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Selected Age-Related Factors of Auditory Processing Among Normal Hearing Listeners

by

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ABSTRACT

Auditory abilities among listeners from the age of 20 to 75 years were obtained from 143 clinically normal hearing (pure tone thresholds <20dB HL from 250 to 8000 Hz) individuals. Five groups of individuals from 20-34 years (mean age = 24.7, N 30), 35-44 years (mean age = 38 years, N = 30), 45-54 years (mean age = 49.27 years, N = 28), 55-64 years (mean age = 60.8 years. N = 25), and 65-75 years (mean age = 70.8 years) were tested. Four measures of auditory processing were: 1) linear frequency glide discrimination centered at 1 kHz and 2.6 kHz in quiet and speech spectrum noise, 2) gap detection in broadband noise, 3) frequency selectivity in forward masking measured at 0.5 kHz and 4.0 kHz with 3 narrowband maskers placed asymmetrically above around the probe, and 4) phonetic discrimination for voicing and place of articulation of stop consonants in both quiet and cafeteria noise. Glides swept upward or downward and converged on the same offset frequency or diverged to varying frequencies. Significant age-related effects were found for the oldest group of listeners on all measures. For the linear glide task, there was no effect for the direction of the glide for any age group. The effect of endpoint frequency was significant with converging glides being more difficult to discriminate than diverging except for the 45-54 year olds. Background noise was significant only for listeners aged 55 and over. At the high frequency region listeners aged 45 and over showed significant differences relative to younger listeners for endpoint frequency and for background noise. For listeners aged 45 and over, gap detection thresholds were significantly larger than for younger listeners. Masked thresholds were not different among the groups at 0.5 kHz, but elderly listeners had shallower low frequency slopes and smaller Q10dB values at 4.0 kHz. VOTs show a significant linear increase with age. Principal components analysis revealed two underlying constructs of spectro-temporal and temporal auditory abilities. Results of this study indicate that auditory abilities do not necessarily change in a linear fashion as a function of age.

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DEDICATION

To R.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

I. Introduction

The human auditory system is capable of resolving changes as small as 1% of a frequency difference or 1 dB in intensity (Wier, Jesteadt, & Green, 1977). Sensitivity to interaural time differences is even more remarkable with time delays as small as a few microseconds being discernable (Viemeister & Plack, 1993). Sensory changes, (specifically a decline in processing) are a ubiquitous characteristic of mature organisms, and the auditory system is not immune from this. Given the remarkable resolving power of the auditory system, it is important to understand how these processes change across the life span.

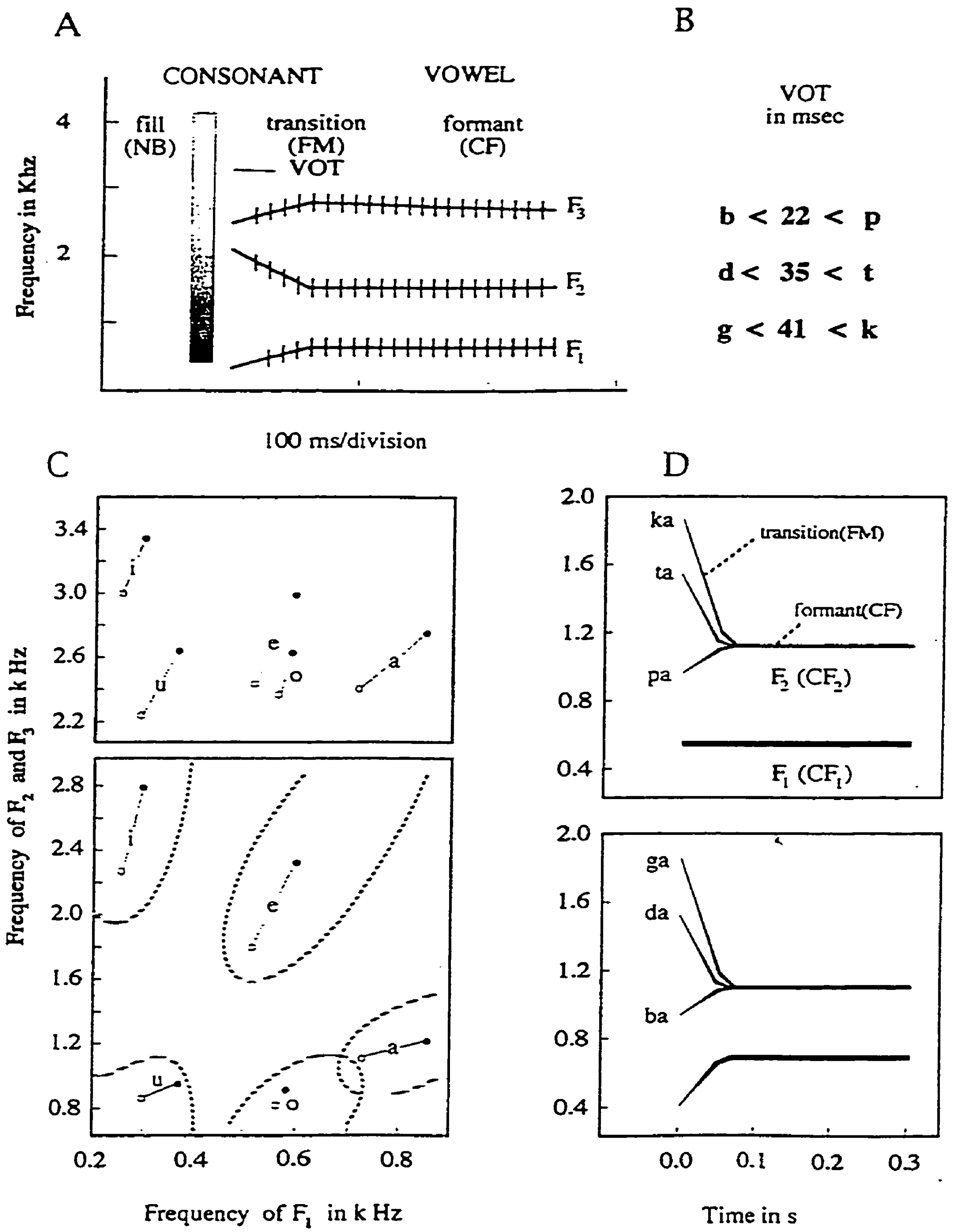
Hearing loss is the third most chronic disability among older adults; superseded only by arthritis and hypertension (Binnie, 1994). The incidence and prevalence of hearing loss both increase with age such that hearing loss (as measured by pure tone audiometry) shows an early onset (in the third to fourth decade of life) and between 25% and 48% of adults aged 75-79 years have some form of audiometrically measured hearing loss (Hull, 1996; Willot, 1991). Central auditory processing disorders among the elderly are reported as high as 10-20% in a stratified random sample in the United States (Cooper & Gates, 1991), but rise to 80-90% in a clinical population (Stach, Spretnjak & Jerger, 1990).

To effectively process information from competing sound sources, the auditory system must, with either binaural and/or monaural processing cues, separate and analyze the individual components of a complex sound. An exemplar of such a complex sound is speech, which is a spectrotemporally modulated signal (i.e., modulations both in a given frequency channel and along the spectral axis) (Chi, Gao, Guyton, Ru & Shamma, 1999) with varying durational components all of which are important for speech intelligibility.

Spectral representations of a speech signal show several distinctive features (Figure 1). First, the fricative consonants /s/ and /sh/ can be identified by bands of high frequency energy concentrated at approximately 2-3 kHz for the former and above 4.4 kHz for the latter. Second, there are dark bands of resonance energy called formants, which are peaks of spectral energy specific to the vocal tract configuration. The lowest is the first formant (F1), the second lowest is the second formant (F2), and so on. These components are critical in the identification of vowels which are identified by combinations of F1, F2, and F3. The perceptual identity of a vowel is modeled as a function of the first two or three steady-state formants of the vowel (Nabelek, 1988). Third, formant transitions are increases or decreases in frequency that occur over short periods of time and are critical to the identification of many consonants.

The stop consonants, /b/, /d/, /g/, /p/, /t/, and /k/ are identified by the formant transitions preceding the vowel (Liberman, 1988). What differentiates the 'voiced' stops /b/, /d/, and /g/ from the 'voiceless' stops /p/, /t/, and /k/ respectively is that though they are produced with the same vocal tract configuration, there is a temporal relationship among the parameters. Specifically, the voice-onset time (VOT), which is the timing between the release of built-up air and the onset of voicing is different (Taylor, 1990). VOT is almost zero milliseconds (ms) for a voiced stop but can be over 30 ms for a voiceless stop (Walsh & Diehl, 1991). Though other information such as burst intensity, or F1 onset are cues for identification, VOT duration is the dominant and decisive phonetic contrast frequency (Walsh & Diehl, 1991).

Figure 1 . Information bearing elements in human speech sounds. (A) schematized sonogram of Noise burst, transition (FM), Constant frequency (CF), and voice onset time (VOT). (B) The phonetic boundaries for distinguishing /b/ from /p/ ; /d/ from /t/, and /g/ from /k/. (C) the relationship between the frequencies of F1, F2, and F3 of five vowels. The average frequencies of males (open circles) are lower than those of female (closed circles) speakers. The areas surrounded by the dashed lines represent formant frequencies for unanimous classification of vowels. (D) Schematized sonograms of how phonetic identification changes as a result of changes in formant transitions of F2. (adapted from Suga, 1997, p. 296, reprinted by permission).


A
B
CONSONANT
VOWEL
fill
(NB)
transition
(FM)
VOT
formant
(CF)
Frequency in Khz
4
2
F3
F2
F1
100 ms/division
VOT
in msec
b < 22 < p
d < 35 < t
g < 41 < k
C
D
Frequency of F2 and F3 in k Hz
Frequency of F1 in k Hz
Time in s
ka
ta
pa
transition(FM)
formant(CF)
F2 (CF2)
F1 (CF1)
ga
da
ba
i
u
e
o
a

An internal analysis for segregation of critical components depends upon the coherence/ incoherence of sound onset, the shared/ unshared spatial location of the sound sources, and differences in harmonic structure and all allow the subsequent organization of sound images into an internal map of the acoustic environment (Bregman, 1990). Aspects of both spectrotemporal and spatial location analyses performed by the auditory system serve the purpose of sound source determination and identification (Yost & Sheft, 1993) and are critical for three fundamental tasks (Evans, 1992).

An initial task is a separation of individual frequency components from a source of several frequency components; a process is termed frequency selectivity and is the ability of the auditory system to resolve the individual components of a sound. The spectral complexity of the sound is the main determinant of its perceived timbre, and in conjunction with temporal cues, is critical for determining the pitch of a signal (Hull, 1996; Slawinski & Fitzgerald, 1998). In speech this corresponds to the perceived laryngeal frequency and is essential information in being able to differentiate between speakers (Greenberg,1988 ; Slawinski, 1994; White & Plack, 1998). A second task is enhancement of spectral and temporal contrasts of the resolved frequency components to compensate for signal-to-noise (S/N) ratios in naturally occurring sounds and to aid in a third task which is to extract behaviorally meaningful cues from the results of the peripheral spectral analysis (Evans, 1992). As far as behaviorally meaningful sounds such as speech are concerned, this includes determining the spacing of the frequency components and their changes over time (Hall, Grose, Buss & Hatch, 1998).

Psychophysical studies have shown age-related deficits in various auditory tasks including: frequency discrimination (He, Dubno & Mills, 1998); intensity discrimination (He, Dubno & Mills, 1999); temporal resolution (Cranford & Stream, 1991; Fitzgibbons & Gordon-Salant, 1998; Snell, 1997; Snell & Rekhi, 1999); frequency selectivity (Cheesman, Hepburn, Armitage & Marshall, 1995; Sommers & Gehr, 1998), localizing a sound (Schneider, Pichora-Fuller, Kowalcuck &Lamb, 1994), understanding speech (Grose, Poth &Peters, 1994; Plomp, 1986; Prosser, Turrini & Arslan, 1991), selective attention, (Barr & Giambra, 1990; Hasher & Zacks, 1988; Murphy, McDowd &Wilcox, 1999); and, discrimination of frequency glides (Elliott, Busse & Bailet, 1985; MacNeil & Slawinski, 1992; 1996) even after the effects of differential hearing loss in the high frequency region are statistically parceled out. Additionally, elderly individuals with 'normal' hearing, (or hearing abilities such that no impairment or difficulty is predicted), demonstrate diminished performance with speech and complex signal perception relative to young adults (Fitzgibbons & Gordon-Salant, 1997).

When hearing disability is assessed by self-report, elderly listeners are more likely than younger listeners to experience problems in everyday auditory tasks. Elderly listeners reported more problems in understanding speech in quiet, noisy, and distorted listening conditions, and there was considerable variation in the age progression of different self-reported hearing problems (Slawinski, Hartel & Kline, 1993). Problems associated with perceiving speech in background noise increased the most with age, followed by problems in the perception of normal speech, temporal 'cues' of speech, distorted speech, and high-pitched sounds. Least changed across age were difficulties associated with telephone communication and detection of environmental sounds (Slawinski, et al., 1993).

A growing body of both empirical and theoretical knowledge in the past decade, has focused mainly on a classification of 'young' versus 'elderly' listeners, and the relevance of how this dichotomous division provides insight into age-related changes is unclear. Auditory changes may be a life-long process or a punctuated acceleration that manifests an impact only later in life. There is very little knowledge concerning how various auditory abilities change across the life span. The purpose of this research was to investigate this specific question. Age-related changes in the perception of complex signals may be a function of alterations in frequency discrimination, frequency selectivity, temporal resolution, intensity discrimination, and/or information processing. All of the above abilities show age-related declines, and can be impacted by anatomic, physiologic, or behavioral abilities. Therefore, this introduction will begin with a brief review of the auditory system followed by the changes noted among the aged, and then a review of selected age-related psychophysical changes will be discussed. Discrimination of linear frequency glides will then be discussed followed by a rationale and outline of the present investigation.

Brief Overview of Anatomy and Physiology

Anatomical changes are noted at all levels of the auditory system (Marshall, 1981). Figure 2 shows the external, middle and inner ear systems. Major central auditory pathways are schematically shown in Figure 3. Sound waves are initially modified by the shape of the pinna and the conditions of the auditory canal. The pinna and the external auditory meatus (ear canal) direct sound waves to the tympanic membrane which serves as the boundary between the external and middle ear (Tonndorf, 1988). The resonant and mechanical properties of the pinna, the ear canal, and the tympanic membrane complement each other in that they enhance the gain of the acoustic signal between 2 kHz and 5 kHz, a region important for speech perception (Tonndorf, 1988).

The middle ear ossiclular chain, (the malleus, the incus, and the stapes) acts as a mechanical transformer and connects the tympanic membrane and the oval window of the inner ear. The ossicles are joined such that oscillations of the eardrum are transmitted down the chain to the footplate of the stapes which is attached to the oval window by the annular ligament. By channeling the energy vibration of the larger tympanic membrane to the smaller area of the oval window, the ossicular chain produces the additional force required to set the fluid of the cochlea in motion.

The cochlea of the inner ear is a coiled fluid-filled structure approximately 3.5 cm long and contains the ganglion cells of the cochlear portion of the VIIIth cranial nerve (Carpenter & Sutton, 1984). Membranes partition the cochlea into the scala vestibuli, the scala tympani, and the scala media (cochlear duct). The basilar membrane (BM) forms the floor of the cochlear duct and is a crucial component in the mechanism that transduces the mechanical energy of the sound waves to chemoelectrical impulses. Fibers in the BM are short and densely packed at the basal end and become longer toward the apical end; that is, the BM is narrow and stiff at the base, and wide and more flacid at the apex (Carpenter & Sutton, 1984). Piston-like motion of the stapes transmits sound energy to the perilymph in the scala vestibuli. This energy transmitted to the perilymph produces travelling waves in the BM that move from the base of the cochlea to the apex.

On the surface of the BM is the Organ of Corti which contains one row of inner hair cells (IHCs) (approximately 3500) and three rows of outer hair cells (OHCs) (approximately 12000) (Ruggero, 1991). IHCs and OHCs are innervated by two types of fibers from the cochlear branch of the VIIIth cranial nerve. Type I fibers innervate a small number of IHCs (2-3) and comprise the majority of cochlear afferents (Ruggero, 1991). The second type, Type II fibers innvervate many OHCs and constitute about 10% of the nerve bundle. Different parts of the BM stimulate specific sets of hair cells and since afferent fibers are maximally sensitive over a limited range of frequencies and intensities a tonotopic representation of frequency is established (Ruggero, 1992). The mapping of frequency onto location on the BM gives rise to the place code of perception, while temporal aspects of the stimulus (e.g., waveform, fine structure, envelope) are preserved in the pattern of activity of auditory nerve fibers (Ruggero, 1992). The dual presence of place and timing cues is pervasive in auditory perception.

Spiral ganglion neurons terminate in the cochlear nucleus (CN) in the cerebellopontine angle of the brainstem. Nerve fibers bifurcate within the nucleus; one branch terminates within the anterior ventral CN; the second branch proceeds to the posterior ventral CN and the dorsal CN (Mountain, 1995). Though the cochlear nuclei contain many cell types distinguished on the basis of appearance, electrophysiologic properties and connections, cochleotopic organization is maintained as apical fibers (low frequencies) are represented ventrolaterally; basal fibers (high frequencies), dorsomedially (Mountain, 1995).

The complex central auditory connections from the CN to auditory cortex in the superior temporal gyrus are schematically illustrated in Figure 3 . The superior olivary complex (SOC) is the first junction in the ascending pathway where neural signals from both ears converge and is the site of the initial computation of information related to binaural cues. Three primary SOC nuclei receive input from the CN: the medial superior olivary complex, the lateral superior olivary complex, and the medial nucleus of the trapezoid body. This is the primary sound localization pathway, but for speech analysis the paths through the intermediate and dorsal striae are more important and these striae bypass the SOC (Brugge, 1991). Fibers from the SOC ascend in the lateral lemnisucs on both sides and terminate in the nuclei of the lateral lemniscus and in the inferior colliculus (IC) (Brugge, 1991). In addition to providing input to the IC, axons within both the medial and lateral SOC synapse with neurons from cranial nerve VII which innervate the stapedius muscle and underlie the stapedius reflex (Mountain, 1995).

At the thalamus, the medial geniculate body (MGB) and the lateral division of the posterior group (Po) are the major nuclei associated with the auditory system. Thalamic nuclei show distinct patterns of tonotopicity and connectivity. The ventral division of the MGB receives input from specific layers of IC neurons and show narrowly tuned, frequency selective units (Clarey, Barone & Imig, 1992).

Auditory radiations from the MGB project to auditory cortex located in the transverse temporal gyrus (Heschl's gyrus) in the superior temporal gyrus (STG). Auditory cortex is a laminar structure that can be segregated into several fields based upon tonotopicity and connectivity patterns. Tonotopoically organized fields include: A1 (primary auditory cortex), AAF (anterior auditory field), PAF (posterior auditory field), and VPAF (ventroposterior auditory field). The temporal plane behind Heschl's gyrus is usually larger in the left hemisphere. Though it has been suggested that this may be due to the linguistic dominance of the left hemisphere, the proportion of individuals with a larger left temporal plane is about 65% which is considerably less than the 90-95% of individuals who show left hemisphere dominance for language (Heimer, 1995).

Various animal studies have advanced the understanding of auditory cortical processing. Spectral content of an acoustic signal is represented in cat auditory cortex by bandpass filters with systematically varying center frequency and bandwidth (Schreiner, Mendelson, Raggio, Brosch & Krueger, 1997). In the ferret, AI neurons show a symmetry axis with cells which are selective to the rate and direction of frequency modulated (FM) tones (Shamma, 1995). Also neurons in AI of chicks, are particularly sensitive to rapid temporal changes in stimulus amplitude such as tone or noise onsets, clicks, and amplitude modulated (AM) signals (Heil, 1997; Heil, Langner & Scheich, 1992). Neurons selective to FM and tuned to certain bandwidths have been found in the lateral belt areas of STG in rhesus monkeys (Rauschecker, Tian & Hauser, 1995).

The primary auditory pathway surfaces in Heschl's gyrus within the temporal lobe and the auditory association areas within the left temporal lobe are actively involved in speech reception (Blumstein, 1997 ; Ojemann, 1994). Brain imaging and neuropsychological studies have shown that specific aspects of music, such as pitch and timbre, are represented predominantly in the right hemisphere along with prosody of speech (Zattore, Evans & Meyer, 1994). By contrast, rhythm and speech-like sounds incorporating short-duration spectral changes (such as formant transitions) show greater left hemisphere activation of the posterior superior temporal gyrus (STG) (Johnstrude, Zatorre, Milner & Evans, 1997). In humans, the superior temporal sulcus which runs the whole of the temporal lobe is not only 'sensitive' to, but also 'selective' to voice sounds (Bellin, Zatorre, Lafaille, Ahad & Pike, 2000).

Greater activity is seen in primary and secondary auditory cortices during counting of target words compared to passive listening of word lists indicating that selective attention modulates both the magnitude and extent of cortical activation and involvement (Grady, van Meter, Maisong, Pietrini, Krasuski & Rauschecker, 1997). Differential cortical activation is seen in the left hemisphere of subjects when listening to their maternal language, and a language they do not understand (Mazoyer et al 1993). When listening to their native language, activity was distributed across the temporal and frontal areas of the left hemisphere. In contrast, when listening to a foreign language, both hemispheres were activated and mostly in the superior temporal gyri (Mazoyer et al 1993). Discrimination of noise bursts activates the primary auditory cortex, whereas discrimination of acoustically matched speech syllables activates secondary auditory cortices bilaterally (Zattore et al 1992).

The efferent pathway includes descending pathways from the auditory cortex to the MGB, the IC, and other brainstem nuclei. The principle link in this pathway is the olivocochlear (OC) bundle which originates from neurons in the principle and accessory SO nuclei. Efferents in OC are hypothesized to be involved in enhancing perception of transient signals in noise (Giraud, Garnier, Micheyl, Lina, Chays & Chery-Croze, 1997).

Figure 2. View of the human external, middle, and inner ear. From Kandel, Schwartz & Jessell, (2000).

