 kHz. By age 70 this rises to about 30 dB at 3-4 kHz and 45 dB or more at 6-8 kHz.

Because a number of studies have found reduced discriminability and other auditory impairments in individuals with hearing loss, we would expect that elderly individuals in the later stages of presbycusis would experience a loss of accuracy in localising and discriminating among sounds and become more

susceptible to the effects of maskers. A more interesting question, therefore, is whether there is a loss in discriminability, and an increased susceptibility to maskers in elderly individuals whose hearing is in the normal range. In other words, are there aging effects in hearing that are independent of hearing loss?

Frequency discrimination. Konig (1957) found that frequency discrimination decreased linearly between 25 and 55 years of age before becoming markedly worse at older ages. An interesting result in this study was that the worsening performance beyond age 55 occurred for both low and high frequencies. Increased difference limens at the high frequencies could be attributed to sensorineural hearing loss. However, older subjects whose audiometric thresholds were slightly elevated in the low frequency region (10-20 dB from 125-500 Hz) showed over a five-fold increase in the difference limen at 125 Hz. Because this rather large change in the difference limen was associated with such a small change in audibility at this frequency, Konig's data suggest that the larger frequency difference limens found in the elderly can occur in the absence of any significant hearing loss. Abel, Krever, and Alberti (1990) found clear indications of increased frequency difference limens at both 500 and 4000 Hz for elderly listeners (40-57 years old) with good hearing (HLs \leq 20 dB at 4 kHz, \leq 15 dB at lower frequencies). More recently, Moore and Peters (1992) reported that some older listeners with normal hearing and near-normal auditory filters had very large frequency difference limens at low frequencies. Thus, these studies suggest that the major loss in frequency discrimination with age is occurring in the low-frequency region even though loss of hearing sensitivity occurs primarily at the high frequencies.

Why is the loss in frequency resolution more severe at the low as opposed to the high frequencies? First of all, it should be noted that frequency discrimination in young subjects at low frequencies ($\Delta f = 1$ to 2 Hz) is much better than at high frequencies where Δf can vary between 10 and 50 Hz. The excellent resolution found at these low frequencies is unlikely to result from the stimulation of two different populations of receptors due to the shift of the locus of maximal vibration along the basilar membrane; rather, it is most likely based on a discrimination of differences in interspike times. At low frequencies, neural impulses are phase locked to the stimulus. Therefore the minimal interspike time for a 100 Hz pure tone is 10 msec as opposed to 9.8 msec for a 102 Hz tone. A high degree of precision in this phase lock, then, would permit a frequency discrimination based on interspike time. In aged ears, however, there is some indication that there is a loss of synchrony. Such a loss of synchrony might be expected to have a large effect on low-frequency difference limens. Because the degree of phase locking decreases with increases in frequency, a loss of synchrony should not have a dramatic effect on high-frequency difference limens.



Thus, the effects of age on frequency discrimination are consistent with a loss of synchrony in the aged ear.

Intensity discrimination. Although the effect of hearing loss on intensity discrimination has become a topic of renewed interest in recent years (e.g., Buus, Florentine, & Zwicker, 1995; Florentine et al., 1993; Schroder, Viemeister, & Nelson, 1994), very little is known about intensity discrimination in elderly subjects with good hearing. What little evidence there is, however, suggests higher intensity difference thresholds in elderly subjects. Florentine et al. found elevated intensity increment thresholds in two older subjects whose hearing was in the normal range. Moreover, because the incidence and severity of sensorineural hearing loss increases with age, it is clear that in a random sample of elderly listeners, there will be many listeners who will have poor intensity resolution.

Frequency selectivity. Frequency selectivity refers to the ability of the auditory system to differentiate the spectral components of a complex sound. For example if two pure tones, widely separated in frequency, are played simultaneously, the listener hears each tone separately. The ability of the auditory system to decompose a complex sound into its component frequencies is, of course, limited and may change with age.

Baer and Moore (1993) showed that a loss of frequency resolution can lead to difficulties in hearing speech in noise. They simulated a loss of frequency resolution in young normal hearing subjects by smearing the spectrum of a speech signal while preserving its temporal characteristics. The intelligibility of speech in quiet was hardly affected when the spectrum was smeared to approximate the loss of resolution found in a hearing impaired ear. However, when the same subjects were tested in noise with the smeared-spectrum speech, speech intelligibility was adversely affected. Thus a loss in frequency selectivity with age could account, in part, for the difficulties experienced by elderly subjects in noisy situations.

The decomposition of an auditory signal into its component frequencies may be likened to passing the incoming sound through a bank of independent and overlapping bandpass filters (Fletcher, 1940). In this model the ability of the system to resolve two different frequencies would be limited by the widths or bandpasses of these filters. Patterson, Nimmo-Smith, Weber, and Milroy (1982) measured auditory filter widths at 500, 2000, and 4000 Hz in elderly listeners who were in the early stages of presbycusis. Patterson et al. found that the bandwidth of the auditory filter increased with age. Moreover, the filter's efficiency decreased with age in the sense that the signal-to-noise ratio required for signal detection within the filter increased with age. Glasberg, Moore, Patterson, and Nimmo-Smith (1984), in determining how the shape of the auditory filter changed with age, noted that bandwidth increased and efficiency decreased with age. It is interesting to note that this increase in bandwidth

was mostly due to a broadening of the low-frequency side of the filter.

Because the elderly subjects in the preceding studies were in the early stages of presbycusis, some or all of the widening of the auditory filter could have been due to the hearing loss accompanying the elevated audiograms. Sommers and Humes (1993) found that elderly listeners with normal hearing had auditory filters that were nearly identical to those of young subjects with normal hearing. On the other hand, older listeners with hearing losses had broader auditory filters. Interestingly, when young normal-hearing subjects were tested with a masking noise that raised their audiometric thresholds to the level typical of the older hearing-impaired subjects, the measured auditory filter width in these young subjects were nearly identical to those found in the hearing-impaired elderly. Recall that Schmiedt et al. (1990) found that the tuning curves for aged gerbils were characterised by elevated thresholds at their CF and were somewhat broader near the CF threshold than the tuning curves for younger gerbils (see Figure 2). If the tuning curves for aged humans were of the same relative shape, we would expect an increase in threshold with age and a broadening of the auditory filter when young and old are tested at the same SPL level, which is exactly what Sommers and Humes (1993) found. In this regard it is also interesting to note that the data of Peters and Moore (1992a, b) suggest that the apparent effects of age upon frequency selectivity might be mediated by hearing loss. The available data, then, suggest that the widening of the auditory filter with aging is strongly correlated with hearing loss.

Simultaneous masking. The ability of a listener to detect and process a signal in background noise is likely to be important for speech understanding in everyday situations where there is often considerable background noise. Miller (1981) measured the ability of older subjects to detect pure tones in a broadband masker. Elderly listeners whose absolute thresholds were normal at 483 and 2954 Hz also had normal thresholds for the detection of these two tones in a broadband masker. Pichora-Fuller and Schneider (1991) determined diotic thresholds for pure tones masked by a broadband noise in elderly subjects who were in the early stages of presbycusis. There were no significant differences in masked thresholds between the elderly group and the young normal group for frequencies ranging from 250 to 909 Hz. On the other hand, masked pure tone thresholds are elevated in elderly subjects with hearing losses (Margolis & Goldberg, 1980). The available results suggest that when absolute thresholds are normal, the ability to detect a signal in broadband noise is unaffected as is the width of the auditory filter.

Pure tone signals can also be masked by a narrowband noise. When the pure tone signals are outside the frequency limits of the masker noise, the elevation in threshold produced is referred to as the spread of masking. Studies have indicated that thresh-

olds at frequencies outside of the noise band are higher in presbycusis listeners, that is, the spread of masking is greater in presbycusis listeners (e.g., Jerger, Tillman, & Peterson, 1960). However, Klein, Mills, and Adkins (1990) found no difference in the spread of masking with age, provided that the elderly subjects had normal hearing. Again, masked thresholds appear to be unaffected by age unless there is a concomitant hearing loss.

Forward and backward masking. A speech sound to be detected and identified is typically preceded and followed by other speech sounds. The detection and identification of this speech sound could be masked by the preceding and subsequent sounds. An increase in the degree of either forward or backward masking with age would therefore have a deleterious effect on speech understanding. Nelson and Turner (1980) have shown that the time course for recovery from forward masking is longer in hearing-impaired individuals. Thus, elderly individuals who are experiencing hearing losses are, no doubt, more susceptible to forward masking effects. However, because of a lack of studies of the effects of forward masking on elderly listeners with good audiometric thresholds, it is not known whether the time course of forward masking changes with age per se or whether it is mediated by hearing loss.