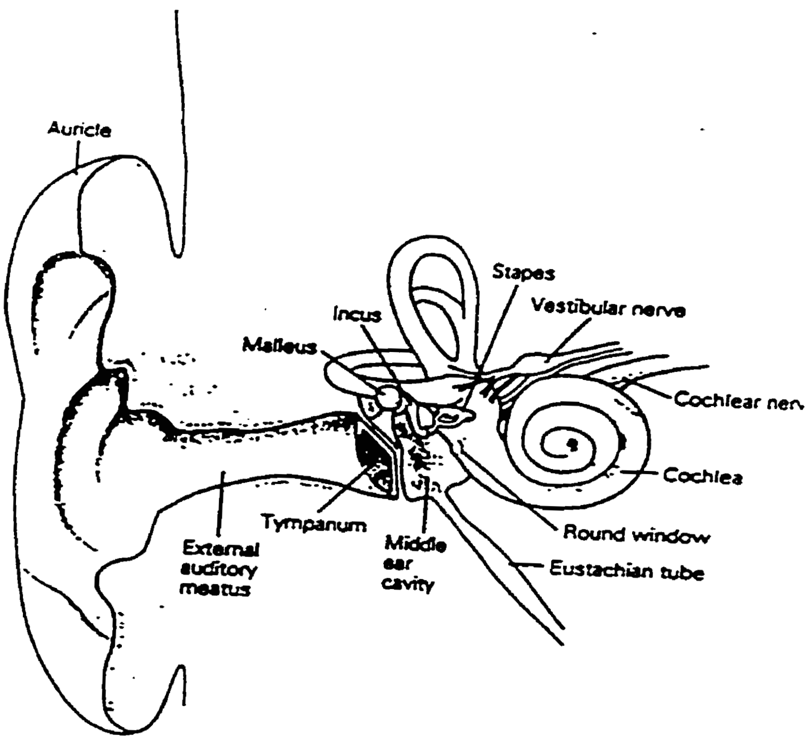
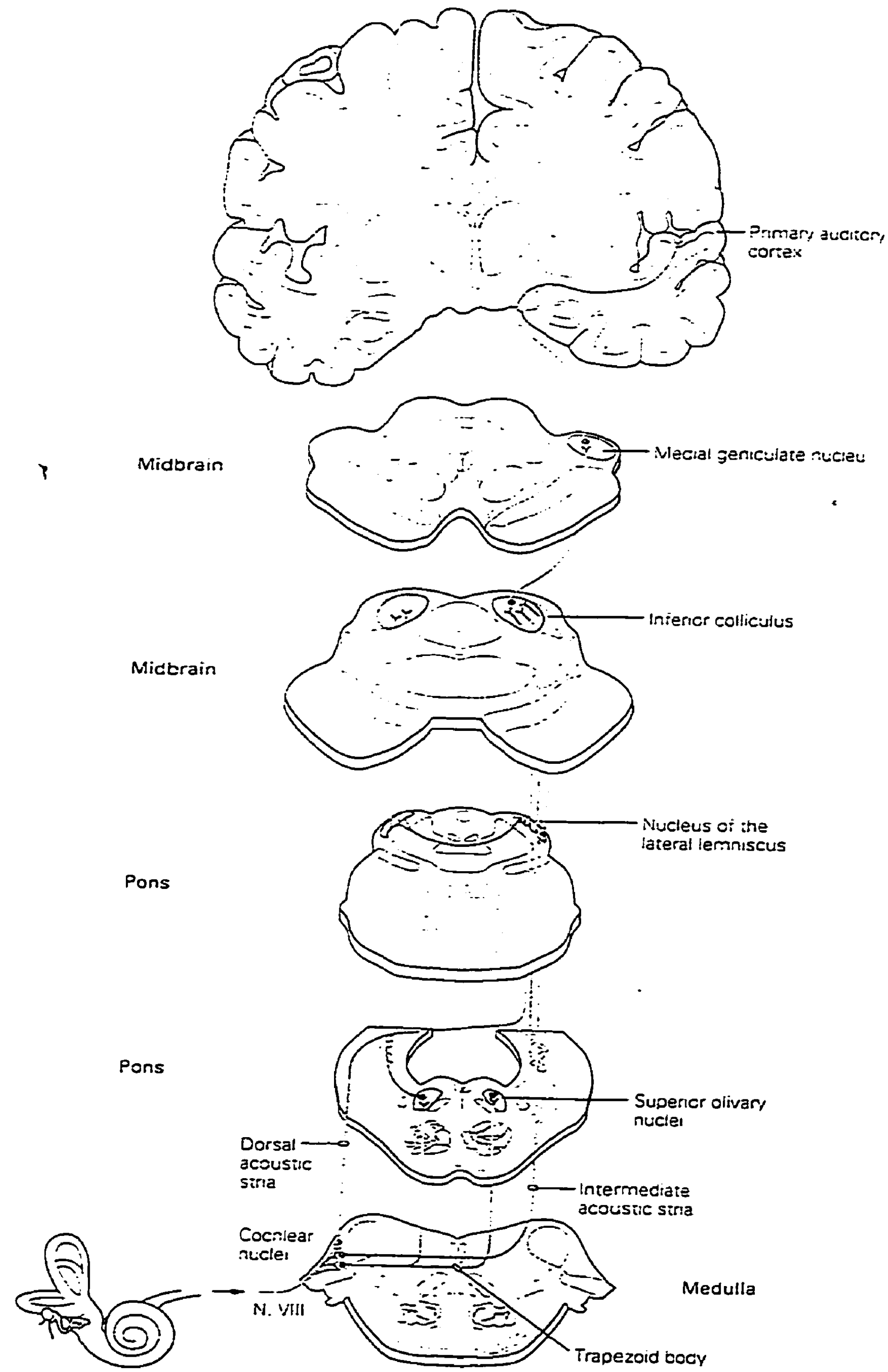


Figure 3. Central auditory pathways. From Kandel, Schwartz & Jessell, (2000).



Changes in Anatomy and Physiology

The cochlea and the spiral ganglion cells are particularly vulnerable to the aging process such that changes are independent of noise exposure and have been noted in animals reared in quiet (Willott, 1991, Willott, 1996). IHCs and OHCs are differentially impacted though. Wright, Davis, Bredberg, Ulehova, and Spencer (1987) found IHC loss with aging was restricted to the cochlear base whereas OHC loss was occurred in both the base and the apex. At the level of the auditory nerve, tuning curves at the center frequencies of individual units show elevated thresholds, and broader selectivity (Schmidt, Mills & Adams, 1990). At the level of the brainstem, Boettcher, Mills, and Norton (1993) found that the magnitude of auditory brainstem responses (ABRs) in quiet reared gerbils was significantly reduced in older animals as was the slope of the function relating the amplitude of the ABR to stimulus intensity. Willott (1996) found that glycinergic tuberculoventral interneurons in the deep layer of DCN which inhibit neurons projecting to other parts of the central auditory system are lost in old mice with severe hearing loss suggesting that these inhibitory neurons are vulnerable to cochlear pathology and/or aging. Ison, Agrawal, Pak and Vaughn (1998) found that temporal acuity as measured by the acoustic startle reflex increased with maturation and then began to decline among middle aged mice. In the IC of middle age mice, increases in spontaneous activity are noted in electrophysiological recordings (Willott, 1996).

In summary, anatomical changes, independent of noise exposure, exist at levels of the aging auditory system from the cochlea to the IC. As noted by Schneider (1997), reductions in cellular units, or changes in the outputs of auditory circuits means that information reaching the central auditory system will be impaired. Probable implications for human auditory perception include monaural processes such as elevated thresholds, reduction in frequency selectivity and temporal resolution, and changes in binaural processing such as localization, and binaural unmasking.

Cortical plasticity in conjunction with the tonotopic organization of the auditory system may have implications for hearing. Tonotopic organization depends upon the existence of anatomic connections from the cochlea to the appropriate tonotopic regions. Neurons in the IC and cortex which normally respond to high frequency sounds shift their responses to lower frequencies after their ability to respond to the high frequencies was ablated in middle aged mice (Willott, 1984; 1986). Indeed it is plausible that some of the changes seen in aging human auditory systems are the result of cortical reorganization, and this plasticity varies at different levels of the central auditory system. Willott (1996) and Willott, Bross, and McFadden (1994) reported that as sensorineural pathology developed in the basal cochlea of aging mice, the degree of plasticity differed in the VCN, IC and cortex. Plasticity was greatest in the cortex, followed by the IC, and then the VCN. In cortex and the IC, neural responses shifted to lower 'best frequencies', while VCN neurons showed elevated thresholds with little plasticity.

Selected Psychophysically Measured Changes

i. Pure tone thresholds

Though several age-related changes of the auditory system have been documented, the most ubiquitious is presbycusis. Presbycusis is the progressive, primarily sensorineural hearing loss that occurs with age and is typically characterized by a decrease in hearing sensitivity predominantly in the high frequency region and increased difficulty in understanding speech particularly in listening conditions such as noise or reverberation (Working Group on Speech Understanding and Aging, 1988).

Hearing loss associated with aging commences as early as the third decade of life (Davis, 1989). Longitudinal studies have shown that the increase in hearing thresholds not only begins early in life but also shows gender differences. Pearson, Morrell, Gordon-Salant, Brant, Klein, and Fozard (1995) reported gender differences in hearing levels, rate of change in hearing level, and that hearing sensitivity declines gradually and progressively with aging, even in a screened population. The rate of hearing loss is more than twice as rapid in men as in women at most frequencies and ages. On average, men have better low frequency thresholds (< 1.0 kHz) up to age 30, at which point hearing decline is noted at all frequencies. Women, relative to men, have better high frequency thresholds (Pearson et al., 1995), and continue to have better high frequency thresholds throughout the life span (Gates, Cooper, Kannel & Miller, 1990; Pearson et al., 1995). These gender differences increase slightly with increasing age, because of differences in the rate and time course of threshold changes for men and women. Some research has not confirmed the existence of gender-related differences in the rate of sensitivity decline (Davis, 1989), but gender differences in pure tone thresholds are not disputed. In general, the decline in auditory thresholds can be approximated as 1 dB per year beyond age 30 (Brant & Fozard, 1990). This loss of sensitivity may be the origin of deficits in other auditory functions such as temporal resolution, frequency selectivity, and a loss of speech understanding (Divenyi & Haupt, 1997).

ii. Temporal Resolution

Temporal resolution or temporal acuity is defined as the ability of the auditory system to respond to rapid changes in the envelope of a sound over time. If the response of the system is sluggish, that is temporal acuity is poor, then the internal representation of the signal will not be a faithful reproduction of the information contained in the signal (Viemeister & Plack, 1993). Processing of temporal information may occur via monaural and / or binaural inputs, and these processes operate on different time scales (a few milliseconds for monaural resolution versus small fractions of milliseconds for binaural resolution). Monaural temporal processing is more involved with tasks such as following a speech signal whereas binaural processing contributes to separating the signal from competing sounds (Viemeister & Plack, 1993). Consequently both processes make unique contributions to tasks such as speech perception.

The importance of temporal resolution to speech intelligibility remains robust in techniques of spectral reduction provided that the low frequency modulations of the signal are maintained (Eisenberg, Shannon, Martinez & Wygonski, 2000; Shannon, Zeng, Wygonski, Kamath & Ekelid, 1995). Rosen (1992) classified the temporal structure of speech into three categories: envelope cues, periodicity cues, and temporal fine-structural cues. Envelope cues are in the range of 2 to 50 Hz and transmit phonetic and prosodic information such as segment duration and rise/fall time. Periodicity cues are in the range of 50 to 500 Hz and convey information about consonant voicing and manner. Temporal fine structure is in the range of 6 to 10 kHz and conveys information about the spectral distribution of energy of the speech signal. Shannon et al (1995) divided the speech signal into three discrete spectral regions (0-500 Hz; 500-1500 Hz; and 1500-4000 Hz) and determined the amplitude envelope of the speech signal in each of the three regions. The amplitude envelope of the three spectral regions was then used to modulate bandlimited noise that corresponded to the spectral region (i.e., the amplitude envelope of the low frequency region was used to modulate a bandlimited noise of 0-500 Hz; the middle frequency region envelope modulated a bandpass noise of 500-1500 Hz and the high frequency envelope modulated a high frequency bandpass noise of 1500 - 4000 Hz). These three amplitude modulated noises were then combined to reproduce a signal that retained only the temporal properties of the original speech signal. Recognition of the signal as speech exceeded 90% despite the loss of spectral fine-structure.

Temporal resolution measured by detecting a gap in signals with identical magnitude spectra such as broadband noise typically show thresholds of 2 - 3 milliseconds (ms) except at very low sound levels where thresholds increase (Green, 1985). The long term magnitude spectrum of a sound is not changed when the signal is played back in time, and discrimination of a time-reversed signal from the original thus reflects sensitivity to the difference in the time pattern of the signal. Thresholds measured this way are also on the order of 2 - 3 ms. (Moore, Glasberg, Plack & Biswas, 1988). Gap detection thresholds, however, are dependent upon the temporal position of the gap within a signal (Eggermont, 1995; Snell & Hu, 1999), and on the bandwidth of the signal more so than the center frequency of the signal (Buus & Florentine, 1985; Glasberg & Moore, 1989). Eggermont (1995) reported that neural coding of gaps was poorer when they occurred close to stimulus onset rather than 500 ms later. Snell and Hu (1999) also reported elevated thresholds for gaps placed early in a signal. Phillips, Taylor, Hall, Carr, and Mossop (1997) reported that gap thresholds increase to about 30 ms from

10 ms as the duration of leading element decreased to about 5 ms. There is also an inverse relationship between the bandwidth of a signal and gap detection; the wider the bandwidth, the smaller the threshold (Buus & Florentine, 1985). Two basic reasons have been postulated for this. One, wider bandwidths may provide a greater amount of information transmitted to the central auditory system (Hall, Grose, Buss & Hatch, 1998). Second, the apical region of the cochlea is responsive to the low frequency end of the spectrum, and gap detection supported by the apical region of the cochlea is relatively poor (Buus & Florentine, 1985; Florentine, Buus &Wei, 1999). It has been proposed that the narrower auditory filters of low center frequencies have poorer temporal resolution (i.e., longer ringing responses), and these longer response times have been implicated in a 'slower decision process' and in partially filling in and obscuring the gap in a signal (particularly with sinusoidal signals) (Shailer & Moore, 1987). However, if the filters are equally sharp, (the same Q10dB), the ringing would be longer for low frequency units. This is because the same Q10dB value indicates that filters will ring for the same number of periods, and since the periods are shorter for high frequency units, the poorer temporal resolution may not be related to the frequency selectivity of the units at all. Also, the rapidity of random fluctuations in the signal increases with the bandwidth of the signal. The consequence of this is that narrowband signals have a greater 'stimulus uncertainty', specifically there are inherent fluctuations in the stimulus envelope which may be confused with an intended gap (Florentine, Buus & Wei, 1999; Shailer & Moore, 1987).

Models of temporal resolution assume that the ability to detect fluctuations in a signal is limited by a smoothing process in the auditory system. This process has often been incorporated within a more complete model of temporal resolution which comprises a band-pass filter, a rectifier and power law nonlinearity, a smoothing device (implemented as a low-pass filter or sliding temporal integrator) and a decision device (Buus & Florentine, 1985; Moore, Glasberg, Plack & Biswas, 1988). The temporal integrator can be fundamentally viewed as a temporal moving average mechanism that converts an oscillating message into a stable auditory output.

Moore et al., (1988) describe the smoothing device as a sliding temporal integrator or temporal window. In this 'temporal window model' it is assumed that detection of a decrement occurs when the output level of the temporal window equals or exceeds a certain criterion level in dB referred to as Δ O. This 'smoothing' most certainly operates on neural activity, but for the most part the models operate on simple transformations of the signal rather than its neural activity.

Viemeister (1979) proposed a model of temporal resolution to account for the detection of sinusoidal amplitude modulation in a broadband noise carrier. This model comprises the following stages: a bandpass 'predetection' device, filter, a half-wave rectifier, a first-order low pass filter, and a decision device based upon the standard deviation of the output of the low-pass filter. A similar model was proposed by Forrest and Green (1987) to account for both gap detection and modulation detection in broadband noise. The primary difference between the two models lies in the decision device, which for Forrest and Green is based upon the maximum and minimum output of the low-pass filter within the observation interval. In this latter model the filter is assumed to have a time constant of 3 ms. This max/min decision device is very similar in concept to the Δ O of the temporal window model.

Changes in Temporal Processing with Age

It can be predicted that age-related changes in the size of the temporal window, the time constant of the filter, or the criterion level will result in reduced temporal resolution. (Moore, Glasberg, Donaldson, McPherson & Plack, 1989). The most common measure of temporal acuity among the aging is gap detection thresholds which do not depend upon any of the parameters or assumptions of the above models (Schneider, 1997). Listeners with hearing loss have larger gap detection thresholds relative to normal hearing listeners (Buus & Florentine, 1985; Glasberg & Moore, 1989; Tyler, Wood & Fernandes, 1983).

Since many elderly listeners have some degree of hearing loss, it is impossible from some studies to determine whether temporal processing deficits that are noted in the elderly are a function of peripheral hearing loss and/or are independent of the aging process. Moore, Peters & Glasberg (1992) measured thresholds for the detection of gaps in sinusoidal signals as a function of frequency in elderly hearing-impaired and elderly subjects with 'near normal' hearing. The results showed that the 'near normal hearing' elderly had higher gap detection thresholds than younger subjects and that no differences were found between the hearing impaired elderly and the near normal hearing elderly. Schneider, Speranza, and Pichora-Fuller, (1994) reached a similar conclusion in a study which measured thresholds for detecting a gap between two Gaussian modulated 2 kHz tones. Although in this study thresholds for the elderly 'normal hearing' listeners spanned a slightly broader range, gap detection thresholds were not only longer but more variable for the elderly listeners relative to the younger listeners. Gap detection thresholds in the older group were, on average, twice as large as in the younger group. Moreover, gap detection thresholds appear to be independent of the degree of hearing loss (Schneider, Pichora-Fuller, Kowalchuck & Lamb, 1994). Snell (1997) more rigorously controlled for high frequency hearing loss in elderly listeners measuring gap detection thresholds for noise burst stimuli in young and elderly listeners with pure tone thresholds of < or = to 20 dB HL from 250 to 4000 Hz. Again gap thresholds were significantly larger in elderly subjects. He, Horowitz, Dubno, and Mills (1999) found significantly larger gap thresholds for normal hearing elderly listeners, but only when the gap was close to signal onset and offset.

In addition to detecting gaps in the auditory stream, a listener processing speech often has to discriminate among temporal intervals. Abel, Krever, and Alberti (1990) studied the difference limen for changes in stimulus durations at two reference durations (20 and 200 ms) in younger and older 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 silent intervals between tones for a reference duration of 250 ms. Four groups were tested: young normal hearing; young hearing impaired; old normal hearing; and, old hearing impaired. The findings suggest an age-related deficit in duration discrimination that is independent of hearing loss which had no effect on duration discrimination, but older listeners (both normal and hearing impaired) had higher thresholds than their younger counterparts.

Trainor and Trehub (1989) found deficits in the ability to correctly order the sequence of tones differing in frequency in several different conditions. Some tasks required a simple discrimination between the sounds; others required an identification of the order in which the tones appeared. Older listeners were less accurate than younger adults and the performance did not correlate with hearing loss. Humes and Christopherson (1991) and Neils, Newman, Hill, and Weiler (1991) also report sequencing deficits, or difficulties in temporal ordering of stimuli that appears to be independent of hearing loss.

In summary, a number of factors affect the detection of temporal changes in a signal. There appears to be agreement in that in all studies some of the elderly listeners, regardless of their audiometric profiles, were found to have losses in temporal resolution, but the effects of listener age on gap detection are not clear. Schneider et al (1994) reported that gap thresholds of elderly listeners were more variable and about twice as large as those from younger listeners. Moore et al (1992) reported that age-related differences in their study were due to the data of a few elderly listeners who had markedly large gap thresholds though the majority of the elderly listeners had gap thresholds within the range of younger listeners. Although considerable overlap in gap thresholds between young and elderly listeners was also reported by Snell (1997), her conclusion differed from that of Moore el. al., (1992) in that mean gap thresholds were larger for elderly listeners than for younger listeners in all conditions studied. Analysis of individual data led Snell to conclude that the mean differences among age groups reflected shifts in the distribution of the elderly listeners toward poorer temporal resolution.

A confounding factor in measuring temporal resolution for elderly listeners may be hearing loss which is commonly associated with age. Lutman (1991) found that gap detection deteriorated with hearing loss but not with age for three groups of listeners aged 50-59 years, 60-69 years, and 70-79 years. Fitzgibbons and Gordon-Salant (1995; 1996) reported higher gap detection thresholds for elderly listeners relative to young listeners and that hearing loss had no systematic effect on gap detection.

iii. Frequency Selectivity

Frequency selectivity refers to the ability of the auditory system to differentiate the spectral components of a complex sound, and this process of decomposition is modelled as a bank of independent and overlapping bandpass filters with varying center frequencies. The filters are not linear but are level dependent with the upper skirts of the filter becoming sharper and the low frequency slopes becoming shallower as signal level increases (Glasberg & Moore, 1990). The shape of the auditory filter is thought of as a weighting function applied to the power spectrum of a sound to determine the effective magnitude of the output of a filter at a given center frequency (Glasberg & Moore, 1990).

The output of this series of filters reflects the excitation pattern of a given sound which is a representation of the activity or excitation evoked by a sound as a function of characteristic frequency or place in the auditory system (Moore, 1993). Information can be combined across filters to enhance signal detection such as in comodulation masking release (CMR) (Hall, Haggard & Fernandes, 1988). CMR refers to the phenomenon that a masked signal is easier to detect when the masker has coherent envelope fluctuations across multiple frequency regions than when the fluctuations either differ across frequencies or are in a limited region (Eddins & Wright, 1994).

Measures of frequency selectivity are psychophysically can be estimated from masking paradigms, and have been determined with ripple noise (Houtgast, 1972); simultaneous masking (Zwicker & Shorn, 1978), nonsimultaneous masking, (Bacon & Moore, 1986), profile analysis (Lentz, Richards & Matiasek, 1999), and notched noise

(Glasberg & Moore, 1990). Psychophysical tuning curves (PTC) are a simplified measure of frequency selectivity and can be measured if the level of a tone is set very low, e.g. 10 dB above threshold, and the level of a masker required to just mask the tone is determined, i.e., the level of the masker where the tone is just audible is determined. Because the signal is at a low level, it is assumed that it will produce activity in just one auditory filter. Furthermore, it is assumed that at threshold, the masker produces a constant output from the filter in order to mask the fixed frequency. Thus the tuning curve represents the masker level required to produce a fixed output from the auditory filter as a function of frequency. The premise is that two audible frequencies presented simultaneously to the ear can be heard, or resolved, only when the proper frequency separation and level relations exist.

PTCs are assumed to be analogous to the electrophysiologically measured physiological tuning curves of single auditory fibers. To reproduce these neurophysiological tuning curves, the masker is treated analogously to the simulating tone. Thus, the threshold of a very faint pure test tone at the frequency equivalent to the characteristic frequency of the fiber, masked by a louder masker is measured. The level of the test, or probe, tone is kept low so that only a small area is stimulated (Bacon & Moore, 1986; Patterson & Moore, 1986; Zwicker & Schorn, 1978).

Tuning curves derived in this manner have differentiated changes in frequency selectivity on the basis of three measures: the low frequency slope, the high frequency slope, and the Q value (Davidson & Melnick ,1988; Forentine, 1992). Slopes of the high frequency skirts can be on the order of 200-300 dB/octave depending on the center frequency (Davidson & Melnick ,1988). The Q value is a measure of sharpness of the tuning curve and is computed as center frequency where the filter function has decreased by either 3dB or 10dB from its maximum value divided by the bandwidth (BW); the higher the Q value, the narrower the tuning curve is at the tip (Holube, Kinkel & Kollmeier, 1998; Kollmeier & Holube, 1992; Rosen, 1997). Estimates of 3dB BW are about 10% of the center frequency (Bacon & Moore, 1986; Moore, Glasberg & Roberts, 1984) while values for the 10dB BW can range from 30% in simultaneous masking to 16% in forward masking (Bacon & Moore, 1986). Typically, listeners with cochlear pathology show flat tail regions or elevated Q values, or both (Zwicker & Fastl, 1990).

Patterson (1976) developed a method of the 'notched noise method' of measuring frequency selectivity. In this paradigm, a probe signal is placed between two bands of noise with a variable notch or gap between them. Filter shapes can then be estimated by measuring signal threshold as a function of the width of the notch. Patterson, Nimmo-Smith, Weber, and Milroy (1982) described a family of mathematical expressions with the form of an exponential with a rounded top, called roex, could be fit using two parameters: p which defines the filter's passband and r which limits its dynamic range. The shape of the filter, W(g) is given by

$$W(g) = (1-r)(1+pg)\exp(-pg)+r \qquad (1)$$

where W is the intensity weighting function of the filter and g is the normalized distance from the filter's center frequency. The parameter p defines the slope of the upper and lower halves of the filter and is allowed to differ for the upper and lower slopes. Moore and Glasberg (1989) measured auditory filter shapes with this method for frequencies from 0.1 to 10 kHz. The equation relating the equivalent rectangular bandwidth (ERB) of the filter to center frequency is described by

$$ERB = 24.7\,(4.37F + 1) \tag{2}$$

where F is the frequency in kHz. Filter parameters determined with this method are dependent upon probe level (eg., Moore, Vickers, Plack & Oxenham, 1999; Glasberg & Moore, 1990; Wright, 1996). More recently, Rosen, Baker and Darling (1998) have used a variant of this: the polyfit model which is dependent upon probe level, and not masker level.