Moore (1989) argues that a backward masker has an uncertain effect on the threshold of a preceding target. He notes that "the amount of backward masking obtained depends strongly on how much practice the subjects have received, and experiments in our laboratory suggest that highly practised subjects often show little or no backward masking" (p. 119). However, Turner, Zeng, Relkin, and Horwitz (1992) have shown that a backward masker, but not a forward masker, can interfere with frequency discrimination. They interpreted their results as indicating that the masker interfered with the phase locking mechanism used for low frequency discrimination. Raz, Millman, and Moberg (1990) examined the effects of backward masking on frequency discrimination in both young and old listeners. When the masker was acoustically dissimilar from the target, older adults were more susceptible to the effects of the masker.

Older adults with hearing losses are likely to be more susceptible to the effects of non-simultaneous maskers. However, without further studies it is not possible to determine whether these effects are mediated through hearing loss.

Monaural temporal processing. A recent study by Shannon, Zeng, Kamath, Wygonski, and Ekelid (1995) illustrates the importance of temporal information in speech perception. In one of their conditions Shannon et al. divided the speech signal into three spectral regions (0-500 Hz, 500-1500 Hz, and 1500-4000 Hz) and determined the amplitude envelope of the filtered speech in each region. The amplitude envelope of the speech in the low-frequency spectral region was then used to modulate a bandlimited noise (0-500 Hz); the amplitude envelope of the

speech in the middle-frequency region was used to modulate a bandpassed noise (500-1500 Hz), and the amplitude envelope of the speech from the high-frequency region was used to modulate a high-frequency bandpass noise (1500-4000 Hz). These three amplitude-modulate noises were then added together to produce a signal that retained only the temporal properties of speech in these three broad frequency regions. Surprisingly, speech recognition for sentences processed in this way exceeded 90%. Clearly, a large amount of information in the speech signal is conveyed by the temporal pattern of the speech envelope.

Given the importance of temporal information in speech recognition, any loss of temporal processing abilities with age is likely to affect speech understanding. Psychophysically, the temporal resolving power of the auditory system is typically measured in four ways. First, one can lengthen a gap in a continuous tone or noise until the listener can just detect its presence. Second, one can vary the degree of amplitude modulation of a tone or noise to determine the modulation depth that can just be detected. Third, one can determine the minimal change in the duration of a tone or a gap that can just be detected. Fourth, the time interval between two or more tones differing in frequency can be varied to determine the minimum intertone time that will permit the listener to correctly perceive the temporal ordering of the tones.

With respect to gap detection a number of studies (Buus & Florentine, 1985; Fitzgibbons & Gordon-Salant, 1987; Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Glasberg, Moore, & Bacon, 1987; Irwin, Hinchcliff, & Kemp, 1981; Irwin & McAuley 1987; Long & Cullen, 1988; Moore & Glasberg, 1988; Moore, Glasberg, McPherson, & Black, 1989; Tyler, Summerfield, Wood, & Fernandes, 1982) have reported that hearing-impaired listeners have larger gap detection thresholds. Because many of these impaired listeners are relatively old, it is important to determine whether temporal resolution covaries directly with age, or is mediated by hearing loss. Moore, Peters, and Glasberg (1992) determined the minimal gap that could be detected in a long-duration tonal signal for young normals, an elderly group with good hearing, and an elderly group with hearing loss. A low-level notched noise was used to mask the spectral splatter produced by the introduction of the gap. The first finding of interest was that gap detection thresholds in the elderly groups did not appear to be related to hearing loss. Moreover, the average gap detection thresholds of the older individuals were larger than those of the young control group. However, Moore et al. attributed this effect to the inclusion in the elderly group of some individuals who had rather large gap-detection thresholds.

Schneider, Pichora-Fuller, Kowalchuk, and Lamb (1994) had young and old subjects discriminate a gap between two Gaussian modulated 2 kHz tone pips and a short, 2-kHz continuous tone



of the same total energy. Gap detection thresholds in the older group were, on average, twice as large as in the younger group. Moreover, gap detection thresholds appeared to be independent of the degree of hearing loss in the older group, a result later confirmed by Schneider, Speranza, and Pichora-Fuller (1994). In summary, the studies on gap detection in the elderly suggest: (a) that gap detection is independent of hearing loss in the elderly, and (b) that gap detection thresholds increase with age.

Because amplitude modulation of a white noise does not change its long-term power spectrum, the detection of such modulation is presumed to reflect sensitivity to temporal changes in the amplitude envelope of the noise. As the Shannon et al. (1995) study indicates, a great deal of speech information is apparently conveyed by the amplitude envelope of the speech signal. Bacon and Viemeister (1985) determined amplitude modulation thresholds (the just detectable modulation depth) for several frequencies of modulation in normal and hearing impaired listeners. Modulation thresholds were independent of frequency for frequencies up to 16 Hz. For modulation frequencies higher than 16 Hz, the depth of modulation required for threshold increased with increasing frequency. Beyond 1 kHz, no modulation could be detected. Hearing impaired listeners were, in general, less sensitive to amplitude modulation and, unlike normal listeners, their amplitude modulation thresholds were dependent on the level of white noise. Bacon and Gleitman (1992) determined modulation detection thresholds in normal and in hearing impaired subjects with a flat hearing loss. Seven of the eight hearing-impaired subjects had amplitude modulation thresholds similar to those of normal hearing subjects. Thus, there is some evidence that hearing impairment can affect this measure of temporal resolution. More work is needed in this area to determine if the normal hearing elderly are impaired with respect to amplitude modulation.

In addition to detecting gaps and/or amplitude modulations in the auditory stream, a listener processing speech often has to discriminate among temporal intervals. Abel et al. (1990) studied the difference limen for changes in stimulus duration at two reference durations (20 and 200 ms) in young and old listeners. Duration discrimination was poorer in older listeners and appeared to be unrelated to hearing loss. Fitzgibbons and Gordon-Salant (1994) measured duration discrimination for tone bursts and for silent intervals between tone bursts for a reference duration of 250 ms. Four groups were tested: young, normal hearing; young, hearing impaired; old, normal hearing; and old, hearing impaired. Although hearing loss had no effect on duration discrimination, older listeners (both normal and hearing impaired) had higher thresholds than younger listeners (normal and hearing impaired). These two studies suggest that there is an age-related deficit in duration discrimination that is independent of hearing loss.

A listener is not required to integrate information across different regions of the basilar membrane (different auditory filters or critical bands) in order to: (a) detect a gap in a simple stimulus, (b) detect the presence of amplitude modulation in a white noise, or (c) discriminate changes in the duration of stimuli. However, the ability to correctly order the appearance of two sounds stimulating different regions of the basilar membrane is likely to be important for processing speech stimuli. Trainor and Trehub (1989) studied the ability of young and older listeners to correctly order tones differing in frequency in several different conditions. Some tasks only required that the listener discriminate between two different orderings while other tasks required that they identify the order in which the tones appeared. Older adults were less accurate in these tasks than younger adults. Moreover, performance did not correlate with hearing loss. Temporal ordering deficits in elderly listeners have also been reported by Humes and Christopherson (1991) and Neils, Newman, Hill, and Weiler (1991).

This brief survey indicates fairly clearly that there is a loss of temporal resolving power in the elderly that is not necessarily related to hearing loss.

Binaural processes. In everyday listening situations, the sound waves impinging upon the left and right eardrums often differ substantially from one another because the direct sound emitted by a source may take longer to reach one ear than the other and be differentially attenuated by the head, and because the indirect sounds (reflections off of objects or walls) have been differentially delayed and attenuated because they have taken different paths and encountered different reflecting and absorbing surfaces. The ability of the listener to use this binaural information is amply demonstrated by a consideration of the so-called "cocktail party effect" when the relative effectiveness of binaural and monaural tape recordings of a large, noisy party in a reverberant room are compared. The binaural signals are recorded from microphones positioned in the listener's ears. In the binaural presentation, the listener's perception is reasonably close to the original conditions in that sound sources appear to have specifiable and different locations, and the listener is able to concentrate on one source to the exclusion of others. In the monaural presentation, however, all sound sources appear to originate at the stimulated ear, and the listener finds it much more difficult to concentrate on a single source. Clearly, a loss of binaural information will have a deleterious effect on speech understanding in a noisy situation. Age-related changes in binaural processing therefore might be expected to affect both sound localisation and the ability to focus in on, or unmask, a signal in noise.

Very little is known about sound localisation in the elderly other than that the ability to localise sounds is affected by hearing loss. Noble, Byrne, and LePage (1994) compared 87 hear-

ing-impaired individuals (mean age 66 years) to six young controls. Subjects localised bursts of pink noise in an anechoic chamber by verbally identifying the loudspeaker producing the sound (the loudspeakers were numbered). Sound localisation was poorer in the hearing-impaired group (who were also older) relative to the young normal controls with the degree and kind of impairment dependent on the type and severity of hearing loss. However, Noble et al. noted that variation in the ability to localise sounds in the elderly group was only partly explained by the nature and degree of hearing loss. Therefore, we might expect that normal-hearing elderly might be impaired with respect to sound localisation.