Changes in Frequency Selectivity with Age

There is no question as to where frequency selectivity occurs in the auditory system. It is in the cochlea and frequency selectivity alters with cochlear pathology. Moore, Vickers, Plack and Oxenham (1999) found that the ERB increased with OHC loss which would alter the nonlinear input-output function of the BM. Peters and Hall (1994) reported that comodulation masking release was not affected among elderly and young listeners. Given the preponderance of data on cochlear pathology and aging, frequency selectivity measures should show an age-related decline. However, from the data on aging listeners, only cases of severe hearing loss show a consistent pattern of frequency selectivity changes irrespective of the type of paradigm (Florentine, Buus, Scharf & Zwicker, 1980). Moore, and Patterson (1984) reported that even though subjects had similar hearing losses there were large differences between the skirts of the auditory filters. Dreschler and Festen (1986) found that listeners with conductive hearing loss showed similar auditory filter widths compared to normal hearing listeners.

It is important to understand however, that a definition of 'clincially normal' hearing can include a range of 40 dB spanning –20 dB HL to +20 dB HL (Silman & Silverman, 1991). The usage of the term 'clinically normal' has become pervasive throughout the literature and it cannot be assumed that thresholds for discrimination of complex sounds are unaffected by hearing thresholds which can potentially span such a large range (40 dB as above). However, though there exists large variability in the thresholds of listeners which are categorized as having normal hearing, the literature is replete with studies which demonstrate a significant connection between elevated thresholds beyond normal and discrimination results. Therefore, despite the large range of values, the use of the term 'normal hearing listeners' is considered a viable categorization of listeners, by this author, when differentiating age-related effects among various groups. A better approximation of age-related changes may be had by using listeners which have audiograms which are closely matched and not just within the range considered audiologically normal.

Patterson, Nimmo-Smith, Weber, and Milroy (1982) measured frequency selectivity as indicated from derived auditory filters from stopband noise centered around 0.5 kHz, 2 kHz, and 4 kHz probe tones. Auditory filters broadened with age in their population of study (23 to 75 years) at each probe frequency, with the greatest loss of selectivity occurring at 4 kHz. The dynamic range of the filter decreased with age as well. However, elderly participants in this study all had varying degrees of hearing loss and the so it is difficult to conclude that the diminished frequency selectivity could be attributed to age 'per say' and not to hearing loss. Decreased frequency selectivity with age was also noted in a study by Glasberg, Moore, Patterson, and Nimmo-Smith (1984). However, here too, the confound of age and hearing loss was not addressed. Matschke (1991) obtained psychophysical tuning curves with a simultaneously masked probe in listeners aged 20 to 70 years of age who had 'normal hearing for their age'. For listeners over 60, a decline in frequency selectivity was observed; however, since 'normal hearing' for people over 60 years involves some elevation of high-frequency thresholds, a contribution of hearing loss to these results cannot be ruled out.

Zwicker and Schorn (1978) obtained simultaneously masked tuning curves from several diagnostic categories of hearing pathology including presbyacusis. Listeners with average hearing losses of 35 and 50 dB at 0.5 kHz and 4 kHz respectively had tuning curves that were shifted upward (reflecting the elevation in thresholds) and were shallower (reflecting reduced frequency selectivity). In a later study, Zwicker and Schorn (1990) frequency resolution in presbyacusic listeners was further reduced by the addition of background noise at 4 kHz, but not at 0.5 kHz.

Results of tuning curves obtained from more than 1100 adults in the National Study of Hearing in Great Britain (Lutman, 1991; Lutman, Gatehouse & Worthington, 1991) revealed that frequency selectivity declined with age and hearing loss. When hearing loss was accounted for, there was only a minor decline in frequency selectivity that depended upon age. However, tuning curves were measured with only three data points and may not have produced a sufficiently fine-grained result of frequency selectivity. If elderly listeners are in the early stages of presbyacusis then some, or all, of the widening of the auditory filters could have been due to the hearing loss accompanying the elevated audiograms.

Reduced frequency selectivity in aging listeners may not necessarily be the result of peripheral hearing loss. Sommers and Humes (1993) reported that elderly listeners with normal hearing had auditory filters that were nearly identical to those of younger listeners with normal hearing. In contrast, elderly listeners with hearing loss had broader filters, and when filters were measured in younger listeners with masking noise that raised their thresholds to be equivalent to those of the hearing impaired, auditory filters were nearly identical among these two groups. Patterson, Nimmo-Smith, Weber, and Milroy (1982) measured frequency selectivity in listeners 23-75 years of age and found that the passband of the filter broadens in a linear fashion with age. Though many of their elderly listeners had some form of hearing loss, Patterson et al (1982) found that filter widths increased about 2% per year past age 20. Sommers and Gehr (1998) reported that auditory filter shapes derived in simultaneous masking paradigms were similar for young and elderly listeners (average age of 20 years versus 70 years) with nearly identical normal audiograms. However, frequency resolution assessed with a forward masking paradigm showed considerably sharper tuning only for younger listeners. The increased frequency selectivity for the younger adults was noted primarily for the high-frequency side of the filter. Their explanation was based upon a reduction in auditory suppression among the elderly.

According to the suppression hypothesis, (Houtgast, 1972; Moore & O'Loughlin, 1986), lateral suppression can influence auditory filter shapes in nonsimultaneous masking because the temporal discontinuity between signal and masker allows suppression to reduce the effective level of the masker without altering excitation arising from the signal, i.e., suppression functions to increase S/N ratios at the output of the filter. In simultaneous masking, however, suppression will have equivocal effects on the signal and the masker. Consequently, the S/N ratios at the output of the filter will remain constant and masked thresholds for the signal will be unaffected. If the function of suppression can be seen as one of enhancing spectral contrasts than an age-related impoverishment of this ability could impair the auditory system's ability to improve spectral contrasts for formants and other phonetically important features of speech. Lateral suppression is a peripheral phenomenon taking place in the cochlea; lateral inhibition is a central nervous phenomenon taking place from the cochlear nucleus up (Willot, 1991). Willot (1991) has noted changes in lateral inhibition in the aging structures of mice and therefore, changes noted among the elderly are not necessarily peripheral. It is difficult to separate out the factors of suppression, hearing threshold, and frequency selectivity as these are functions of the OHCs.

In summary, a finding of changes in frequency selectivity among different paradigms suggests that these age-related changes are independent of hearing loss. Broader auditory filters can influence frequency resolution which in turn can affect speech processing. Specifically, increased filter widths can affect speech processing in at least two ways: a) the masking of lower level components by louder components of the speech sound, and b) reduced audibility due to greater masking by background noise. Therefore, an increase in the width of the auditory filter would make it more difficult to filter out undesirable noise, and additionally, any phonemic discriminations that depend on pitch changes, differences in silent periods, rapid transitions, or amplitude fluctuations will be more difficult for elderly listeners with this difficulty compounded by the presence of background noise. Indeed, negative correlations between speech intelligibility in broadband background noise and the width of the auditory filters have been reported (Horst, 1987; Stelmachowicz & Jesteadt, 1984).

iv. Phonetic Identification

Speech is an acoustically complex signal, (see figure 1) whose structure is shaped not only by the physiological constraints of the speech apparatus (the vocal tract) in speech production, but also by the constraints of the auditory system in speech perception (Blumstein, 1997). The 'structure' of produced speech is a direct result of the properties of the acoustic transmission line where the glottal wave source gets filtered to produce an acoustic spectrum that is characterized by different resonances along the frequency plane. It is this set of varied spectra that can be formed by different configurations of the vocal tract which we identify as the vowels and consonants of speech.

Changes in Phonetic Identification with Age

To extract phonetic information from a stream of speech, a listener must be sensitive to the temporal relationships among subphonemic elements such as prevoicing, release, and vowel duration. Slawinski (1994) and Slawinski and Marieno (1989) showed that with age, changes occur not only in the <u>perception</u> of these elements, but also in the <u>production</u> of them. Specifically, in a continuum in which the transition duration distinguished the stop consonant /b/ from the semivowel /w/, (shorter for /b/; longer for /w/), elderly listeners perceived the semivowel /w/ at a shorter duration (Slawinski & Marieno, 1989). Prolongation was also noted in the production of these subphonemic elements (Slawinski, 1994).

As to whether spectral or temporal aspects are more impacted, the results are mixed, and often confounded with the hearing status of the listener. Price and Simon (1984) reported that aging listeners required a longer silent gap before reporting 'rapid' versus 'rabid', though listeners had normal thresholds only to 2.0 kHz. Gordon-Salant

(1986) found that elderly listeners showed greater confusions of place distinctions of /b/-/d/-/g/ (a spectral contrast) than confusions of voicing (/b/-/p/) despite clinically normal thresholds from 0.5 to 8.0 kHz. A contrary result was reported by Gelfand, Piper, and Silman (1986) where normal hearing elderly showed greater recognition of voiced versus voiceless distinctions. Dorman, Marton, Hannley, and Lindholm, (1985) reported no differences in 'chop' – ' shop' or 'slit' – 'split' distinctions (a temporal contrast), but greater difficulty for stop consonant discrimination (a spectral contrast). However, hearing status was mixed among this group.

If the elderly are tested under ideal conditions of quiet with nondegraded speech, then appears to be only a small deficit in speech intelligibility that is not predicted by the pure tone audiogram . This effect can be on the order of a 10 dB needed increase when compared to young normal listeners, however the impact is disproportionately larger when the listening conditions are less than ideal (Prosser, Turrini & Arslan, 1991). Possible acoustic processing mechanisms that might account for these findings include: attenuation of consonants, diminished intensity processing, widening of critical bands, and loss of temporal integration characteristics. Although deficits in speech recognition are more pronounced in elderly hearing-impaired listeners (Dubno, Lee, Mathews & Mills,1997; Gordon-Salant, 1986), elderly normal-hearing listeners nevertheless show a deficit relative to young normal hearing listeners (Cheesman, Hepburn, Armitage & Marshall, 1995; Dubno et al., 1997; Gordon-Salant, 1986; Hargus & Gordon-Salant, 1995; Humes & Roberts, 1990). Such findings are most evident in noisy situations and suggest causal factors related to age, independent of hearing loss. However, intensity changes in a signal are more effective for 'essentially normal' hearing listeners than are changes in duration (Gordon-Salant 1986).

Other studies have shown that the performance of elderly normal hearing individuals is more similar to that of elderly hearing impaired individuals and not young normal hearing listeners on tasks of speech recognition in reverberant noise (Helfer & Wilber, 1990) and word recognition in broadband noise (Stuart & Phillips, 1996). Gelfand, Piper, and Silman, (1986) assessed speech recognition scores in quiet as a function of age for groups of normal hearing individuals, and though elderly listeners showed decreased percent correct performance, the consonant confusions made by the elderly were the same as those made by the younger subjects suggesting a decrement in aging in the 'efficiency' but not in the 'kind' of speech recognition ability. Speech perception in quiet may be influenced by the degree of hearing loss, whereas speech perception in noise (particularly speech spectrum noise or multitalker babble) may be dependent on frequency resolution (Plomp, 1986), or temporal resolution (Stuart & Phillips, 1996).

Corso (1981) argued that a simple peripheral-versus-central hypothesis; which can be argued to be analogous to a spectral versus temporal hypothesis, is not likely to account for age changes in speech intelligibility, and that a 'varying proportionality hypothesis' is more appropriate. The assumption is that receptor and first order neuron changes accrue slowly through life. Central degenerative changes, while slow to occur, accelerate once initiated. Therefore, the changes which are behaviorally measured vary in proportion to the specific site of the degenerative changes. Specifically, deficits in speech intelligibility would reflect increasing central degeneration with advancing age, becoming most apparent under difficult listening conditions. Plomp and his colleagues proposed a model in which hearing loss is viewed in terms of two components: 1) attenuation, or reduced audibility; and, 2) distortion, or effectively reduced S/N ratio (Plomp 1978; Plomp & Mimpen, 1979; Plomp & Duquensnoy, 1982). Attenuation manifests itself in the pure tone audiogram as a threshold elevation; distortion does not. The distortion component is plausible in terms of abnormal auditory filters as internal representations of the spectral components of sounds analyzed by abnormally wide filters will not effectively resolve the spectral peaks in the signal. Additionally, the S/N ratio is altered (lowered) so that individual components are obscured. Within this framework, the findings of Gelfand et al. (1985) suggest that older individuals experience an effect analogous to the listening to speech materials at an effectively reduced signal to noise ratio (SNR). The decrease in performance with increasing age especially in noise conditions despite relatively high levels of presentation is suggestive of the distortion component of Plomp and Duquensnoy's model.

Therefore, elderly listeners with good hearing are more affected by speech distortions than are elderly listeners with a hearing loss even when each group is compared to younger listeners with the same hearing sensitivity (Gordon-Salant & Fitzgibbons, 1993, 1995). One proposition is that elderly subjects perform on speech tests as if they had a lower functional SNR than younger persons. Gordon-Salant and Fitzgibbons (1995) describe functional SNR as the effective SNR of speech when external noise (noise from the environment) as well as internally produced (system) noise are combined. This functional SNR may be influenced by : 1) decreased internal signal strength in the aged auditory system; 2) increased neural noise; or, 3) a combination of these two factors. The implication of their findings is that aging effects can be modeled as if there were more noise added to the speech after it is received. Lutman (1991) describes a similar phenomenon as 'excess' disability, or a disability that is greater than that which would be expected on the basis of hearing impairment alone.

Although many observed declines in speech communication can be attributable to changes in the audibility of speech caused by decreased hearing sensitivity, other factors such as changes in temporal acuity, frequency resolution, and central auditory processing (Patterson, Nimmo-Smith, Weber & Milroy, 1982; Pichora-Fuller, 1997; Schneider, 1997), can occur with advancing age and in the absence of any measurable increase in auditory thresholds. He, Dubno and Mills (1998) reported that even with closely matched audiograms (less than 20 dB HL for 0.5 kHz to 4 kHz), elderly listeners demonstrated poorer frequency discrimination abilities than younger subjects.

Although results from the Working Group on Speech Understanding and Aging (1988) raised the possibility that cognitive factors influence auditory abilities such as speech processing, others insist that factors such as peripheral hearing loss (Duquesnoy, 1983; Humes & Christopherson, 1991; Humes & Roberts, 1990) or central auditory processing deficits (Jerger, Mahurin & Pirozolo, 1990) can account for most, if not all, the variability in age-related changes in auditory ability. Humes (1996) uses a highly schematic overview of the auditory system from periphery to cortex to contrast three hypotheses as possible accounts for age-related changes in speech understanding: 1) the peripheral hypothesis; 2) the central-auditory hypothesis; and, 3) the cognitive hypothesis. Humes equates the peripheral hypothesis with cochlear function, the central-auditory hypothesis with brainstem, midbrain, thalamic and cortical function, and the cognitive hypothesis with non-modality specific cortical function. He designates psychological processes corresponding to the three sites as respectively: 1) peripheral encoding; 2) neural transmission and feature extraction; and, 3) information processing, labeling and storage. The hypotheses differ therefore in terms of the primary site of age-related damage in the auditory system that is implicated. An implicit assumption in such 'biophysical' modeling is that distinct physical changes can be correlated with particular behaviors. However, there is a clear lack of correspondence between specific types of physical change and specific behavioral results.

Humes and Roberts, (1990) evaluated the peripheral hypothesis : that the degree of pure tone hearing loss is the primary factor underlying speech perception difficulties in the elderly. Presbyacusic and young listeners with simulated hearing loss performed equivalently on monaural identification tasks in conditions of reverberation, background noise, and both reverberation and background noise (Humes & Roberts, 1990). In a later study, with the same listener conditions, the battery of measures was extended to include the Test of Auditory Capabilities, clinical measures of cognitive functioning (WAIS-R, WMS-R) and a larger battery of speech tests including open-set recognition of sentence-final words (Humes, Watson, Christensen, Cokely, Halling & Lee 1994). All speech measures were highly inter-correlated and the degree of sensorineural hearing loss (as measured with pure tone averages of 1, 2, and 4 kHz) was the primary factor associated with speech perception or word recognition performance.

Large scale studies using tests of auditory performance, auditory and visual tests of cognitive performance, and tests of speech perception and word recognition in quiet and noise reveal three major conclusions (van Rooij & Plomp, 1990; 1992; van Rooij, Plomp & Orlebeke, 1989). One, the primary factor associated with speech perception or word recognition performance was degree of pure tone hearing loss. Two, cognitive measures accounted for a small additional proportion of the variance, especially for a group selected from the general public. Three, performance on cognitive tasks was not modality specific.

Though the above studies show consistent results, the findings regarding central auditory processing offer a different perspective. Jerger, Jerger, Oliver, and Pirozzola (1989) administered standard audiometric testing, standard neuropsychological testing for cognitive impairment, and four tests of central auditory processing that use speech materials. Half of their sample demonstrated central auditory processing abnormalities but neither the standard audiometric nor the neuropsychological measures could predict central auditory processing deficits. This finding that was also reported by Jerger, Mahurin, and Pirozzolo (1990) and supported in a later study with four different age groups matched for audiometric thresholds (Jerger, 1992).

In summary, there is an inverse relationship between speech perception measures and age, and deleterious effects of noise and reverberation are exacerbated with increasing age. Next to the high frequency loss which is documented among an aging population, the most ubiquitous complaint is that of reduced speech intelligibility especially in adverse conditions (e.g., noise, reverberation) (Pichora-Fuller, Schneider & Daneman, 1998). Deficits have been found with a variety of materials, ranging from nonsense syllables (Gordon-Salant, 1986; Humes & Roberts, 1990) to full sentences (Duquesnoy, 1988; Gelfand, Ross & Miller, 1988), even when listeners are matched on not only their pure-tone audiograms, but also their performance in quiet. Pure-tone audiometry does not predict the nature and extent of hearing difficulties in adverse conditions (Bergman, 1980; Duquesnoy, 1983; Plomp, 1986), and is inadequate for identifying specific age-related changes in auditory processing responsible for speech comprehension difficulties.

Despite having relatively good hearing as defined by conventional audiometric criteria, a person's ability to hear can interact with the acoustic conditions in everyday environments and can potentially create handicapping situations. Pure tone hearing loss is significantly correlated with performance on speech perception and word recognition tasks, but performance of central auditory processing cannot be predicted from pure tone audiometry. Models which have emphasized either peripheral or central factors are for the most part correlational studies which do not provide evidence of causality. There are however, sizable correlations between audiometric thresholds and measures of speech perception and word recognition with little additional variance being accounted for by a selection of standard cognitive measures.

v. Perceiving Unidirectional Frequency Glides

A method for determining auditory processes involved in phonetic identification is to use acoustic signals which are analogous to phonetic segments, but have the linguistic element removed. Linear frequency glides the have been studied because of their analogous nature to the consonant component of speech (cf. Figure 1). They therefore are an elemental signal with some complexity that is intermediate between pure tones and the whole signal whose representation one wants to understand (Rauschecker, 1999). The discriminability of cues for consonant perception is a complex issue because it involves not only the additional factor of transition rate, but also the bandwidth of shorter consonant-like glides (20-50 ms) is broader than the bandwidth of longer glides. In addition, as one dimension (e.g., frequency) covaries with another (e.g., duration), it is very difficult to isolate the auditory properties on which a response is based. Discrimination can be based on transition rate, end point frequency, average frequency duration, bandwidth, or a combination of such parameters. Interpretation of results becomes even more complicated when more speech-like stimuli are used when fundamental frequency and additional varying resonances are involved. To avoid some of the complexities associated with speech-like stimuli, many studies have measured the just noticeable differences in frequency and duration of tonal glides (Sergeant & Harris, 1962; Pollack, 1968; Nabelek & Hirsh, 1969; Tsumura, Sone & Nimura, 1973; Collins & Cullen, 1978; Schouten, 1985; Dooley & Moore, 1988).

Discrimination of linear glides depends upon the duration of the signal, the rate of change, the frequency region and the direction of the glide. Improved detection with increasing duration is a well established result commonly referred to as temporal integration (TI). Classical TI of signals is viewed as a frequency-dependent, energy-based detection process (Formby & Muir, 1988). Sergeant and Harris (1962) determined 'threshold glissando rates' in Hz/ms for durations up to a duration of 10 seconds of a 1500 Hz signal. Threshold was 17 Hz/ms for glides of 75 ms and decreased to values between 5 and 7 Hz/ms for durations between 1 and 10 seconds. Nabelek (1978) reported that the thresholds for constant tones reached a minimum at 1 second whilethresholds for gliding tones continued to fall at least to durations of 5 seconds. Cullen and Collins (1982) controlled for this confound by using fixed durations with fixed rates of change. As duration increased, thresholds systematically decreased, consistent with classical TI. In addition, as rate of change increased, thresholds increased. Thresholds decreased for falling glides systematically as duration increased. Rising glides tone had lower thresholds but only for the longer durations of 20 and 40 ms and not for the shorter durations of 5 and 10 ms. Cullen and Collins (1982) argued this could be explained on the basis of cochlear mechanical characteristics. That is, when the temporal progression of the tone glide frequency change is opposite to the high-to-low frequency representation along the cochlear partition (i.e., a frequency rising tone-glide), displacement of successive points along basilar membrane may move more nearly in coincidence. This phasic displacement of a region of the basilar membrane (BM) would, in turn generate greater synchrony of activity in the array of afferent fibers innervating the region, thereby leading to lower threshold values.

Several studies have noted direction asymmetries for glide detection, but the results are contradictory. Nabelek and Hirsh (1969) found that at 1 kHz, thresholds were smaller for the rising glides, and at 4 kHz were lowest for the falling glides. Elliot, Hammer, Scholl, and Wasowicz (1989) reported no effect for direction of the glide for formant stimuli in a comparable frequency region. Tsumura, Sone, and Nimura (1973) found an asymmetry with upward sweeping glides having thresholds about 20% greater than those for downward sweeping glides. Dooley and Moore (1988) found that at most durations and center frequencies tested, average glide detection thresholds for upward sweeping glides were larger than those downward sweeping glides, although the differences were small except at 2 kHz. Schouten (1985) reported that detection thresholds for downward glides were greater than for upward glides. Madden and Fire (1997) reported that downward glides were more difficult to detect than upward glides but only for their 50 ms duration stimuli. Demany and his colleagues (Demany & McAnally, 1994; Demany & Clement, 1998) have reported perceptual asymmetry between peaks (i.e., local maxima) and troughs (i.e., local minima) of frequency modulated signals. This peak/trough asymmetry has been found not only for pure tones with vertex frequencies of 250, 500, and 1000 Hz, but also for harmonic complexes with vertex frequencies of 200 and 500 Hz (Demany & Clement, 1998). Specifically, the perceptual saliency of peaks was greater than that of troughs across a variety of modulation amplitudes, signal durations, and frequency regions.

Collins and Cullen (1978) used an adjustment procedure to determine the just detectable level of a steady tone or a frequency glide in a background of broadband noise. Threshold was found to be dependent upon both the duration and the extent of the frequency glide. They reported that downward glides could be detected at a lower level than upward glides when the signal duration was less than 50 ms. In a later study (Cullen & Collins, 1982) they found that this asymmetry was rate dependent: as the rate of frequency change increased, the difference in threshold between rising and falling tones became more marked.

Horst (1989) controlled for the interdependence of rate, extent and duration, by using signals with triangular spectral envelopes. The signals were harmonic complexes that had a fundamental frequency of 100 Hz and a center frequency in the 2000 Hz region. Signals always had the same initial and final frequency, and the trajectories, i.e., the 'height' of the modulation function varied. Thresholds for modulation discrimination were higher than those for modulation detection which in turn were higher than those for detection of a frequency difference. In terms of modulation discrimination, the thresholds showed a very clear dependence on the slope of the spectral envelopes. The shallower the envelope, then the higher the threshold value was. The same pattern was evidenced in the signals presented against a background of noise in that higher thresholds were noted for signals which had a shallower spectral envelope (25 dB/oct). More importantly however, the noise had an influence on thresholds only for very low signal-to-noise ratios. This was particularly marked for the signals with shallower slopes where the thresholds were increased by a factor of about 2-3 times. Horst (1989) postulated that the discrimination of dynamic signals is done by a mechanism which treats the signals as quasistationary. In this model it is assumed that the modulation trajectories to be discriminated are compared section by section and that the durations of these sections depend on the shape of the trajectory, although there are no supporting data and the time window is not specified though glide discrimination and spectral integration does deteriorate below durations of 20-30 ms.

Pitch determination of glides is dependent upon direction, the proportion of the total signal that is the glide, and rate of change. Nabelek, Nabelek, and Hirsh (1970) examined 'pitch' perception of gliding tones by having listeners match the pitch of a steady state frequency tone to that of a test burst tone. Data for the signals which changed throughout 100% of the signal showed that when the burst duration was short and the frequency range traversed by the glide was small, pitch matches were near the geometric mean of the initial and final frequencies. As duration of the frequency glide increased, pitch matches moved closer to the final frequency of the glide. In general, an increase of frequency extent caused a shift of the matches from the arithmetic mean of the glide toward the final frequency. For signals which changed throughout only a portion of the signal (25%), the results depended upon the frequency extent of change. Transitions at the beginning of the burst were matched to the frequency of the steady state part. When the transition occurred after some delay, pitch judgments shifted toward the initial frequencies. This means that rising glides were matched to the lower frequency and falling glides toward the higher frequency.

Schouten (1985) found that with brief tones (20-50 ms) and gliding rates between 0 and 60 octaves/second, glides with zero or low glide rates were judged to be going down irrespective of the actual direction of the glide and of duration. For rising signals to be reliably identified required a glide rate of at least 10 octaves/sec over a duration of at least 20 ms. Schouten suggested that steady tones are heard as falling in pitch, and that the extent (rate) threshold for discriminating rising from falling tones was not significantly different from the threshold for discriminating rising tones from steady tones. In contrast, Kluender and Jenison (1992) presented listeners with two glides separated by broadband noise and asked listeners to match the pitch of the second to the first. Their results show that listeners consistently underestimate the pitch match, and that the faster the rate of change in the first signal, the greater the underestimation. Pols and Schouten (1986) measured the frequency excursion required for the correct discrimination of steady from both up and down glides, and of up glides from down glides using glide durations up to 40 ms. They found that thresholds for discriminating up glides from steady tones were lower than those for discriminating down glides from steady tones. Furthermore, they reported that the thresholds for discriminating up glides from down glides were about the same as those for discriminating up glides from steady tones consistent with Schouten (1985).

Some of these theories were put forth to explain the pitch associated with a complex tone consisting of the simultaneous presence of many components and may not be generalizable to a frequency transition complex. Horst (1985) theorized that frequency glide discrimination is based upon treating a signal as a series of quasi-stationary segments, but there is no supporting data as of yet, nor has the time window been specified although transition discrimination and spectral integration deteriorate markedly for durations below 20-30 ms. Others (e.g., Dooley and Moore 1988) have proposed that transition discrimination is based upon a sampling theory where differences in stimuli are determined from samples taken at different points along the stimulus, but again no specified time function is given. Schouten (1985) proposed a pitch extraction method where the difference between the initial and the final frequency are important.

One factor that potentially complicates the results of some studies is the issue that the signals were presented against a background of noise in order to equalize relative hearing sensitivity and to minimize possible off frequency listening. The bands of noise used have varied between 2800-6000 Hz in width and were moderately intense (60-75 dB SPL). Thus the possibility exists that the effects that are noted are unique to the signal level necessary for detection under those specific conditions. Collins and Cullen (1984) specifically investigated the effect of background noise on the perception of glides. Results could be described by a nonmonotonic function and were also asymmetric. Thresholds for rising glides were nearly constant across the noise levels whereas the falling glides were most impacted by the noise at the intermediate noise levels as opposed to the extremes.

Porter, Cullen, Collins, and Jackson (1991) examined the effects of discrimination when rate of change was held constant regardless of the frequency transition. For 45 to 60 ms duration signals, onset frequency discrimination improved with longer durations. This suggests that duration, and not rate of change affects frequency discrimination. Again there was an asymmetry between rising and falling transitions. When the comparison stimuli had a greater rate of change than the standard (an increment), falling transitions showed smaller thresholds than did rising transitions. The same pattern held for comparison stimuli which had lower rates of change (decrements) than the reference. Though, increments were better discriminated than decrements, the thresholds were lower for falling signals than for rising signals. Porter at al (1991) attributed the results to temporal processing differences in high and low frequency regions, and model their results in terms of an excitation pattern. Since filters in higher frequencies have better temporal resolution than those in lower frequency regions (Fitzgibbons & Wightman, 1982; Fitzgibbons), excitation envelopes will have finer temporal structure than those for lower frequencies. In the cases of frequency glides increasing or decreasing transition extent can be presumed to yield increases or decreases in excitation envelope magnitude which could serve to support discrimination

The idea that excitation patterns underlie detection and discrimination of time-varying signals means the process is dependent upon either (1) differences in the average or peak energy of the envelope and/or (2) differences in their temporal shapes (Moore, Glasberg, Plack & Biswas, 1988). At the initial stage, sets of neural units sensitive to signal energy within a particular band of frequencies produce an 'excitation envelope' that reflects the time course of envelope variation within the frequency band. The excitation envelope is modeled as a half-wave rectification (or squaring) of energy in a specified bandpass region followed by a compressive nonlinearity (Yost, Sheft & Opie, 1989). During subsequent stages of processing, envelope outputs of different CBUs are thought to be summed and temporally smoothed (or low-pass filtered) with the magnitude and/or the shape of the resultant envelope serving to support detection and discrimination (Yost, Sheft & Opie, 1989). There are however, differing details in terms of whether or not the smoothing occurs before or after the summing, whether different weights are assigned to different outputs, or whether the overall envelope is further processed prior to subsequent decision processing (Carlyon, 1992; Carlyon & Stubbs, 1989; Yost, Sheft & Opie, 1989).

Moore and Sek (1998) have argued that the mechanisms involved in frequency discrimination vary depending on the exact nature of the stimuli. Specifically, they suggest that discrimination of pulsed tones depends mainly on the phase locking information up to about 4 - 5 kHz; above that frequency only place information is available. For (frequency modulation) FM detection, the dominant mechanism is argued to depend upon modulation rate; for very low rates, (around 2 Hz), a mechanism based on phase locking appears to be dominant for carrier frequencies up to about 5 kHz. For higher modulation rates, (above 10 Hz), a place mechanism appears to be dominant for all carrier frequencies.

Madden and Fire (1996) measured thresholds for detecting frequency glides and for discriminating frequency glides using 50 ms tone glides. Thresholds were roughly a constant proportion of the equivalent rectangular bandwidth (ERB) of the auditory filter for the center frequencies from 0.5 kHz to 6 kHz. They took this as support for an excitation pattern model where changes on the low frequency slope of the auditory filter are monitored. In a second study (Madden & Fire, 1997), they used both 50 ms and 400 ms duration glides. They suggested that a 'sluggish' temporal mechanism might be able to track the glides of long duration since they had relatively gradual rates of frequency change, whereas it might not be able to track rapid frequency glides. However, thresholds were roughly a constant proportion of the ERB of the auditory filter at both durations consistent with the idea that the low frequency slope of the excitation pattern is monitored. In an extension of this, Moore and Sek (1998) superimposed random level cues in dB/s to disrupt the monitoring of the low frequency slope and found that thresholds expressed as a proportion of the ERB did not vary greatly with center frequencies form 0.5 kHz to 6 kHz suggesting that discrimination did not depend strongly on information derived from phase locking.

't Hart et. al. (1990) have argued that the perception of a glide occurs when the threshold can be approached by

$$G_t = 0.16 / T^2 \qquad (3)$$

where G_t is the glide threshold in semitones/s and T the duration. When a glide is above this threshold, a separate perception of the high and low frequencies occurs. This is reminiscent of the work of Nabelek et. al. (1970) who used the term 'separation' for when only the final part of the burst contributes to the pitch judgement and the term 'fusion' for when the overall pattern contributes to the pitch judgement. d' Alessandro, Rosset and Rossi (1998) have modeled the pitch perception of glides using a weighted time average which incorporates whether the glide is rising or falling and whether the focus of attention is at the beginning or the end of the signal. The difficulty with this model is that the parameters must be known ahead of time and therefore it serves strictly as a functional model, and not as a model of physiological or psychological processes that are taking place.

Porter et al., (1991) and Moore and Sek (1998) model asymmetry based upon cochlear dispersion patterns or asymmetries in the excitation pattern. de Cheveigne (2000) proposes a model of asymmetry based upon temporal cues. His model assumes that the form of the autocorrelation is asymmetric, the neural discharge patterns are 'sharpened' to narrow pulses, and pitch discrimination relies upon higher order modes of the autocorrelation function. This model is a proposition which is meant ".. to describe how this happens, not why it happens". Therefore, models of 'glide' discrimination are based upon either pitch cues, excitation pattern cues, or autocorrelation functions.

Therefore, if discrimination of gliding signals can be used as a metric of elemental auditory processing, it may provide insight into the perceptual problems experienced by the elderly. It is well documented that phonetic contrasts which are spectrally based (eg. stop consonants) are perceived with less precision (i.e., are more confusable) among the elderly, and though the models of linear glide discrimination are not clearly defined, perception and discrimination of these signals could provide insight into age-related changes of auditory perception.

The well documented findings of an increase in pure tone thresholds beginning early in life are not a reliable indicator that other auditory processes show an early onset change, or that the function is linear. Bonfils, Bertrand, and Uziel (1988) found that evoked acoustic emissions thresholds did not vary until the age of 40 and then increased linearly after that among clinically normal hearing listeners. Thus if there are subtle changes in the mechanics of the cochlea, this could reasonably manifest itself in changes in auditory processing particularly if the signal is complex. Snell (1997) and He, Dubno, and Mills (1999) observed a large overlap of data between young and aged normal hearing listeners. An examination of the individual data in Snell (1997) (her figure 2) showed that among the 'young' group of listeners, thresholds appeared to increase around age 40. Alain and Woods (1999) found that the event-related potential component P3b showed progressive and linear changes from age 20 to age 80. Therefore, assessing changes in a cross sectional population of normal hearing listeners should clarify the age-related function of auditory processing.

Aims of the Present Study

There are two principle aims to the present study. The first was to determine which psychophysical abilities change across the life span. The second was to use factor extraction techniques to see which variables work in concert and characterize the aging auditory system. There are four fundamental, yet unanswered, questions which guided this research. One, what specific auditory abilities change across the life-span? Two, can these changes be documented and differentiated among a population of normal hearing individuals by using elemental discrimination tasks? Three, when do these changes occur among the population? Four, are there common underlying constructs which can describe these changes?

1. Changes in psychophysical abilities

The aim of this study was to assess a number of selected auditory factors across the life span. These measures involved the discrimination of linear frequency glides, temporal resolution, frequency selectivity, and phonemic perception. I decided to incorporate several parameters into this study instead of focusing exclusively on one auditory ability measured with several paradigms (e.g., temporal resolution) so that I could discern a general baseline overview of elemental auditory abilities among a cross section of normal hearing listeners.

To examine these abilities as solely a factor of aging, individuals from across the life span who showed normal audiologic profiles participated in this study. Specifically, all participants had normal thresholds on a number of audiometric measures, not thresholds that were 'normal for their age'.

Based upon the limited amount of available data, there is no strict hypothesis regarding specific signals. It is hypothesized, however, that age-related changes are most likely to manifest themselves in signals which rely more on temporal processing. Therefore, phonemic perception should show greater changes across the life span for a voice-voiceless distinctions than for stop consonant discrimination. It is unclear as to whether asymmetries will be found in linear frequency glide discrimination, as the current data are not consistent in this measure. However, using various manipulations of the structure of the signal should provide a clearer understanding of this process.

2. Multivariate Factors of Aging

A second aim of this study was to determine the major auditory performance factors that change across the life span. There were two fundamental questions to be answered with this approach. First, what are the major factors common to different auditory measures and how does age load on these? Second, among the identified factors, how does the performance of normal-hearing individuals compare among various age groups across the life span? Multivariate studies which have been undertaken, certain factors show remarkable similarity across studies for separating aged listeners from young listeners. Rank order of the top factors in these studies (Divenyi & Haupt, 1997; Humes et al. 1994; Smoorenburg, 1992; Jerger, Jerger, Oliver & Pirozzolo, 1989) has been hearing sensitivity accounting for between 45 and 60% of the overall variance. Using a population with nearly identical hearing thresholds will allow for illustrating other constructs which underlying auditory perception.

II: Methods

Participants

The same participants were used in all of the psychophysical measures in this investigation.

Only participants with clinically normal hearing participated in the study. The presence of factors such as: diagnosed hearing disorder, use of amplification devices, and audiological assessment showing mild to moderate, or greater, pure tone hearing loss precluded participation in this study. 143 persons ranging in age from 20-75 years of age were selected for participation based upon meeting certain audiological criteria. If necessary, corrective lenses were worn by all individuals for completion of some of the screening measures.

The final group of listeners represented five age decades as follows: 20-34 years, n= 30; 35-44 years, n= 30; 45-54 years, n=28; 55-64 years, n=25; and 65-75 years, n= 30. Data from one female aged 82 years was also collected but not included in the analysis as she was the only representative of this age group. The two youngest age groups (20-44 years) were recruited from both within the University of Calgary student population and the outside community. Other age groups were recruited from the outside community by replies to public announcements at various senior citizen organizations and media organizations. All participants were native speakers of English (relevant only for the similarity of the phoneme tasks to the phonemes of the English language) and ostensibly in good to excellent health (via self report). Table 1 shows the distribution for participants of each age group in the study. Demographic data regarding health status and educational level were collected on all participants and are shown in Table 2.

Table 1. Mean and Standard Deviation of Age

	Age Group (Years)				
	20-34	35-44	45-54	55-64	65-75
Mean (years)	24.73	38.00	49.27	60.80	70.80
Std Dev	3.43	3.12	4.17	3.05	2.78
N	30	30	28	25	30

Table 1. Mean and standard deviation of age of normal hearing participants involved in this study.

Table 2. Demographic Data for all Participants

Age Group (Years)	20-34	35-44	45-54	55-64	65-75
Gender:					
Male	12	8	11	3	3
Female	18	22	17	22	27
Education:					
<High School					5
High School	3		4	8	12
>High School	4	23	20	15	9
University Degree	23	7	4	2	4
Self Rated General Health					
Excellent	28	27	27	24	28
Good	2	3	1	1	2

Table 2. Demographic measures of gender, education, and self-rated health for all participants in this study. Matrix shows the number of individuals in each group.

Screening Measures

A. Audiological Measures

Because of the limitations of cross-sectional designs, participants were selected to as similar as possible with respect to factors relating to hearing. All participants were required to have hearing which bilaterally met the standards for clinically normal hearing (ANSI 1989). Each participant was required to have pure tone thresholds no greater than 20 dB HL in both ears for the frequencies of .5 kHz, 1kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz, and 8 kHz. No inter-ear differences of 10 dB HL or greater could be present. Normal middle ear status was determined by tympanometry measuring middle ear pressure, compliance, physical volume, and ipsilateral acoustic reflexes at 1 kHz and 2 kHz. All participants were required to have Type A tympanograms.

The three groups of older participants were audiologically screened by certified audiologists at the Calgary Audiology Clinic using a MAICO MIA39 audiometer and an American Electromedics AE 205 tympanometer. Audiological testing of the two younger decades of participants was conducted in the Speech and Audition Lab in the Psychology department of the University of Calgary with an Earscan Acoustic Impedance Microprocessor Audiometer.

Speech scores in quiet were determined with the Northwestern University Auditory Test Number 6 (NU-6) (Tillman & Carhart, 1966). The NU-6 is an open ended speech discrimination test that uses four lists of phonemically balanced monosyllabic words with high interlist equivalency and test-retest reliability . The test is a recorded test with the carrier phrase ' Say the word ...' and a digital tape recording of this test with a male speaker was produced by Auditec of St. Louis. The test is delivered binaurally via headphones at approximately 65 dB SPL and responses are manually recorded by the experimenter. A minimum score of 90% on this test was required for participation in the study.

B. Hearing Handicap Test

All participants subjects completed the Hearing Handicap Inventory of the Elderly - screening version (HHIE-S). The HHIE-S is a simple 10 item questionnaire developed by Ventry and Weinstein (1983) which identifies hearing impairment among individuals. Though the specificity and the sensitivity of this test are 78% and 72% respectively, it was chosen because of the advantages of its relative ease in administration and short duration time of completion. The sensitivity and specificity values are low for diagnostic purposes but acceptable for a screening tool (Lichtenstein, Bess & Logan, 1988).

Tables 3 and 4 show the relevant average screening measures and audiological data for all participants. Table 5 shows the average pure tone threshold for the right ear which was used as the test ear in all cases.

Table 3. Summary Statistics for Audiological Screening Measures

	Age Group (Years)				
Measure	20-34	35-44	45-54	55-64	65-75
NU-6 (% correct)					
mean	94	96	96	94	92
std dev	2.12	1.96	2.04	3.14	1.89
HHI (mean score)					
mean	.40	.67	.40	.53	1.07
std dev	.83	.98	.83	.92	1.03
Frequency of Type A Tympanograms	30/30	30/30	28/28	25/25	30/30
Frequency of Reflex	30/30	30/30	28/28	23/25	27/30

Table 3. Summary values for various audiological screening measures used for all listeners in this study. Metrics shown represent the group mean and standard deviation values for each age group.

Table 4. Group Mean and Standard Deviation Pure Tone Threshold expressed in dB(HL) for Each Age Group. Values shown are for the right ear.

	Mean (std dev.) in dB HL						
Frequency (kHz)	.5	1	2	3	4	6	8
Age Group							
20-34							
mean	1.667	3.000	2.667	3.000	5.333	9.00	3.33
std dev	(3.09)	(2.54)	(2.58)	(3.68)	(4.81)	(3.87)	(4.49)
35-44							
mean	1.667	3.000	2.667	3.000	5.333	9.00	3.33
std dev	(3.09)	(2.54)	(2.58)	(3.68)	(4.81)	(3.87)	(4.49)
45-54							
mean	4.667	6.667	5.667	9.667	9.000	14.00	10.00
std dev	(6.39)	(5.88)	(5.94)	(9.72)	(10.21)	(4.71)	(8.45)
55-64							
mean	5.333	8.667	7.000	9.333	8.667	15.00	15.33
std dev	(5.16)	(3.52)	(6.68)	(8.63)	(9.16)	(4.23)	(5.16)
65-75							
mean	8.333	8.667	8.667	14.00	19.00	16.33	18.33
std dev	(7.24)	(7.19)	(6.67)	(8.06)	(4.31)	(3.99)	(5.23)

Table 4. Mean pure tone thresholds in dB HL for each age group for all participants in this study. Values shown are for the right ear. Note there were no significant inter-aural differences between right and left ear thresholds for any listener.

There were no significant differences between the thresholds for right and left ears of any group. Thresholds for pure tones were analyzed with a repeated measures Analysis of Variance (ANOVA) with age as a between subjects factor and frequency as a within subjects factor. The main effects of age and frequency were significant ($p < .0001$ for each effect), as was the interaction, ($p < .0001$). Simple effects were analyzed with post hoc Scheffe's follow up contrasts computed at each test frequency. At all frequencies tested, thresholds for the eldest age group were significantly larger than thresholds for the youngest age group. At both 6 kHz and 8 kHz, thresholds for the three older age groups (45-75 years), were significantly higher than thresholds for the two youngest age groups (20-44 years).

Average thresholds can also be expressed by a single metric, the pure-tone average (PTA) which represents the average threshold of two or more frequencies. Clinically, the PTA is defined as the average of the thresholds for 500, 1000, and 2000 Hz and has been used as a predictive metric of the speech reception threshold (SRT) (Silman & Silverman, 1991). High correlations between the SRT and the PTA exist, but there are several factors which influence this such as the difference between the thresholds for corresponding frequencies and the degree and configuration of hearing loss (Dubno, Dirks & Morgan, 1984). Some researchers have argued that the PTA based upon the best two of the three frequencies should be used instead of the three frequency average (Dubno & Dirks, 1989; Jerger, 1992). For a relatively homogeneous group of participants such as those in this study who all had clinically normal hearing, the metric of the PTA can be viewed as a simplistic measure of hearing sensitivity which addresses the whole range of frequencies tested.

For the participants in this study, two metrics of the PTA were computed: PTA1 (the average of .5, 1, and 2 kHz) and PTA2 (the average of 3, 4, and 6 kHz). Therefore the PTA1 represents the average of the 'low' frequency thresholds; PTA2, the average of the 'high' frequency thresholds. Table 7 shows the means and standard deviations for the two PTA metrics for the five age groups.

Table 5. Average PTA Metrics for Each Age Group. (The metric in the matrix is hearing threshold in dB HL)

	Metric (dB HL)				
Age Group (Years)	20-34	35-44	45-54	55-64	65-75
PTA1					
mean	2.33	2.33	5.56	7.00	8.01
std dev	2.16	2.16	5.93	3.68	5.81
PTA2					
mean	4.33	4.33	9.42	10.00	14.42
std dev	2.83	2.83	7.15	4.96	4.48

Table 5. Group mean PTA measures for all listeners in this study. PTA1 is the mean of .5, 1, and 2 kHz. PTA2 is the mean of 3, 4, 6, and 8 kHz.

C. Cognitive Measures

Two subtests of the WAIS-R (WAIS vocabulary and the Digit Symbol Substitution) were used to assess cognitive functioning (Wechsler, 1981). Both of these instruments collectively evaluate stored information, visuospatial ability, perceptual motor speed, and memory. The Mini-Mental State (MMS) (Folstein, Folstein & McHugh, 1975) was employed to assess the cognitive mental state of the elderly participants (aged 55 and over). All participants scored 28 or higher out of a possible score of 30. Scores of 20 or less on the MMS are found essentially only in patients with diagnoses such as dementia, delerium, affective disorder and not in normal elderly people (Folstein, Folstein & McHugh, 1975). Table 6 shows the summary statistics of the WAIS subtests for each age group in the study.

Table 6. Summary Statistics for Cognitive Screening Measures

Age Group (years)	20-34	35-44	45-54	55-64	65-75
Measure					
WAIS-V					
mean	64.138	65.369	65.231	64.741	65.186
std dev	8.45	9.096	8.291	9.282	9.60
Digit symbol					
mean	82.40	80.93	77.67	69.87	54.29
std dev	4.08	6.04	5.74	13.86	9.75

Table 6. Group mean and standard deviation values of raw scores for the cognitive screening measures used in this study.

There were no significant differences among the groups for the WAIS vocabulary scores; however, there was a significant age-related decline in Digit Symbol Substitution scores. Post hoc follow up tests showed that scores for listeners aged 55 and over were significantly lower than those of younger listeners, and that the scores for individuals aged 65 and over were significantly different from all other groups. These results agree with previous findings that show a decline in digit symbol substitution across the decades of life (Salthouse, 1992). This metric can be generally taken to describe a slowing in motoric responses across the life span and is included here as a general measure of overall functioning. As there was no baseline measure established for any of the participants in this research to use as a comparison, it is not included in any subsequent analysis. The impact of this on auditory processing is most likely manifested in a slower response time for the 'button-press' responses, but none of these trials were structured such that responses could not be given within the appropriate time interval.

Stimuli and Procedure

The specific stimuli and procedure for glide discrimination, gap detection, frequency selectivity, and phoneme identification will be described in subsequent sections.

Results

SPSS 6.0 for the Macintosh was used for all parametric and non-parametric analyses. Where appropriate, post hoc Scheffe's contrasts were used to follow-up significant interactions. For <u>all</u> analyses, a significance level of .01 was used.

III: Psychophysical Measures

Study One : Discrimination of Frequency Glides

Purpose

The overall purpose of this study was to investigate the effect of frequency region, endpoint frequency, direction of the glide, and presence of background noise on age-related changes in discrimination of frequency glides. Frequency region was investigated by comparing threshold values for a low frequency region to a high frequency region. The effect of the 'structure' of the signal was evaluated by comparing thresholds for signals with varying onset frequencies and a common offset frequency to those with common onset frequencies and varying offset frequencies at both high and low frequency regions. Evaluation of signals in quiet and in noise provided a metric of the effect of background noise.