Binaural unmasking refers to the ability of the binaural system to use interaural cues to unmask sounds. Young adult listeners may be able to perform better in noisy situations because they are able to make more effective use of interaural cues than older listeners. For this reason it becomes important to determine whether or not aging affects binaural unmasking ability.

Laboratory experiments have shown that the detectability of a monaural signal in an ipsilateral monaural masker (S_mN_m) can be enhanced by simultaneously presenting the identical masking noise but no signal to the other ear (S_mN_0). This shows that the intact auditory system is capable of comparing binaural inputs in such a way that the masking effects of a noise in one ear are partially cancelled, or 'unmasked', by the presence of the identical noise in the opposite ear. The difference in threshold between these two conditions ($S_mN_m - S_mN_0$) is called the masking-level difference (MLD).

In addition to the comparison between S_mN_m and S_mN_0 , several other methods of measuring the MLD have been employed (for a review, see Durlach & Colburn, 1978). In each method, the difference between a baseline and a comparison condition is calculated. In the baseline condition, interaural relationships are identical for both signal and masker. Three common baselines are S_mN_m , S_0N_0 (diotic signal and diotic noise), and $S_\pi N_\pi$ (both signal and noise are 180° interaurally out-of-phase, but are homophasic). In the comparison (dichotic) condition, interaural relationships differ for signal and masker. The most commonly employed dichotic condition is $S_\pi N_0$ in which the noise is diotic but the signal in one ear is 180° out-of-phase relative to the signal in the other ear. In addition to $S_\pi N_0$, MLDs have been obtained under dichotic conditions in which: (a) the signal is diotic with the noise 180° out-of-phase (S_0N_π), (b) the signal is diotic with an interaural delay of τ seconds in the noise (S_0N_τ), and (c) both the signal and noise are 180° out-of-phase with an interaural delay of τ seconds in the noise ($S_\pi N_{\pi\tau}$).

Pichora-Fuller and Schneider (1991) determined masking level differences under four dichotic conditions for young normal-hearing listeners and for old listeners in the early stages of

presbycusis. Young and old listeners had equivalent thresholds for pure tones in the S_0N_0 diotic condition. However, the size of the MLD was significantly larger for younger listeners than older listeners with the extent of the difference being dependent on condition. The pattern of results in their paper suggested that the deficit experienced by older subjects might be due to a loss of synchrony in neural firing. Because binaural processing is acutely sensitive to interaural time differences, any loss of temporal resolution in the nervous system would be expected to reduce the size of the MLD (Durlach, 1972).

In a second study, Pichora-Fuller and Schneider (1992) varied the interaural delay in the masker between 0 and 5 msec. The function relating the size of the MLD to delay differed significantly between young and old subjects. Moreover, this difference in pattern was completely accounted for by assuming that temporal jitter is larger in older subjects at short interaural delays, but is nearly equivalent at long interaural delays. The two studies taken together suggest that there is a greater degree of asynchrony in an older listener's auditory system, and that this loss of synchrony significantly reduces the ability of elderly listeners to use interaural differences to unmask an auditory target.

A later study by Grose, Poth, and Peters (1994) also found that even though elderly listeners in the early stages of presbycusis had lower dichotic ($S_\pi N_0$) thresholds than a comparison group of young normal listeners, the two groups did not differ in diotic threshold (S_0N_0). Because diotic thresholds were comparable for both young and old listeners in both Grose et al. and Pichora-Fuller and Schneider (1991, 1992), one cannot attribute the elderly's poorer performance in dichotic conditions to a general decline in the ability to extract signals from noise. Rather there appears to be a loss that is specific to the binaural processing of stimuli.

Grose et al. (1994) also conducted a second study on young and elderly listeners in which the targets were spondee words and the masking noise was speech shaped. A comparison of performance in diotic (S_0N_0) and dichotic ($S_\pi N_0$) conditions indicated that there were no differences between the young and elderly for spondee recognition in diotic conditions. However, young listeners were significantly better at recognising words under dichotic listening conditions. Thus, binaural processing differences between young and old can significantly affect speech recognition.

It should be noted that not all studies of masking level differences in the elderly have found a significant age effect. When studies included an old group with audiometric thresholds strictly matched to the thresholds of young subjects (Kelly-Ballweber & Dobie, 1984) or very strict criteria were used for normal hearing (Jerger, Brown, & Smith, 1984; Novak & Anderson, 1982), young subjects performed about 1 dB better than old subjects, but this age effect was not significant.