Glides had a constant duration of 50 ms, but changed at the same rate for an upward glide or a downward glide. If listeners track the 'rate of change' in a signal, then discrimination of signals which diverge to varying offset frequencies should not be different from signals which change at the same rate, but converge on a common offset frequency. Conversely, if listeners put more perceptual weight on the terminal frequency of a signal, then diverging signals should show lower thresholds than converging signals. If there is an asymmetry in the discrimination of glide direction, thresholds for upward and downward glides should be significantly different.

Given that large variability exists in the literature regarding age effects on discrimination, a more comprehensive psychophysical paradigm, a constant stimuli method measuring the psychometric function, was applied in this study. Obtaining psychometric functions is more time-consuming than measuring thresholds using an adaptive method (cf., Levitt, 1971). The former though, provide estimates not only of the threshold, but also of the variability of the listener's performance in terms of the slope of the psychometric function.

Participants (Described in Section II)

Stimuli

Glide signals were created on a MicroVax II computer using a cosine^2 function and digitally stored on a Macintosh II computer which controlled stimulus delivery. Signals were created at 2 different frequency regions: one centered slightly above 1kHz with a center frequency (CF) of the maximal total glide excursion of 1030 Hz; the second series was slightly above 2500 Hz with a CF of the maximal glide excursion of 2685 Hz. These frequency regions have linguistic relevance for the F2 and F3 regions of many naturally spoken phonemes in the English language particularly the stop consonants (Kewley-Port, 1982).

Two different patterns of glide trajectory, upward or downward, were created. Additionally, two different end frequency conditions were constructed: in one condition, signals started at varying onset frequencies and converged on the same offset frequency; in another, signals started at the same onset frequency and diverged to varying offset frequencies. The series of signals could therefore be described as: converging upward glides; converging downward glides; diverging upward glides; and diverging downward glides. To ease the time demands on the listeners, background noise was presented for only the converging upward and diverging downward series of signals at each frequency region for a total of twelve discrimination conditions (six conditions times two frequencies).

For ease of readership, throughout this document, the signals with a maximal center frequency (CF) of 1085 Hz will be referred to as the low frequency region signal; signals with a maximal CF 2685 Hz will be referred to as the high frequency region signals. Various abbreviations will be adopted throughout this document to facilitate both the description and subsequent discussion of the signals. For clarity the following symbols will be used: DU (diverging up); DD (diverging down); DD-N (diverging down in background noise); CD (converging down); CU (converging up); and, CU-N (converging up in background noise). Figures 4 and 5 show a schematic representation of the signals. For all series the slowest changing signal in the series was designated as the 'standard' and was used as the comparison stimulus in all pairings.

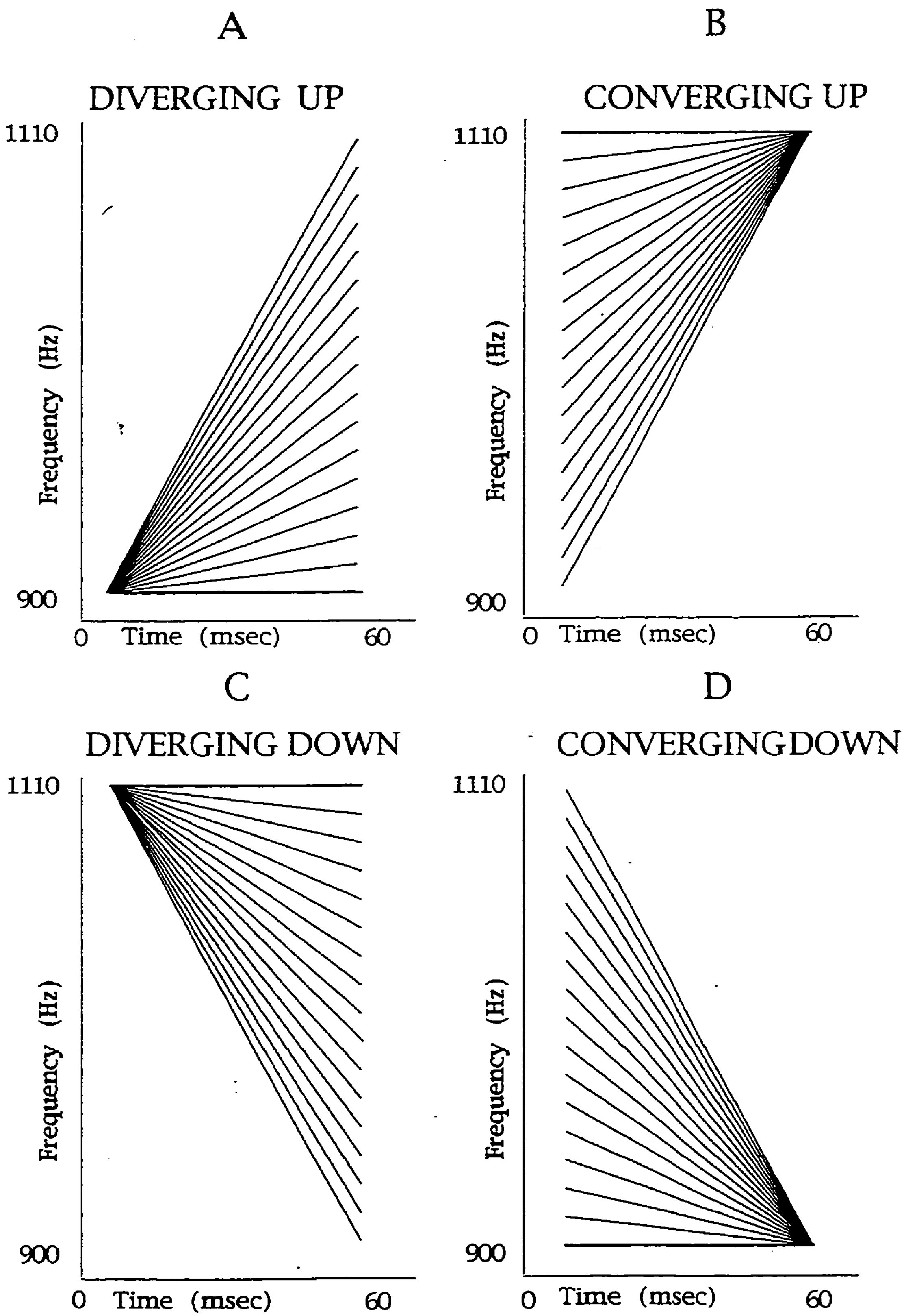
For each frequency continuum, a series of 17 gliding signals were created. At the low frequency region, signals spanned a maximal excursion of 900 Hz to 1110 Hz. For signals which had an upward trajectory and diverged to varying offset frequencies (figure 4 panel A), the initial glide began at 900 Hz and rose to 950 Hz. The second signal was 900 Hz to 960 Hz; the next was 900 Hz to 970 Hz etc. The final signal in the series was 900 Hz to 1110 Hz. For signals which had an upward trajectory that converged on a common offset frequency (figure 4 panel B), the first signal in the series began at 900 Hz and ended at 1110 Hz. The starting frequency was then increased in 10 Hz steps such that the next signal was 910 Hz to 1110 Hz. The final signal in this series was 1060 Hz to 1110 Hz. For the downward trajectory signals which had diverging offset frequencies (figure 4 panel C), the signals began at 1110 Hz and fell to 1060 Hz. The offset frequency was then decreased in 10 Hz steps to a final signal which swept from 1110 Hz to 900 Hz. For signals which had a downward trajectory and converged to the same offset frequency (figure 4 panel D), the signals began at 950 Hz and fell to 900 Hz. The offset frequency was then increased in 10 Hz steps such that the next signal was 960 Hz to 900 Hz with the final signal sweeping from 1110 Hz to 900 Hz.

The same pattern of upward and downward converging and diverging glides were created at a higher frequency region with an arithmetic CF of the maximal glide excursion of 2685 Hz. Frequency steps of subsequent signals were increased by 30 Hz. Pilot data revealed that for gliding signals these were below the threshold value for discrimination for young normal hearing listeners.

For signals which had an upward trajectory and diverged to varying offset frequencies (Figure 5 panel A), the onset frequency was 2370 Hz and the offset frequency was 2520 Hz. The offset frequency then increased in 30 Hz steps until the final signal rose from 2370 Hz to 3000 Hz. The series of signals with upward glides that converged on a common offset frequency (Figure 5 panel B) began at 2370 Hz and rose to 3000 Hz. The onset frequencies were then increased in 30 Hz steps with the final signal beginning at 2850 Hz and rising to 3000 Hz. For signals with a downward trajectory which diverged to varying offset frequencies (Figure 5 panel C) the first signal started at 3000 Hz and fell to 2850 Hz. The offset frequencies then decreased in 30 Hz steps till the final signal of 3000 Hz to 2370 Hz. The series of downward glides which converged to the same offset frequency (Figure 5 panel D) began at 3000 Hz and fell to 2370 Hz. The onset frequency of the signals then decreased in 30 Hz steps till the final signal of 2520 Hz to 2370 Hz was achieved.

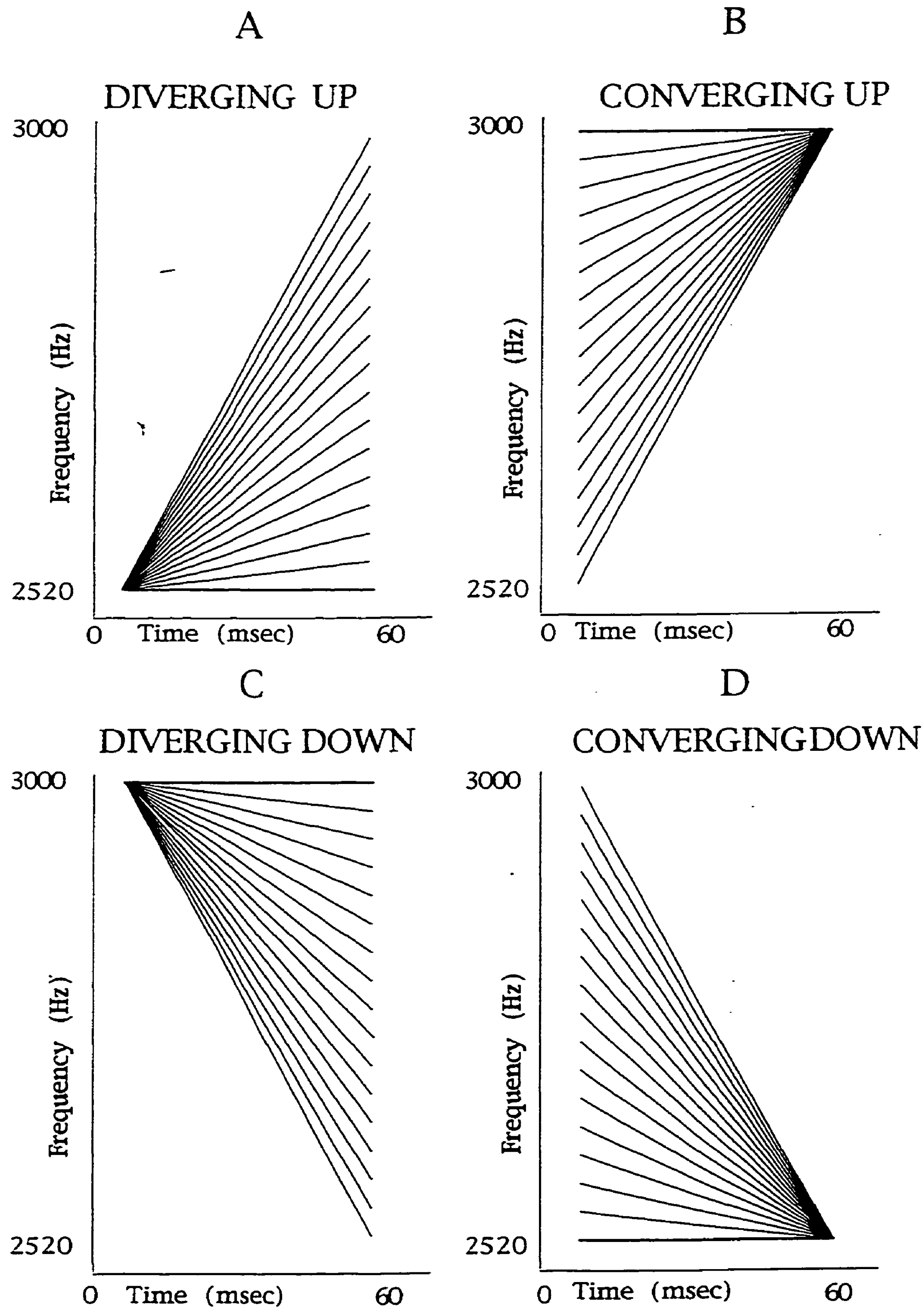
Signals were constructed such that the CF of each glide was roved over a range of frequencies. At the low frequency region, Δ CF spanned a range of 80 Hz from 1005 Hz to 1085 Hz. At the high frequency region, Δ CF spanned a range of 240 Hz from 2685 Hz to 2925 Hz. As the slowest changing signal was the comparison stimulus, CU and DD signals had a decrement in ΔF relative to the onset or offset frequency of the standard respectively. Conversely, for CD and DU signals there was an increment in ΔF relative to the onset or offset frequency of the standard respectively.

Figure 4. Schematic representation of frequency glides at the low frequency region. The standard comparison signal was the slowest changing signal in each series and is shown as a bold line. As described in the text, converging upward(CU) and diverging downward (DD) signals had a decrement in ΔF onset or offset; diverging up (DU) and converging downward (CD) signals had an increment in ΔF onset or offset.



A
DIVERGING UP
1110
900
Frequency (Hz)
0 Time (msec) 60
B
CONVERGING UP
1110
900
Frequency (Hz)
0 Time (msec) 60
C
DIVERGING DOWN
1110
900
Frequency (Hz)
0 Time (msec) 60
D
CONVERGING DOWN
1110
900
Frequency (Hz)
0 Time (msec) 60

Figure 5. Schematic representation of frequency glides at the high frequency regions. The standard comparison signal was the slowest changing signal in each series and is shown as a bold line. As described in the text, converging upward (CU) and diverging downward (DD) signals had a decrement in ΔF onset or offset; diverging up (DU) and converging downward (CD) signals had an increment in ΔF onset or offset.


A
DIVERGING UP
3000
2520
Frequency (Hz)
0 Time (msec) 60
B
CONVERGING UP
3000
2520
Frequency (Hz)
0 Time (msec) 60
C
DIVERGING DOWN
3000
2520
Frequency (Hz)
0 Time (msec) 60
D
CONVERGINGDOWN
3000
2520
Frequency (Hz)
0 Time (msec) 60

Discrimination thresholds were determined under two listening conditions: quiet and in the presence of speech spectrum noise which was low pass filtered at 1kHz and had a 10dB per octave roll off to simulate the long term spectra characteristics of speech. The speech spectrum noise was produced on digital tape by Auditec of St Louis. and was presented ipsilaterally at a spectrum level of 35 dB. Speech spectrum noise was used to simulate the presence of a consonant embedded in background speech noise.

After transference to a Macintosh II computer, digital outputs of the signals were sampled at 10 kHz, fed to a Macpanel, passed through a mixer (Sony 48134), low pass filtered at 4 kHz through two filters in sequence each with a slope of 48 dB/oct, and output to an Industrial Acoustics double walled anechoic chamber. Stimuli were delivered monaurally to the right ear through Kros Pro/4x headphones at a presentation level of 60 dB SPL. Calibration of sound pressure levels at the headphones was measured with a Bruel and Kjaer impulse precision sound level meter (Bruel and Kjaer type 2240) and a Bruel and Kjaer artificial ear (Bruel and Kjaer type 4153) and a 0.5 in. microphone (Bruel and Kjaer 4960). For the noise conditions the digital tapes were played from a Sony Digital Tape Recorder (ES-75) and mixed with the glide signal in the mixer before delivery to the headphones. The noise was played continuously during the background noise condition.

Procedure

A two-alternative forced-choice (2AFC) paradigm was used to determine the smallest discriminable differences that individuals could determine. Each trial consisted of two stimuli with an inter-stimulus interval (ISI) of 500 ms and listeners responded 'same' or 'different' via pushing one of two buttons on a board. Following presentation of each trial, there was a 5 second response time in which responses were recorded. If there was no response from the listener, the computer program generated another trial of two stimuli. Each stimulus in the continuum was paired with the standard 20 times for a total of 320 trials. Fifty 'catch trials' were incorporated into the experimental sessions to serve as a metric of response bias creating a total of 370 trials. To avoid inadvertently 'priming' listeners to respond the 'same' to trials which included the standard stimulus and target stimuli close in proximity to the standard, the catch trials were composed of pairings of the signals most removed from the standard. Specifically, as the standard signal was arbitrarily designated as signal #1, only signals #15, #16, and #17 (i.e., those at the extreme end of the continuum) were used as the signals in the catch trials.

Each continuum of signals at both frequency regions were presented in blocks of 370 trials. Specific order of trials for each continua presented were randomly created by the computer for each listener. Each trial consisted of the standard stimulus and one of the other 16 signals in the series with the standard being either the first or the second member of the pair an equal number of times. Each series of signals were tested within one block though the order of experimental trials within each block was randomized for each participant.

At the beginning of each block, a series of 75 practice trials were given. The practice trials consisted of the extreme stimuli paired with the standard 50 times and 25 catch trials. The intention of the practice trials was not to achieve asymptotic performance, but to establish that each listener understood the demands and the instructions of the task. This assurance of sufficient task familiarity was a judgment determined by the experimenter upon examination of the practice trials results which had to be a minimum of 75% correct.

Results

Due to the large variability which is seen in aging studies, a method of analyses had to be determined which minimized the intra-listener variability when determining numerous psychometric functions from numerous individuals over numerous days. To this end, a method of fitting psychometric functions to binary data, probit analysis, was used.

Data for each discrimination tasks were transformed into percentage correct scores as a function of the frequency separation between a target stimulus and the standard in each series. Percentage correct data were then transformed into probit scores. (See Appendix A for an illustration of the relationship between probit scores and percentage correct scores). Probit regression models can be modeled as a class of generalized linear models in which the response probability function is binomial (Chung, 1999). In a binary response model for variable Y, the probit regression model has the form:

$$P = \Phi(\beta x) \tag{4}$$

where P is the probability of a response, Φ is the cumulative standard normal distribution; β is the parameter vector, and X is the explanatory vector .

In probit analysis, percent correct scores from a 2AFC task are first transformed to probability units or 'probits' (Chung, 1999; Finney, 1971; Helwett & Plackett, 1985) based on a rescaled cumulative normal distribution. Psychometric functions are then determined by an iterative weighted regression process that yields maximum likelihood of the y-intercept and slope parameters. The weighted regression line can then be plotted in probits versus signal parameter space (Helwett & Plackett, 1985).

Watson, Franks, and Hood (1972) reported significant day-to-day variability associated with psychometric slopes obtained using a linear regression analysis. McKee, Klein, and Teller (1985) suggested that at least a portion of slope variability may be attributable to binomial variability which is asymmetric in relationship to the data. Specifically, points near chance are estimated with less confidence than are those near 100%. Despite this asymmetry, the linear regression procedure gives equal weight to each point. In contrast, probit analysis accounts for asymmetry by weighting data points in inverse proportion to their estimated binomial probability such that progressively smaller weight is placed on data obtained at levels that are estimated with less certainty. Arehart, Burns, and Schlauch (1990) reported less variability in slope values of functions measured across days using probit analysis versus using linear regression methods.

Probit transformations were obtained for each individual for each glide signal discrimination task. It is possible to derive probits for several groups of subjects using the 'grouping' variable as an extra parameter. However, while the analysis allows for individual variation in the slope parameters it does not do so for the intercept values. For this reason, individual data were transformed and uniquely fitted with probit values. Thresholds were measured from the 70% correct position on the psychometric function.

Figure 6 shows an example of the fitting of the raw data from one listener to a probit function. In Panel A percentage correct scores are plotted with frequency expressed on a linear frequency scale; in Panel B, percentage correct scores are plotted with frequency expressed on a log scale.

Results

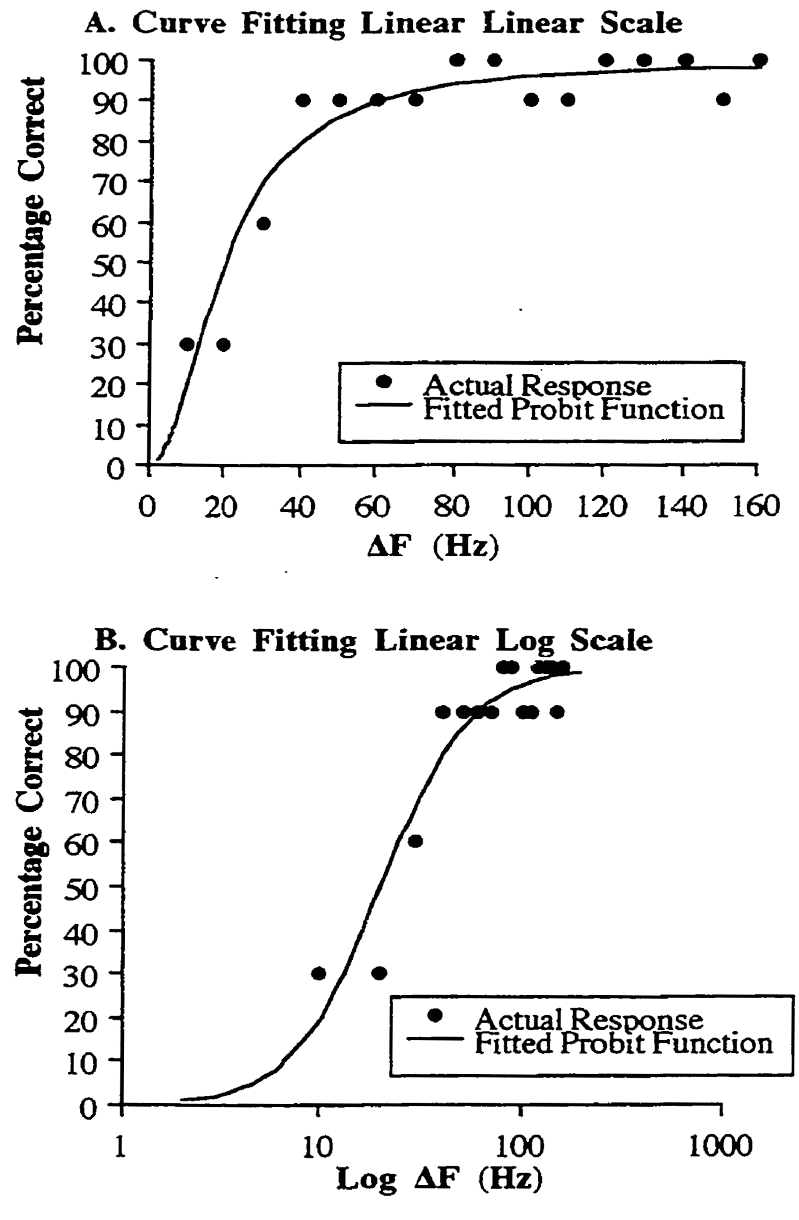
i. Catch Trial Performance

Catch trial performance was analyzed as a metric of response bias and data from individuals who scored less than 75% on catch trial performance was eliminated from analysis involving that particular task. Performance ranged from 80 to 100 % correct across tasks and showed no significant effects for age or signal type. Examination of the data revealed only two instances where individuals scored very low thresholds that were coupled with highly erroneous catch trial performance. No participant scored poorly on catch trial performance and then scored well on the 'different', or experimental trials.

ii. Data Screening

Data were screened for normality of distribution, kurtosis, and presence of univariate outliers. Only one score on all of the tasks had to be eliminated. One task, converging signals in noise for the elderly, showed significant negative skewness (Shapiro-Wilks values significant at the .001 level), and in this case the data were then reflected and square root transformed (Tabachnick & Fidel, 1989). Therefore, the data screening resulted in the loss of one data point based on univariate outliers and transformation of one condition.

Figure 6. Example of Individual Probits and Raw Data. Panel A shows data are from one young subject for discrimination in the low frequency region and are plotted on linear/linear scales of percentage correct and Hz difference. Panel B shows a linear/log scale.



iii. Group Means and Standard Deviations of the Variables

The first level of analysis was to compare group means and standard deviations of the measures. Though thresholds for all participants were clinically normal, there were significant differences among the groups particularly at the high frequency region (Table 4). Therefore, data were analyzed with a series of analyses of covariance (ANCOVAs) with PTA2 (Table 5) as a covariate. Higher order interactions were analyzed with Scheffe's post hoc contrasts, and all significant effects reported are at an alpha level of at least $p=.01$.

Split-half reliability measures showed that responses were significantly different over the second 50% of the trials in a block versus the initial 50% of trials for only 15 out of the 143 listeners in the study, and all 14 listeners were 44 years and younger. Though this represents only 10% of the total sample in the study, it is 25% of the total sample 44 years and younger. Further inspection of the data showed no consistent trend in either type of signal, or order effects. Therefore, this data was included as is, in the analysis.

Trial presentation of the stimuli were designed such that the standard (the slowest changing signal) was the first member of the pair of signals for 50% of the trials, and was the second member of the pair on the other 50% of the trials. Therefore, if the age-related findings are in part determined by a decay of stimulus information, then temporal order effects should be evident among these trials. Specifically, if the sensory output of the first signal has decayed to such a degree by the presentation of the second signal, then trials where the standard was the second signal should be more difficult to discriminate. This would be because information from the first signal would not be as saliently different from the slow changing standard. There were no significant effects for the order of stimuli for any of the listeners in any of the age groups when the data were analyzed this way.

a. Low Frequency Region

Figure 7 illustrates group means and standard errors for each of the 6 glide conditions. Table 7 shows the group means and standard errors (in parentheses) for ΔF for each of the signals and age groups. Also shown are the threshold values for noise conditions, however as not all conditions were presented in noise, these signals are analyzed separately in a later section. As the glide signals had an inherent rate of change in the signal, thresholds could also be expressed as rate of change (in Hz/ms) normalized to the rate of change in the standard. These values represent the required change in Hz/ms above the change in the standard that was necessary for discrimination. The standard in the low frequency region had a rate of change of .833 Hz/ms. The standard in the high frequency region had a rate of change of 2.5 Hz /ms. Appendix B shows threshold values expressed in this way.

<u>Figure 7</u>. Group means and standard errors for 5 age groups for glide conditions in the <u>low</u> frequency region. See text for explanation of abbreviations.

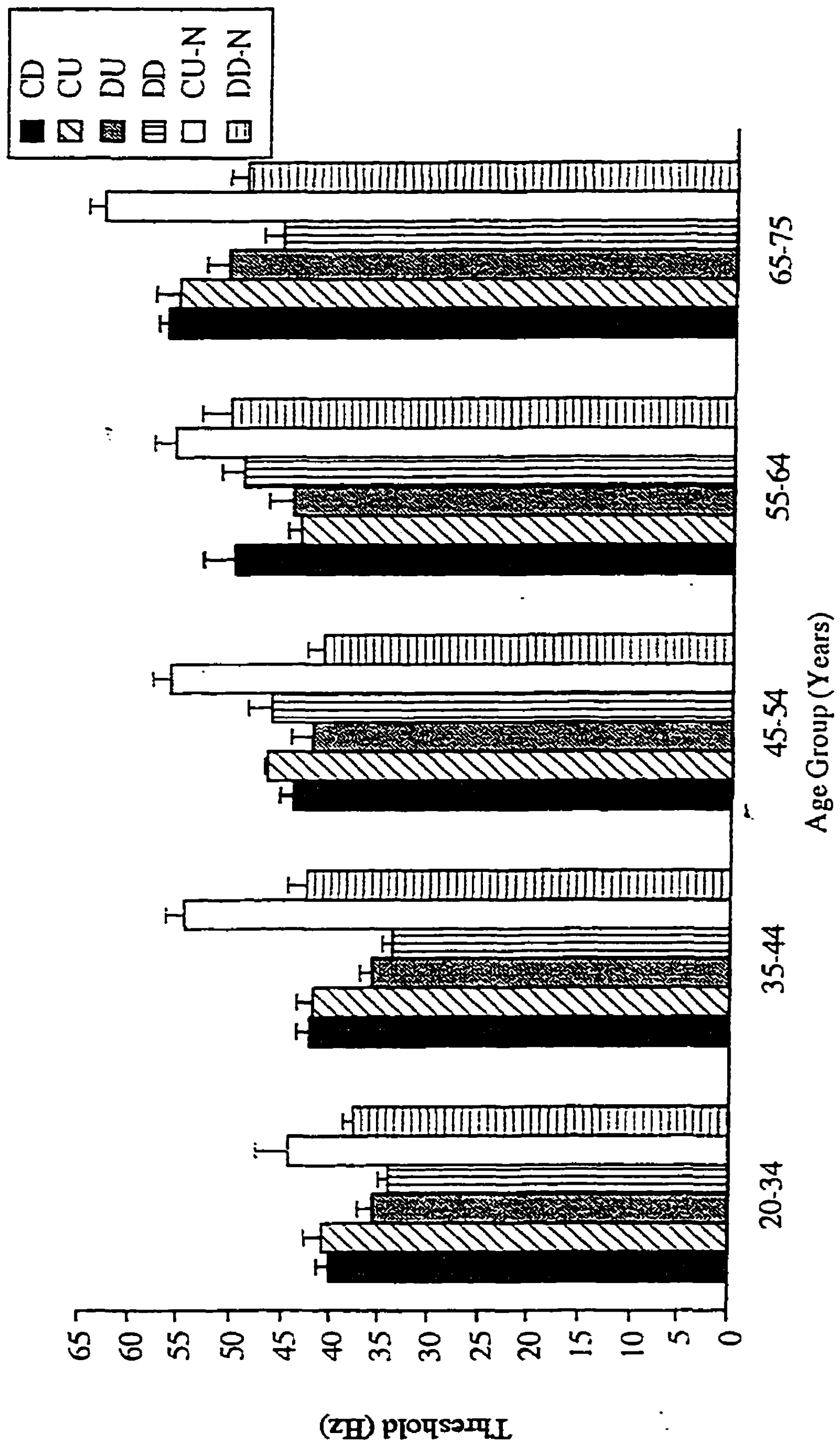


Table 7. Group mean thresholds and standard errors in parenthesis with ΔF expressed in Hz for the **low** frequency region glides.

	Age (years)				
	20-34	35-44	45-54	55-64	65-75
Signal Condition					
du	35.63 (1.42)	35.85 (1.42)	42.22 (2.09)	44.34 (2.38)	50.92 (2.15)
dd	33.86 (1.11)	33.74 (1.07)	46.31 (2.29)	49.21 (2.08)	45.69 (1.81)
cu	40.80 (2.04)	41.91 (1.75)	43.56 (.19)	46.86 (1.5)	55.51 (2.45)
cd	40.14 (1.41)	42.15 (1.51)	44.23 (1.34)	49.94 (2.92)	56.77 (.99)
cu-n	44.48 (3.16)	54.70 (1.75)	56.25 (1.76)	55.83 (2.28)	63.05 (1.61)
dd-n	37.83 (1.08)	42.78 (1.7)	41.19 (1.61)	50.62 (2.5)	49.23 (1.59)

Table 7. Group mean thresholds for the six signal conditions at the low frequency region. See text for explanation of abbreviations of signal conditions. Values in parentheses are standard errors of the mean.

At the low frequency region, the main effects of endpoint frequency (converging versus diverging), transition direction (upward versus downward) and age group were significant, [$F(1,137) = 368.45$, $p<.0001$]; [$F(1,137) = 296.91$, $p <.0001$]; and [$F(4,137) = 12.89$, $p<.0001$] respectively. The two-way interactions between age group and endpoint frequency and age group and transition direction were significant; [$F(4,137)=6.77$, $p <.0001$], and [$F(4,137) = 2.91$, $p <.0001$] respectively. The three-way interaction between age group, endpoint frequency, and transition direction was not ($p=.178$).

Post hoc analysis revealed that for CD signals, 65-75 year olds required larger differences in frequency onset ($M = 56.77$ Hz) relative to 20-54 year olds, [$F(4,137) = 7.839$, $p < .00001$]. This means that signals had to change, on average, .95 Hz/ms faster for this age group to detect a difference. For CU signals, 65-75 year olds were significantly different from the only the two youngest age groups (20-45 years), [$F(4,137) = 4.752$, $p < .001$], and required a ΔF of 55.5 Hz (.93 Hz/ms change) between signals, compared to 40.8 Hz (.68 Hz/ms) for the youngest subjects or 41.9 Hz (.7 Hz/ms) for 35-44 year olds. 45-64 year olds did <u>not</u> perform significantly different from either the youngest or the eldest participants.

Thresholds for DD signals showed significant differences among listeners aged 20-44 years and all other age groups, [$F(4,137) = 9.64$, $p < .00001$]. Listeners aged 45-75 years required significantly larger differences for discrimination, and mean ΔF for frequency offset ranged from 45.69 Hz to 49.21 Hz. For DU signals, 65-75 year olds had significantly higher thresholds ($\Delta F = 50.92$ Hz) than 20-34 year olds ($\Delta F = 35.63$ Hz) and 35-44 year olds ($\Delta F = 35.85$ Hz). For listeners aged 45-64 years ΔF was 42.22 Hz and 44.33 Hz respectively, and was not significantly different from the youngest groups.

The effects of endpoint frequency and transition direction were examined within each age group. There was no effect for the direction of the transition, nor a significant interaction between glide direction and endpoint frequency for any age group. For the two youngest groups (20-44 years) there was a significant main effect for diverging versus converging signals. Converging signals required significantly larger differences for discrimination [$F(1,28) = 11.18$, $p = .006$] with higher ΔF for converging signals (M=40.47 Hz) relative to diverging signals, (M=34.75 Hz) for 20-34 year olds and for 35-44 year olds ($\Delta F = 42.03$ Hz for converging; 34.79 Hz for diverging) [$F(1,28) = 16.76$, $p=.001$]. Terminal frequency was not a significant factor for listeners aged 45-54 years (M=43.88 for converging; M=44.27 for diverging), nor for 55-64 year olds endpoint frequency (M=48.40 Hz for converging; M=46.78 Hz for diverging). The eldest group of listeners, 65-75 year olds, showed the same pattern of a significant effect for endpoint frequency noted for younger listeners with diverging signals being significantly easier to discriminate than converging signals (ΔF=48.31 Hz for diverging; 56.14 Hz for diverging) [($F(1,28) = 17.69$, $p<.001$)].

Summarizing the major trends in the data at the low frequency region for signals in quiet, the effect of transition direction was not significant. There was an effect for endpoint frequency with converging signals requiring higher thresholds than diverging signals for all age groups except the 45-54 year olds. There was no effect for discriminating signals with an increment in frequency offset (DU) compared to signals with a decrement in frequency offset (DD), nor a significant effect for detecting a decrement in frequency onset (CU) compared to an increment in frequency onset. Increased thresholds for 65-75 year olds were noted in all listening conditions.

b. High Frequency Region

Figure 8 illustrates group means and standard errors for the six glide conditions in the high frequency region. Average group thresholds and standard deviations for discrimination of glides in the high frequency region expressed in ΔHz are shown in Table 8. (see Appendix C for thresholds expressed as change in Hz/ms normalized to the rate of change in the standard).

Figure 8. Group means and standard errors for the five age groups in the high frequency region. See text for explanation of the abbreviations.

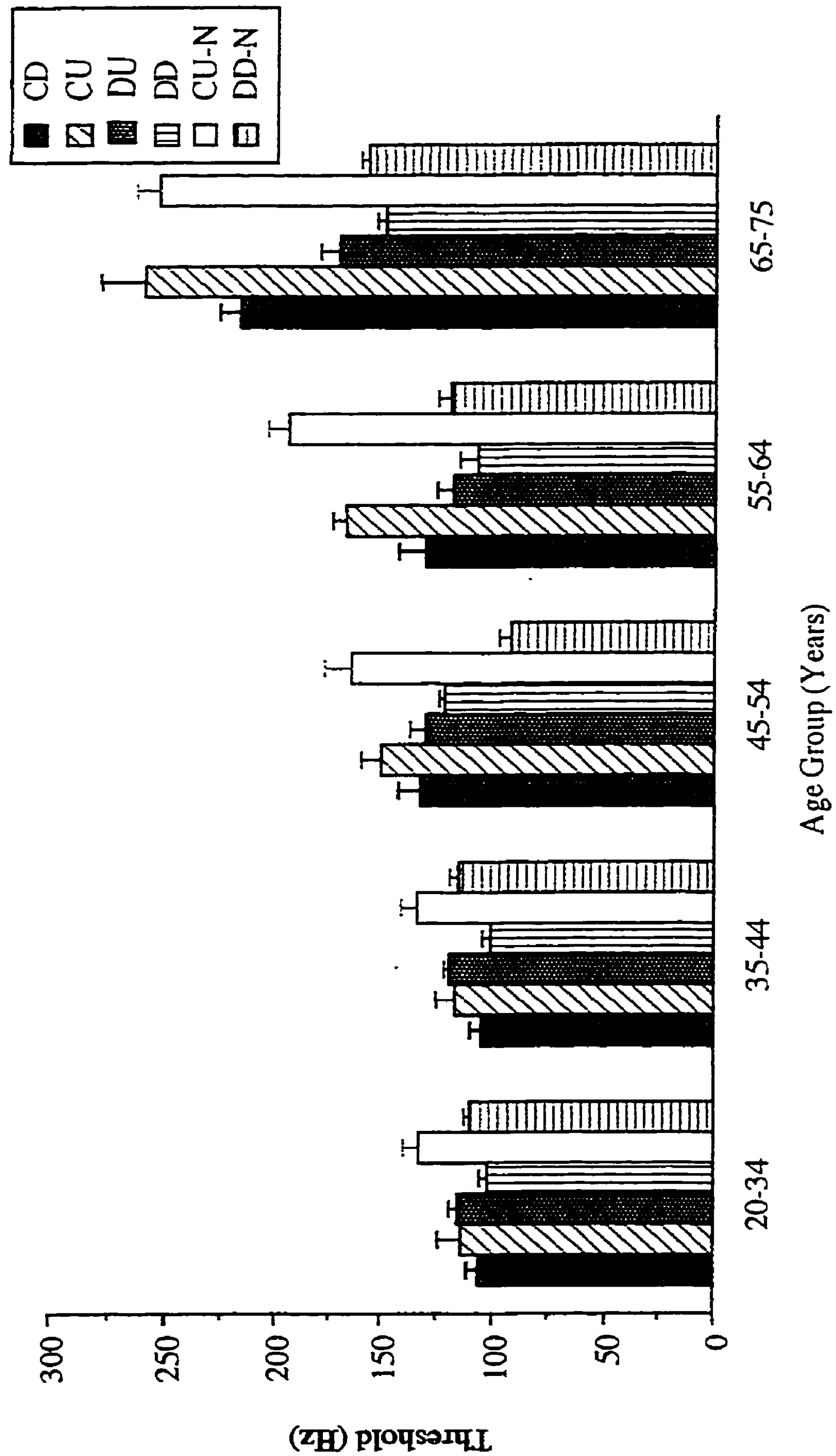


Table 8. Group mean ΔF thresholds and standard errors in parenthesis expressed in Hz for the **high** frequency region glides.

	Age (yrs)				
	20-34	35-44	45-54	55-64	65-75
Signal Condition					
du	115.17 (3.9)	118.86 (2.9)	130.61 (7.6)	117.77 (7.6)	171.22 (9.2)
dd	101.98 (4.3)	100.68 (4.2)	120.78 (2.7)	107.20 (8.1)	149.33 (4.2)
cu	113.3 (10.1)	115.5 (9.5)	151.2 (8.4)	166.9 (6.6)	259.9 (18.4)
cd	106.4 (5.2)	104.3 (5.5)	133.3 (9.9)	130.5 (12.7)	217.2 (8.7)
cu-n	132.23 (8.7)	134.31 (7.3)	164.71 (12.1)	194.60 (9.8)	254.41 (9.9)
dd-n	109.90 (3.5)	116.58 (3.6)	92.05 (5.3)	118.61 (5.9)	157.03 (3.9)

Table 8. Group mean thresholds in Hz for the six listening conditions at the high frequency region. Values in parentheses are standard errors of the mean. See text for explanation of abbreviations of signal conditions.

At the higher frequency region, the main effects of age group, endpoint frequency, and transition direction were all significant; [$F(4,136)=28.21$, $p < .0001$]; [$F(1,61)=18.96$, $p < .0001$]; [$F(1,136)=20.70$, $p < .0001$] respectively. The only significant two-way interactions were between endpoint frequency and age group, [$F(4,136)=6.98$ $p<.0001$], and the interaction between endpoint frequency and transition direction, [$F(1,136)=326.05$, $p < .0001$]. The three way interaction between age group, endpoint frequency, and transition direction was not significant.

Post hoc comparisons were conducted on each of the signal types for each age group differences. For CD signals, 65-75 years needed larger differences between signals than did the other four age groups, [$F(4,136)=13.39$, $p < .00001$]. For 65-75 year olds, ΔF was 217.18 Hz (3.62 Hz/ms); differences for the other four age groups ranged from 104.43 Hz, 1.74 Hz/ms (for the 35-44 year olds) to 133.29 Hz, 2.22 Hz/ms (for the 45-54 year olds). For CU signals, ΔF for listeners aged 45 and over were all significantly higher relative to 20-44 year olds [$F(4,136)=13.375$, $p < .00001$]. ΔF ranged from M= 259.98 Hz for 65-75 year olds to 151.16 Hz for 45-54 year olds to 113.3 Hz for 20-34 year olds.

Diverging signals in the high frequency region showed a different pattern of results. For DD signals, ΔF was significantly higher for 65-74 year olds (149.33 Hz) than three of the other age groups. Two of these were the youngest age groups: 20-34 years (M=101.98 Hz); 35-44 years (M=100.68 Hz); and, the third was the 55-64 year olds (M=107.196 Hz). The 45-54 year olds were not significantly different from the eldest age group (M=120.87 Hz). This same pattern of results was noted in DU signals. A ΔF

value of 171.22 Hz for the 65-74 year olds was not significantly different from ΔF for the 45-54 year olds (M=130.609 Hz). For both of these age groups, ΔF was significantly higher than that for the two youngest age groups (M=115.17 Hz, and M=118.86 Hz for the 20-34 year olds and the 35-44 year olds respectively), and the 55-64 year olds (M=117.768 Hz).

Analyses on the thresholds within each group showed that no significant effect for signal type for listeners 20-44 years of age ($p>.01$). Listeners aged 45 and over did show a significant effect for signal type. CU signals were significantly more difficult to discriminate for 45-54 year olds; 55-64 year olds; and for 65-75 year olds ($p>.001$ in all comparisons). Listeners aged 55 and over also showed a significant effect for the transition direction with thresholds being higher for converging signals than for diverging signals. For 55-64 year olds mean ΔF was 112 Hz for diverging; 148 for converging. For 65 years and older, mean ΔF was 160 Hz for diverging; 238 Hz for converging.

To summarize, for all signal conditions, 65-75 year olds show larger ΔF values. The frequency dependent effect of glide direction is a function of signal type. Only signals which converged on the same offset frequency were more difficult to discriminate, but this effect is noted only for listeners aged 45 and over. For listeners aged 44 and younger, there is no effect for the terminal frequency, or the direction of the glide.

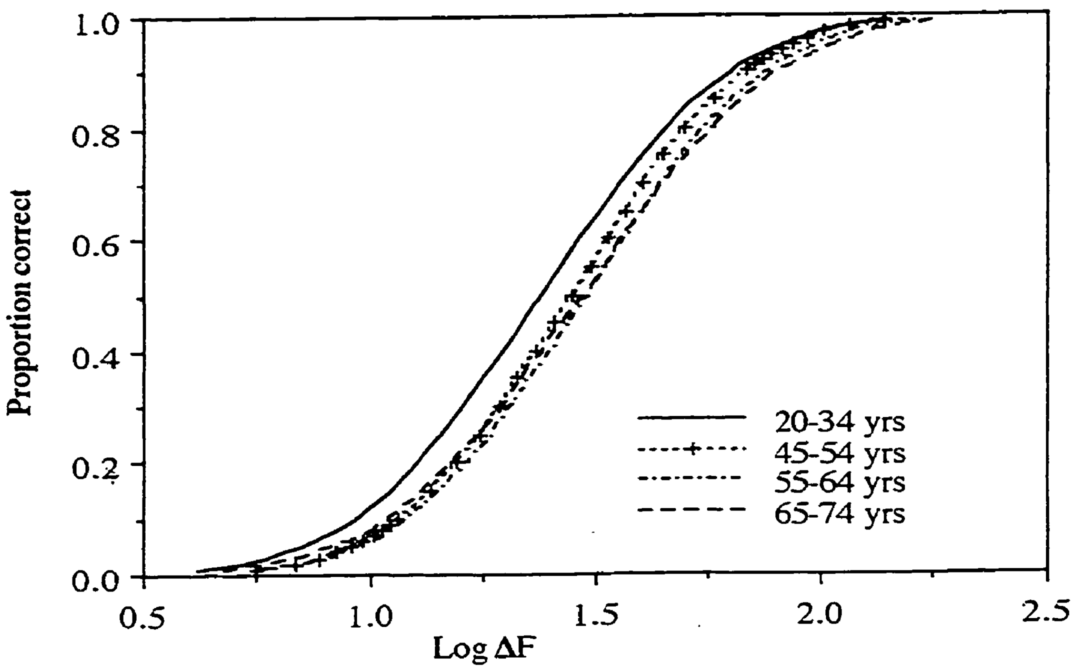
iv. Psychometric Functions

a. Low Frequency Region

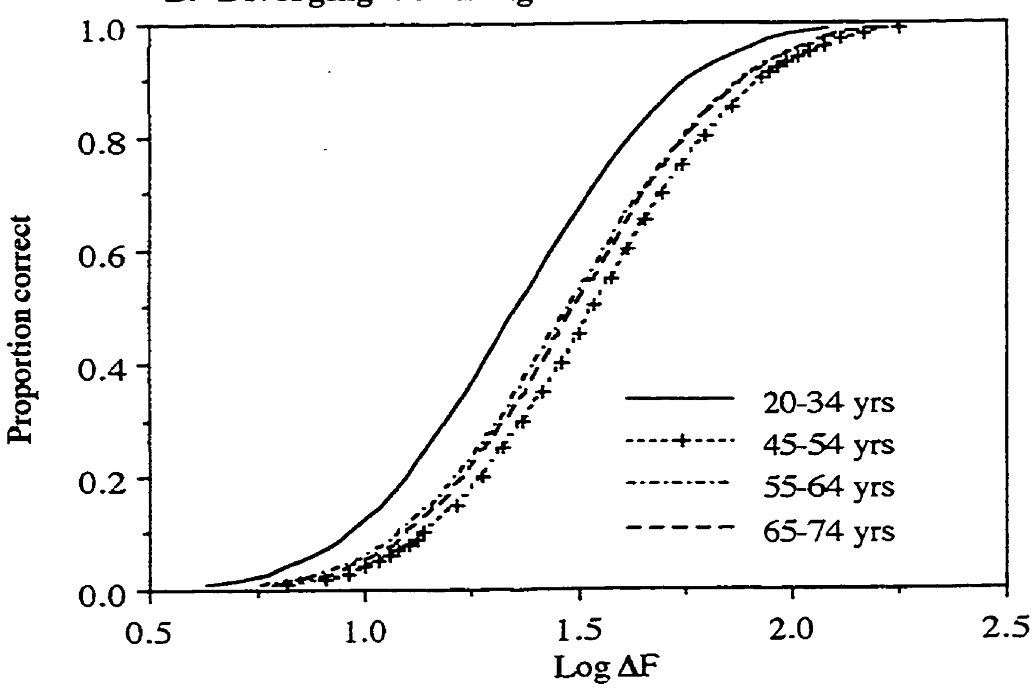
Figure 9 (panels A to F) show the group psychometric functions for all the signal conditions in the low frequency region. As the functions for the 20-34 and 35-44 year olds were overlaid in all conditions except for CU signals in noise, for clarity only the functions for the other 4 age groups are shown in panels A to E. The most distinct pattern emerges in CU signals in noise (panel F). The youngest group of listeners have a function which is considerably shallower than the other listening groups. For most listening conditions, the functions for the elderly are shifted to the right of the other listening groups. Table 9 lists the means and standard errors of the slope values for the various glide discrimination tasks in the low frequency region.