These MLD studies, taken together, are consistent with the hypothesis that there is an age-related loss in neural synchrony that begins to appear in the early stages of presbycusis. Under dichotic conditions, a high degree of neural synchrony is required if signals are to be unmasked. The same is not true for either monaural or diotic signal detection because internal signal-to-noise ratios in these conditions are relatively unaffected by the amount of temporal jitter (Pichora-Fuller & Schneider, 1992). Therefore, a loss of neural synchrony with age will have a significant effect on dichotic but not diotic thresholds.

General Discussion and Conclusions

How can we characterise the aging auditory system? At the cochlear level there is: (a) hair cell loss (primarily outer), (b) decreased vascularization of the stria vascularis, and (c) a reduction of the endocochlear potential but not the cochlear microphonic. The loss of vascularization and the reduction of the endocochlear potential should result in reduced metabolic support for the electromechanical events leading to the generation of neural impulses. With respect to the primary auditory neurons there is: (a) an elevation in the threshold of individual units at their CF, (b) a loss of tuning near the thresholds of individual units (see Figure 2), (c) a threshold elevation in the CAP, (d) an attenuation of the growth of the CAP with stimulus intensity, and (e) a decrease in the maximum CAP. Some of these changes may reflect the loss of metabolic support and/or hair cell loss that is occurring in the cochlea. For example, hair cell loss may explain the higher CF thresholds for individual neurons. Because the tuning of individual hair cells is largely determined by the biomechanics of the basilar membrane, loss of outer hair cells or decrements in metabolic support may result in reduced tuning near CF threshold.

It should be noted that a loss of synchrony in neural firing (perhaps a consequence of reduced metabolic support) would produce both an attenuation in the growth of the CAP with intensity and a decrease in the maximum CAP. Behaviourally, a loss of synchrony might be expected to affect low-frequency discrimination, temporal discrimination, localisation, and binaural unmasking. Psychophysically, this is almost exactly what happens. The frequency discrimination thresholds of elderly listeners with good audiometric thresholds are substantially higher than those of young adults, especially in the low-frequency region. Gap detection thresholds, gap discrimination thresholds, and duration discrimination thresholds are all elevated in the normal-hearing elderly and are independent of hearing loss. Dichotic thresholds but not diotic thresholds are elevated in the elderly in the very early stages of presbycusis. Finally, sound localisation is poorer in the hearing-impaired elderly. (Because of a lack of research in this area, it is not known whether sound localisation ability is reduced in the normal hearing elderly.)

Thus, both age-related changes in the compound action potentials in the 8th auditory nerve, and behavioural changes in frequency discrimination, temporal processing, and binaural processing are consistent with a loss of neural synchrony. An important area for future research is to determine the locus or loci for this loss in neural synchrony and the age-related changes in anatomy and/or physiology responsible for this loss.

The broadening of the tuning curve near CF threshold in older animals may be responsible for the wider auditory filters that are often found in elderly listeners. Whether this loss of tuning results from age-related changes in the biomechanics of the cochlea remains an interesting question.

These age-related changes in hearing have several implications for the elderly in everyday listening situations. First, a loss of neural synchrony would translate into greater difficulty in locating sound sources in a complex auditory environment and a reduction in the ability to discriminate pitch changes in the low-frequency region. Second, the same loss would reduce the listener's ability to use interaural cues to unmask a sound source. This would make it more difficult for an elderly listener to follow a conversation in a noisy environment. Third, an increase in the size of the auditory filter would make it difficult to filter out undesirable background noise. Fourth, any phonemic discriminations that depend on pitch changes, differences in silent periods, or rapid transitions or modulations of amplitude will be more difficult for elderly listeners, with this difficulty compounded by the presence of background noise. Finally, rapid speech might be expected to be more difficult for older than for younger listeners.

It is important to note that these subtle changes in auditory processing abilities in the elderly might have a cumulative effect in a difficult listening situation. First, because of hearing losses, signals are effectively presented at lower sensation levels for elderly listeners. Thus peripheral filtering of background noise is going to be less effective if the tuning curve or auditory filter is broader near threshold. Second, they will be less able to make use of interaural differences to locate and unmask a signal source. Third, their reduced discriminative capacities will be further strained as speech becomes more rapid and as the level of the background noise is increased. The net result is that even though such listeners may experience little if any difficulty in processing speech in a quiet environment, as the environment becomes noisier and the speech faster, their subtle deficits will accumulate until it becomes very difficult to process speech.

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