Figure 9. Psychometric Functions for each signal condition (panels A to F) in the low frequency region. Values are proportion correct plotted as a function of Log ΔF.

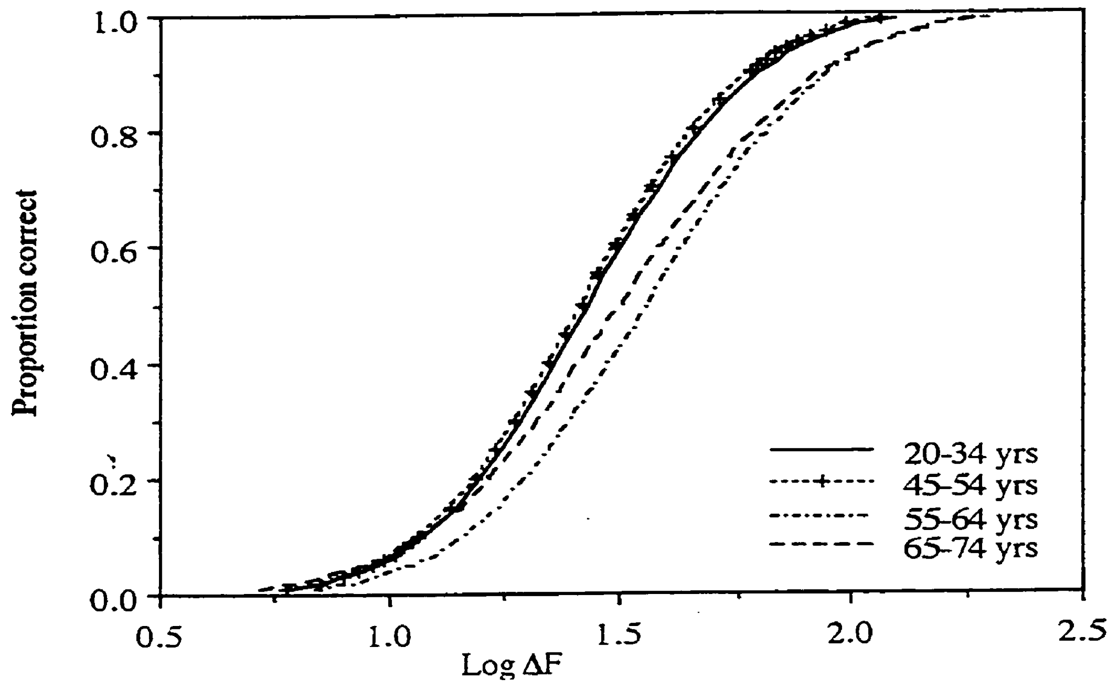
A. Diverging up signals



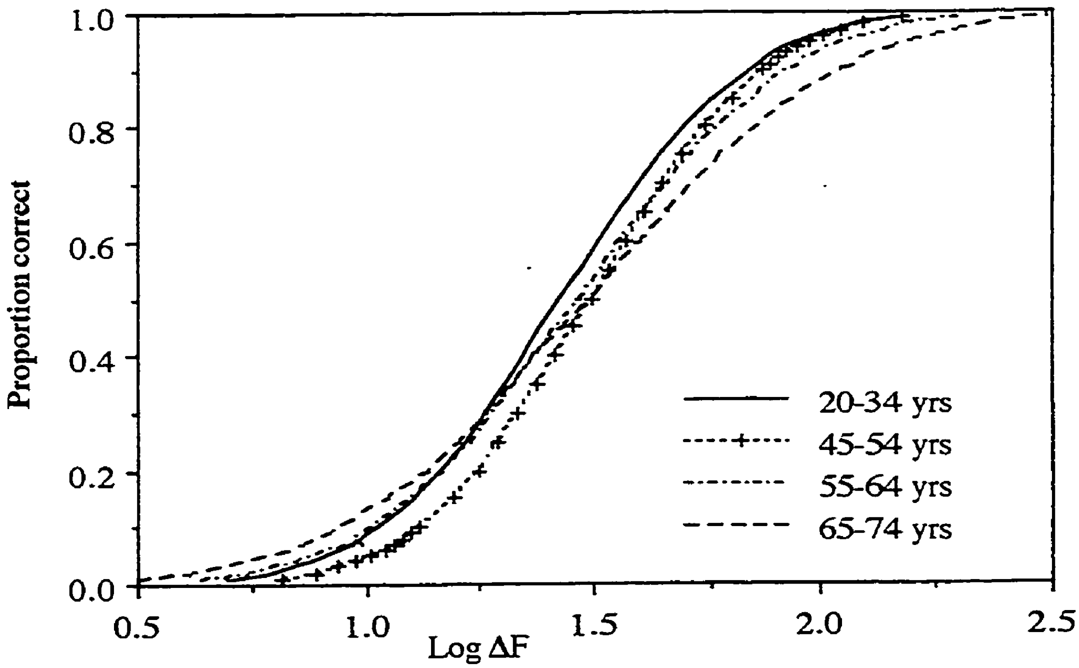
B. Diverging down signals



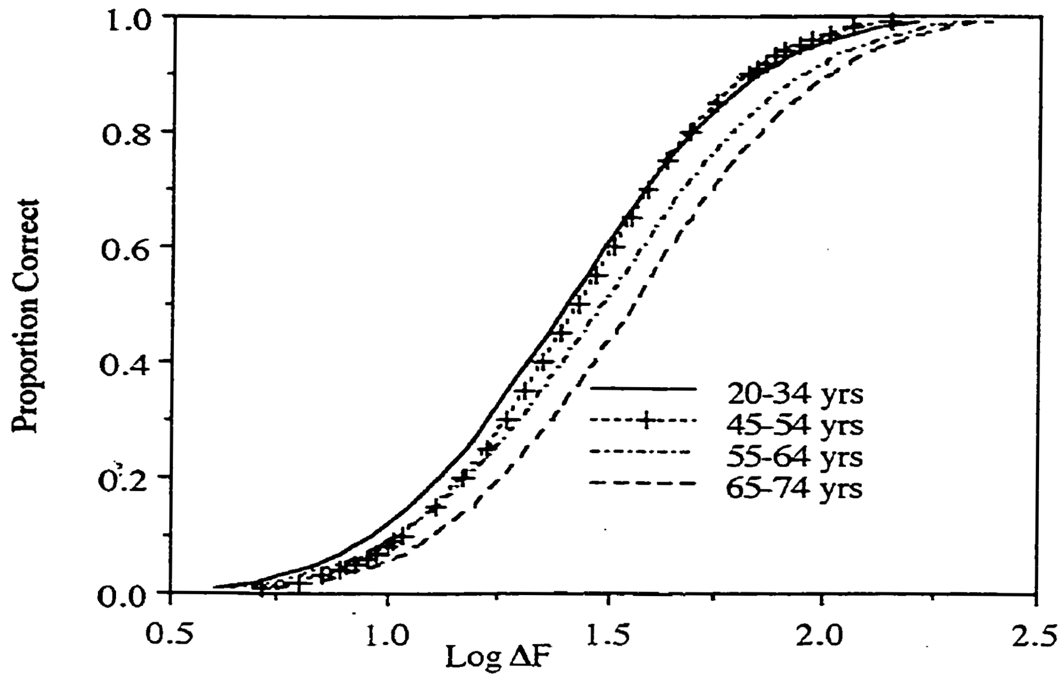
C. Diverging down signals (noise)



D. Converging up signals



E. Converging Down Signals



F. Converging signals (noise)

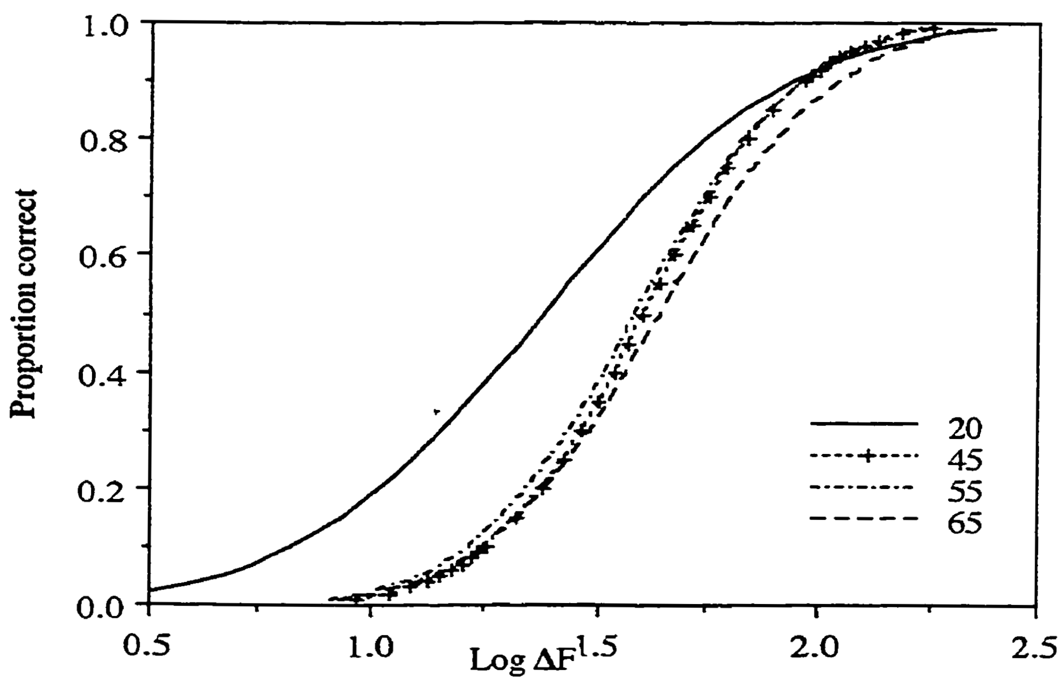


Table 9. Probit Slope Means and Standard Errors in Probits / Log ΔF for Each Discrimination Task in the **Low** Frequency Region.

	Signal Condition					
AGE	DU	DD	DD-N	CD	CU	CU-N
20-34	3.32 (.18)	3.53 (.2)	3.95 (.2)	3.56 (.28)	3.63 (.16)	2.92 (.15)
35-44	3.32 (.18)	3.58 (.21)	4.14 (.16)	3.56 (.27)	3.76 (.16)	3.25 (.19)
45-54	3.45 (.17)	3.41 (.18)	3.67 (.15)	3.18 (.13)	3.29 (.19)	3.64 (.21)
55-64	3.61 (.19)	3.07 (.12)	3.38 (.15)	3.03 (.15)	3.03 (.17)	4.03 (.22)
65-75	3.46 (.16)	3.63 (.17)	3.36 (.13)	3.17 (.19)	2.41 (.09)	3.21 (.22)

Table 9. Group mean slope values for psychometric functions for each discrimination task in the low frequency region. Values in parentheses are standard errors of the mean. Values in the matrix are in Probits / Log ΔF. See text for explanation of abbreviations of signal conditions.

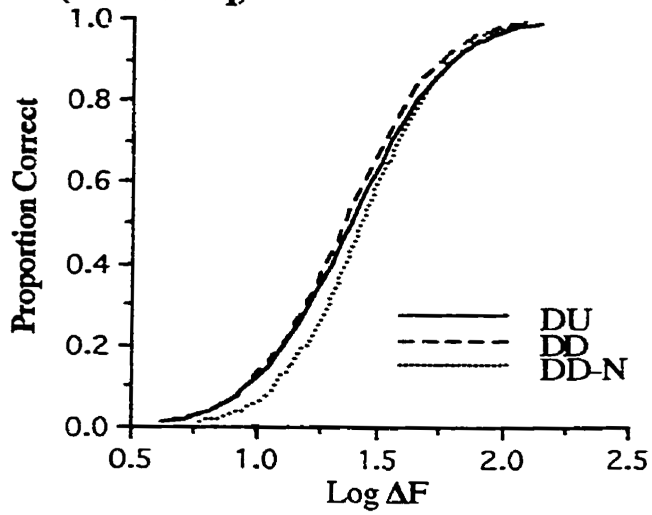
Factorial ANCOVAs with PTA2 as a covariate were conducted on the slope values with 2 levels of endpoint frequency (converging versus diverging) and 2 levels of transition direction (upward versus downward). The main effects of age group, endpoint frequency, and transition direction were not significant, ($p=.168$, $p=.671$, $p=.836$ respectively). The two way interaction between age group and endpoint frequency was significant, [$F(1,136)=8.34$, $p < .001$]. Neither of the two way interactions between age group and transition direction nor endpoint frequency and transition direction reached significance ($p=.418$, $p=.964$ respectively). The three way interaction between age group, endpoint frequency, and transition direction also did not reach significance ($p=.3$).

Simple main effects with post hoc Scheffe's contrasts were used to assess age differences for the interaction between age and endpoint frequency. Only the slopes of the CU signals (panel D, figure 7) for 65-75 year olds were significantly shallower than the slopes of 20-34 year olds or 35-44 year olds (2.414 probits/log Hz compared to 3.631 probits/log Hz and 3.757 probits/log Hz). Therefore, for the low frequency region there was no effect for the direction of the transition on the slope values. The only significant effect noted was for upward glides converging on the same offset frequency, and only for the eldest group of listeners.

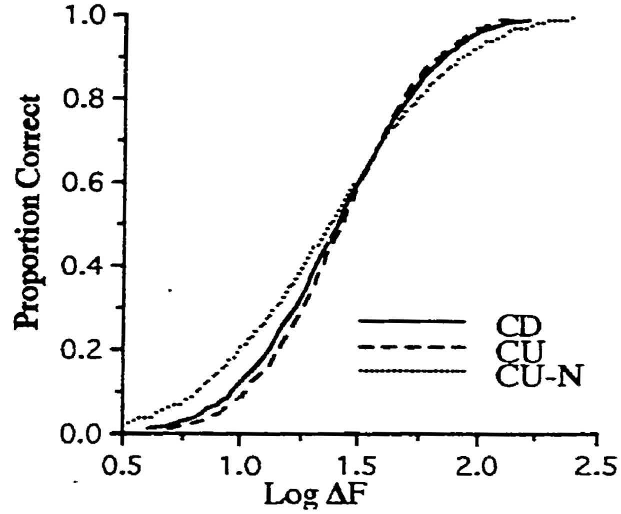
Psychometric functions for signal type within each age group are shown in Figure 10, panels A through J.

Figure 10. Psychometric functions for signal type for each age group in the low frequency region. Values are proportion correct plotted as a function of ΔF for the low frequency region.

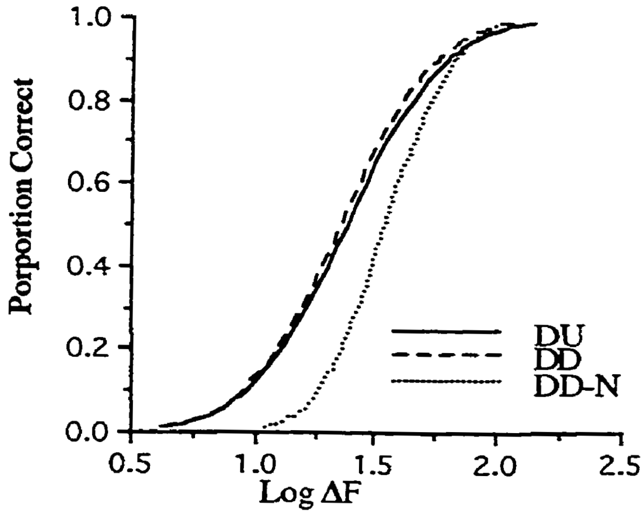
A. Diverging Signals (20-34 yrs) (Low Freq)



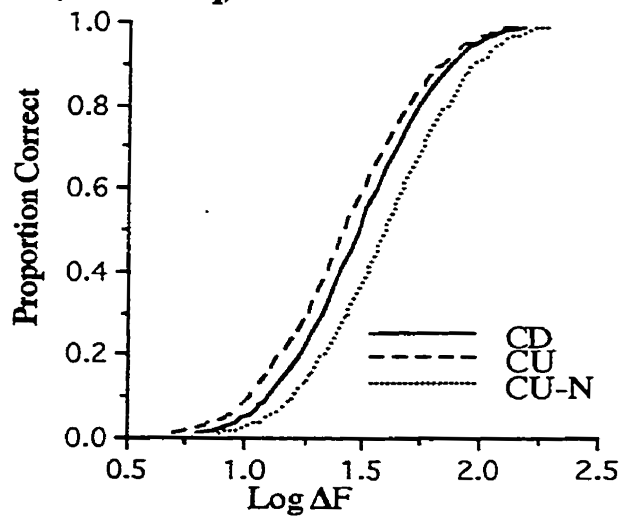
B. Converging Signals (20-34 yrs) (Low Freq)



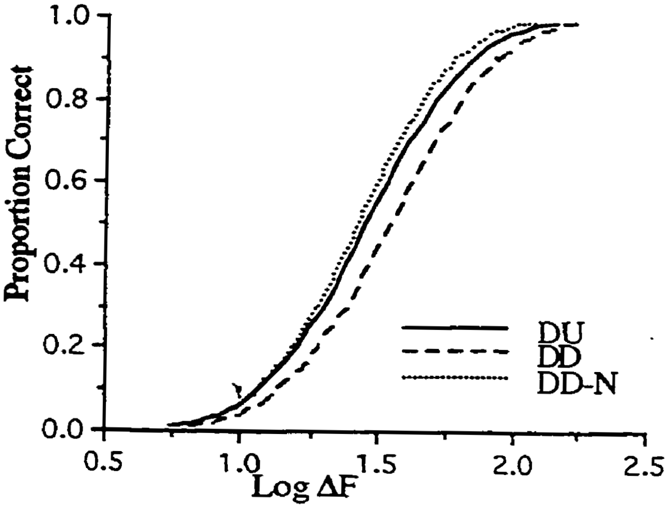
C. Diverging Signals (35-44 yrs) (Low Freq)



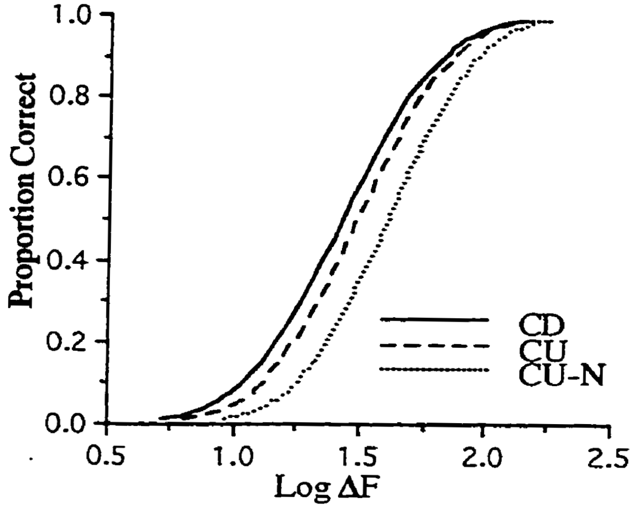
D. Converging Signals (35-44 yrs) (Low Freq)



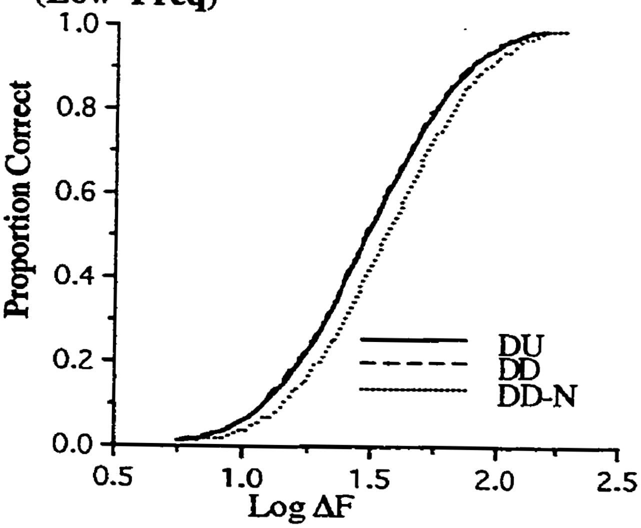
E. Diverging Signals (45-54 yrs) (Low Freq)



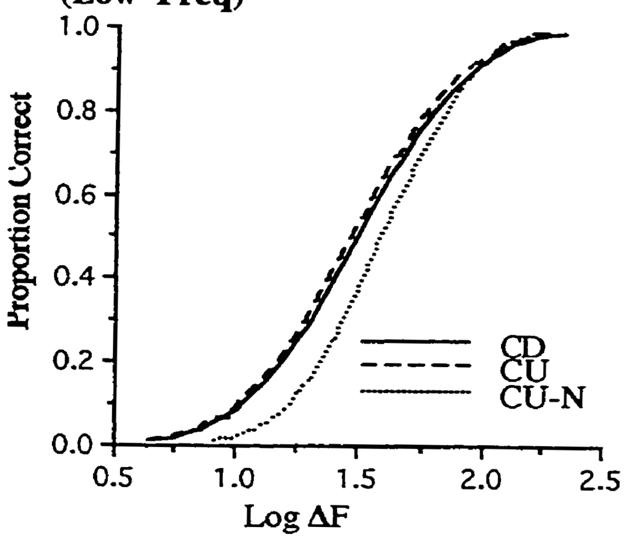
F. Converging Signals (45-54 yrs) (Low Freq)



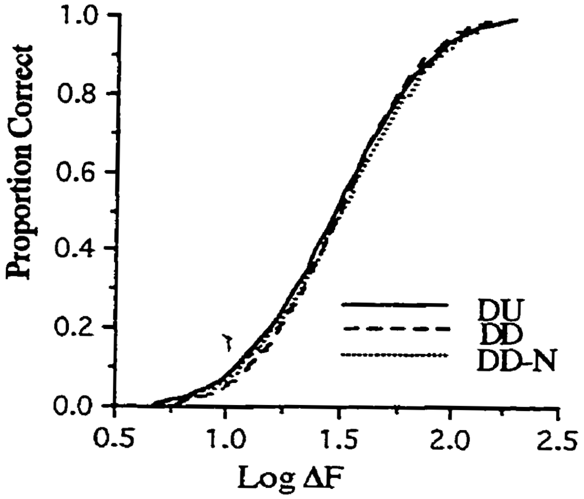
G. Diverging Signals (55-64 yrs) (Low Freq)



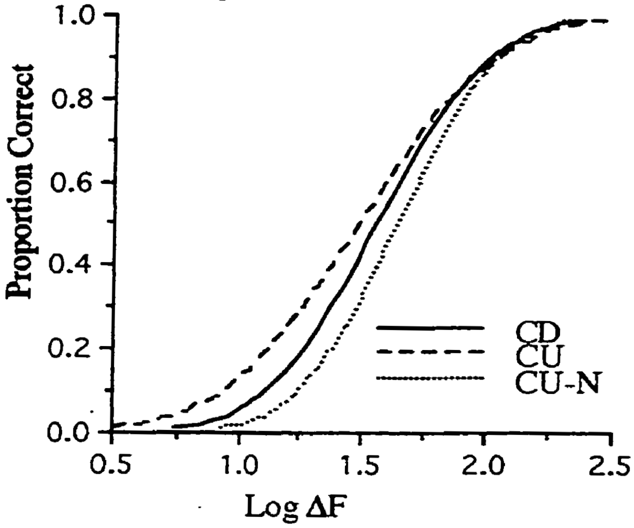
H. Converging Signals (55-64 yrs) (Low Freq)



I. Diverging Signals (65-74 yrs) (Low Freq)



J. Converging Signals (65-74 yrs) (Low Freq)

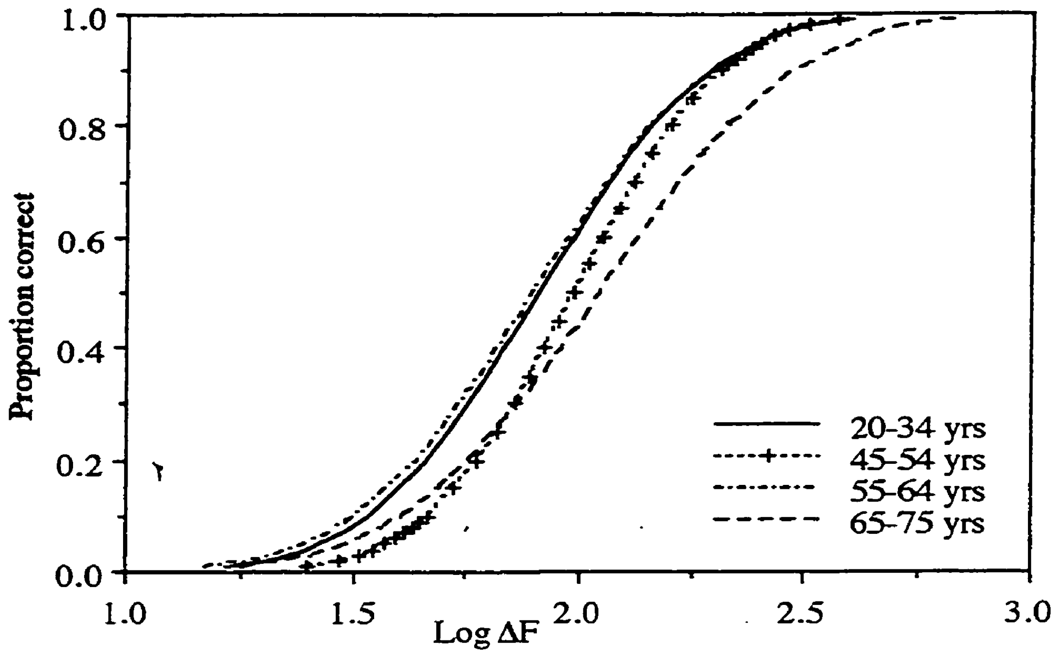


b. High Frequency Slopes

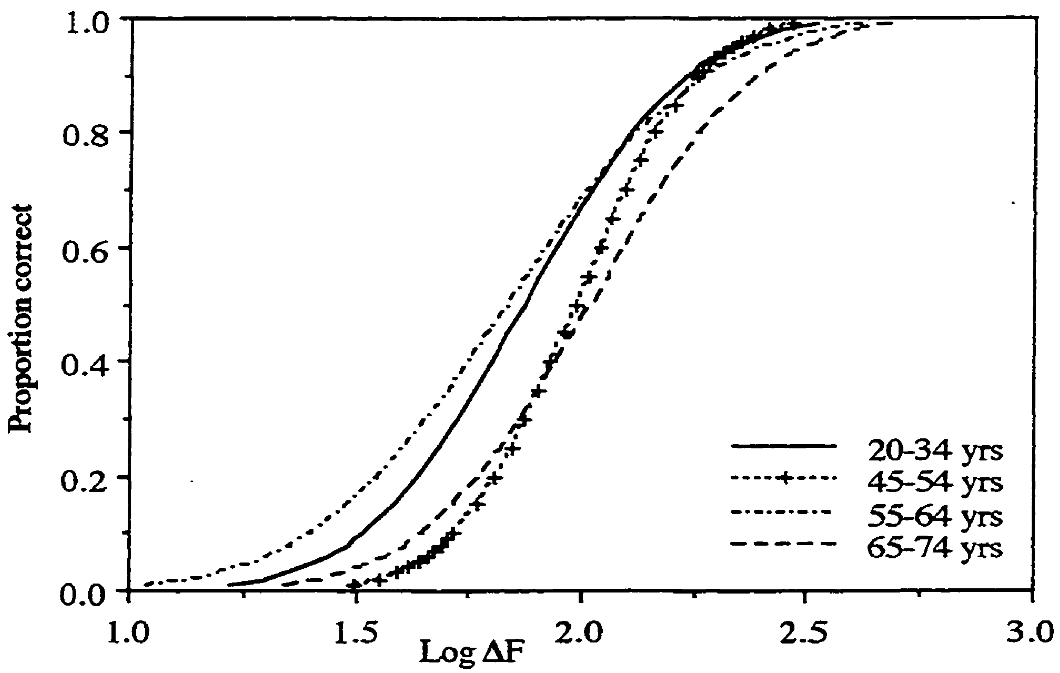
Psychometric functions are plotted for each age group across signal conditions in Figure 11 (Panels A to F). The pattern of slope values is very different for the higher frequency region signals (Table 10). The slopes for the 65-74 year olds are displaced to the right of the functions for the other groups. However, for both sets of diverging signals (panel A and B), slopes for the 45-54 year olds are displaced to the right as well. Panel E (CU in quiet signals) shows a distinct pattern. The 20-34 year olds are clearly separated from 65-74 year olds, and the 45-64 year olds form a distinct group in the center. Psychometric functions for each signal type within each age group are shown in Figure 12 (panels A to J).

Figure 11. Psychometric Functions for each signal condition (panels A to F) in the high frequency region. Values are proportion correct plotted as a function of Log ΔF.

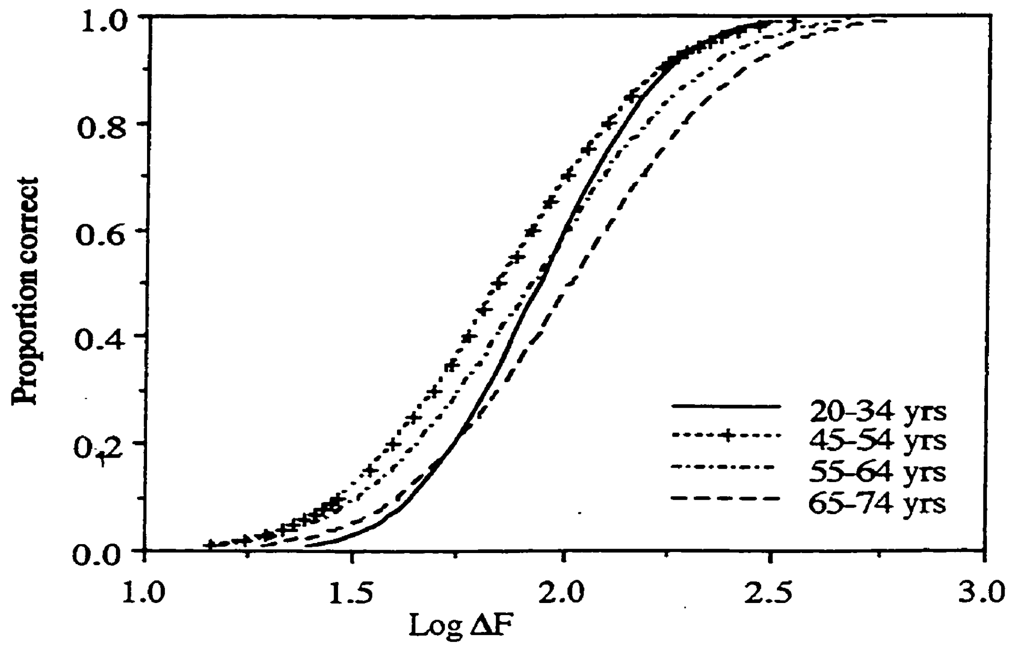
A. Diverging up signals



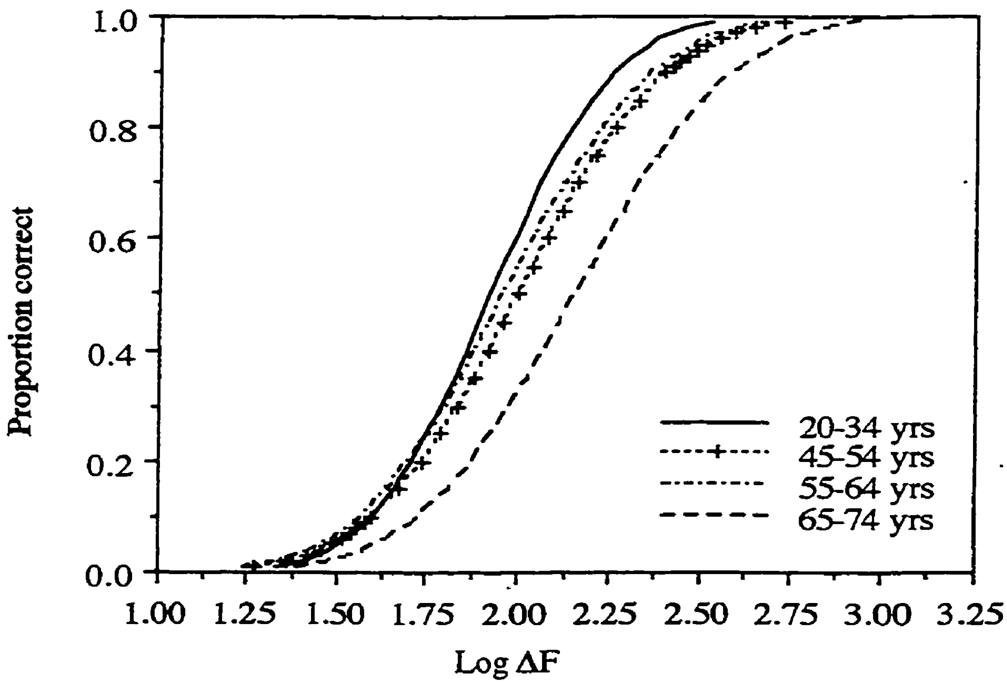
B. Diverging down signals



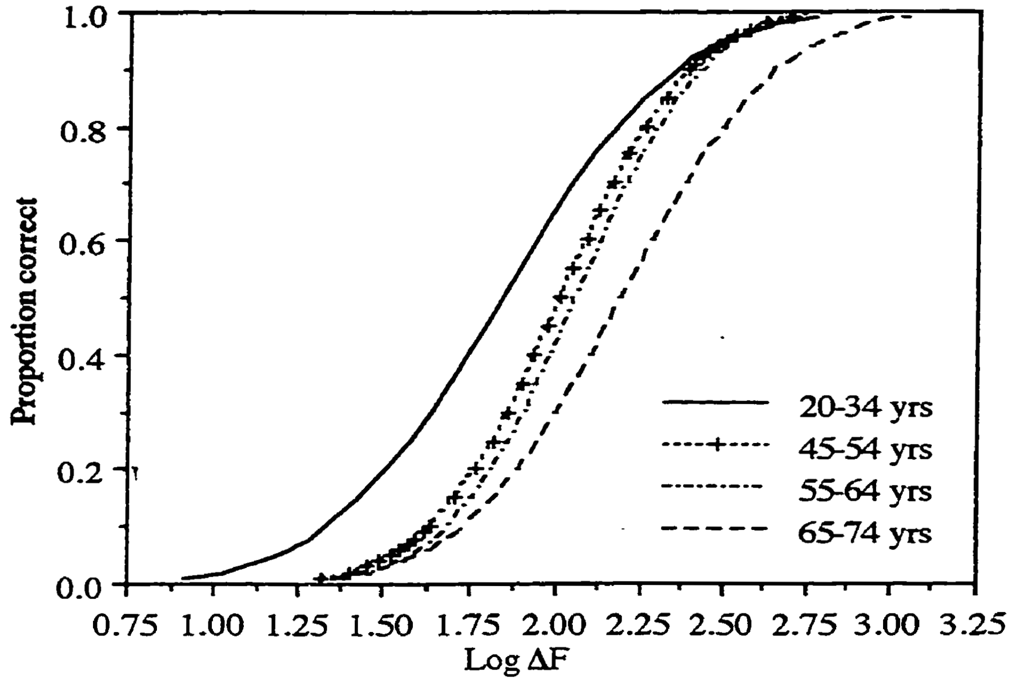
C. Diverging down (noise)



D. Converging down signals



E. Converging up signals



F. Converging up signals (noise)

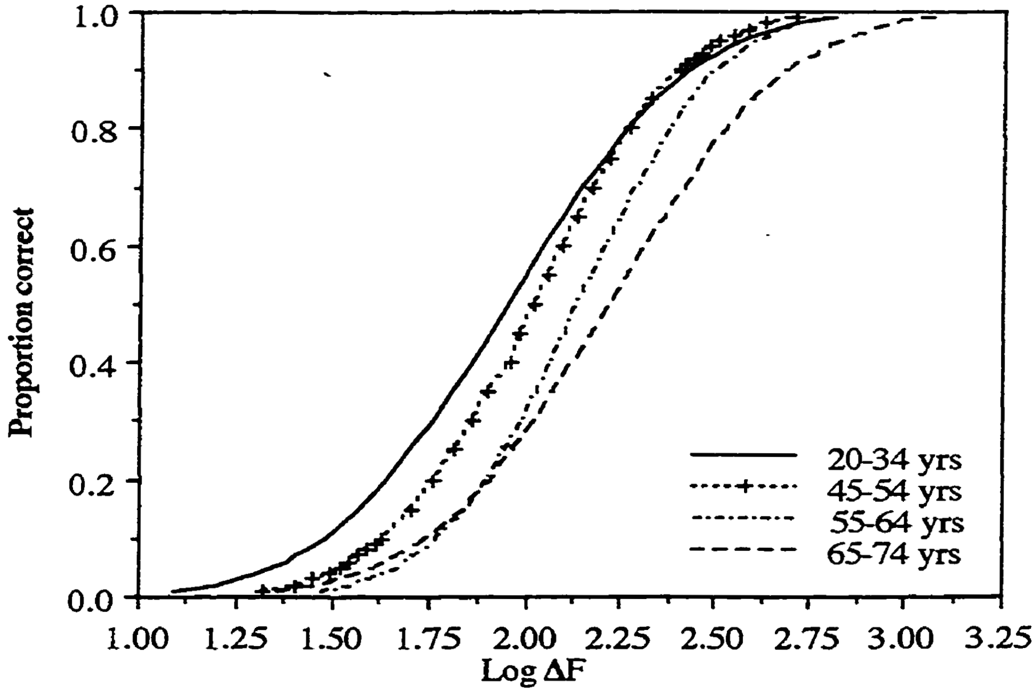


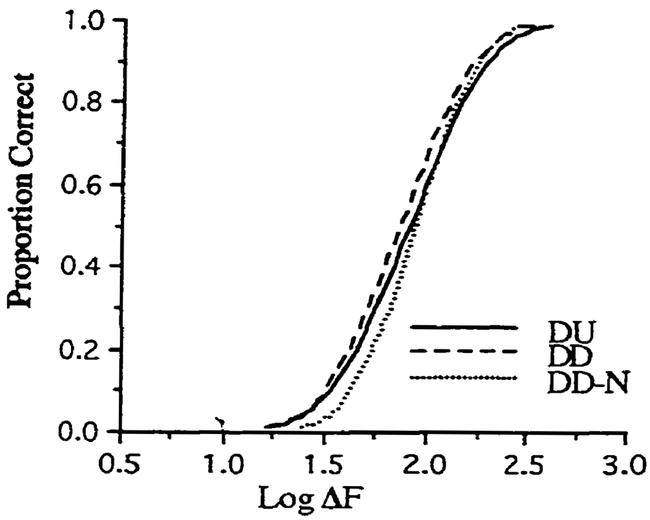
Table 10. Group Probit Slope Means and Standard Errors for Each Age Group for Glide Discrimination Task in the **High** Frequency Region. Values are in Probits / Log ΔF.

	Signal Condition					
AGE (yrs)	DU	DD	DD-N	CD	CU	CU-N
20-34	3.65 (.15)	4.30 (.34)	4.92 (.33)	4.22 (.3)	3.18 (.12)	3.39 (.24)
35-44	3.76 (.12)	4.15 (.32)	4.98 (.38)	4.22 (.3)	3.09 (.14)	3.37 (.22)
45-54	4.12 (.23)	4.87 (.39)	3.22 (.23)	3.17 (.19)	3.54 (.15)	3.36 (.23)
55-64	4.09 (.24)	3.19 (.18)	3.18 (.17)	3.50 (.31)	3.70 (.13)	4.09 (.22)
65-75	3.40 (.11)	4.10 (.3)	3.55 (.19)	2.79 (.16)	3.33 (.33)	3.10 (.21)

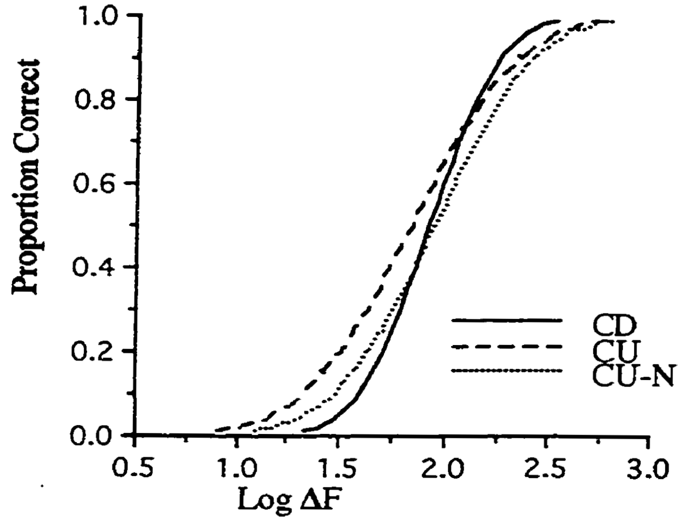
Table 10. Mean slope values for the psychometric functions of glide discrimination in the high frequency region. Values are in Probits / Log ΔF. Standard errors of the means are in parentheses. See text for explanation of abbreviations of signal conditions.

Figure 12. Psychometric functions for signal type for each age group in the high frequency region. Values are proportion correct plotted as a function of ΔF for the low frequency region.

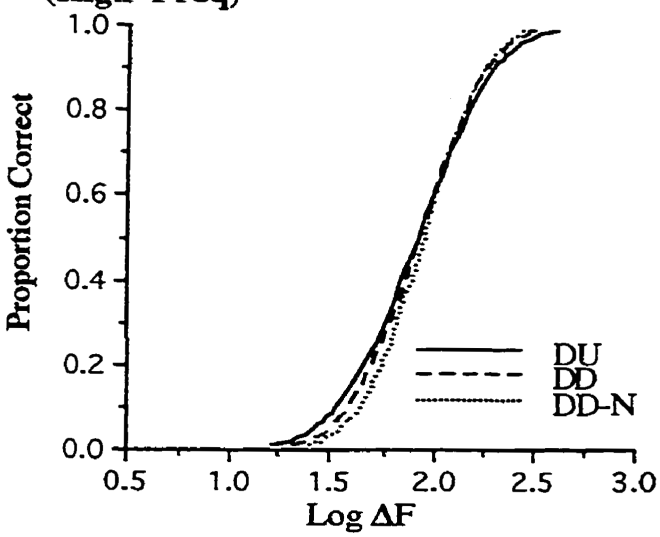
A. Diverging Signals (20-34 yrs) (High Freq)



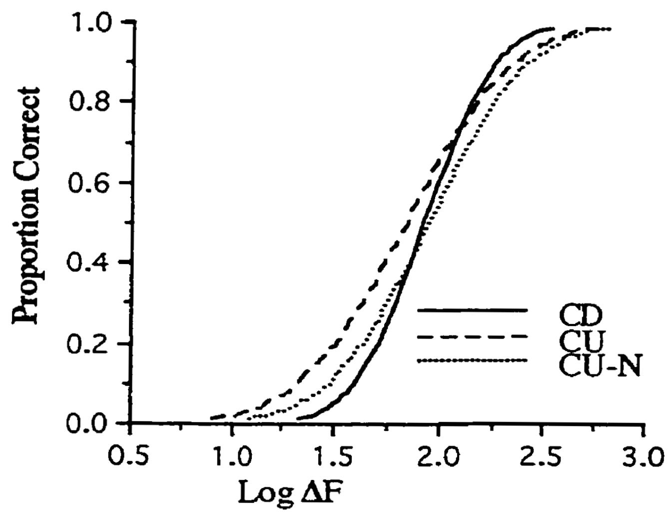
B. Converging Signals (20-34 yrs) (High Freq)



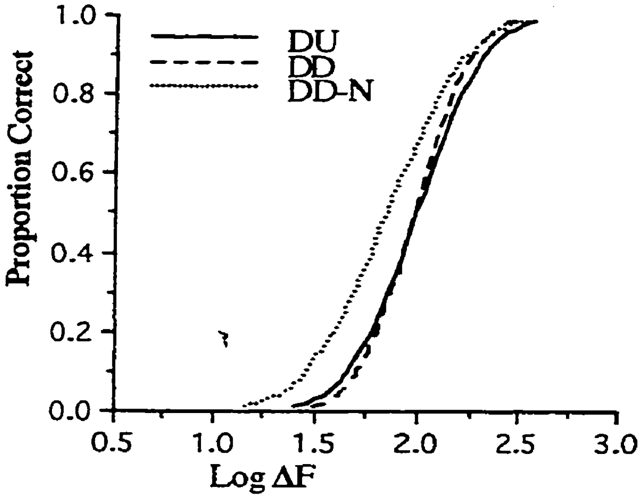
C. Diverging Signals (35-44 yrs) (High Freq)



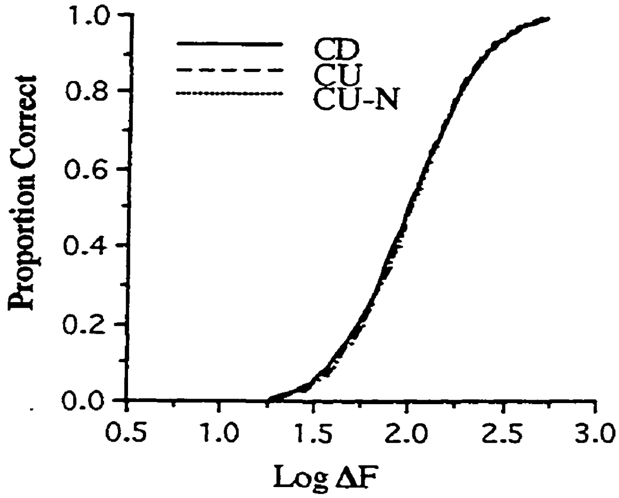
D. Converging Signals (35-44 yrs) (High Freq)



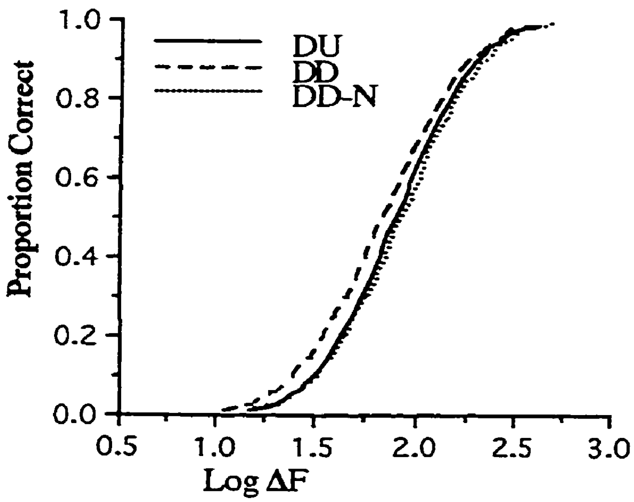
E. Diverging Signals (45-54 yrs) (High Freq)



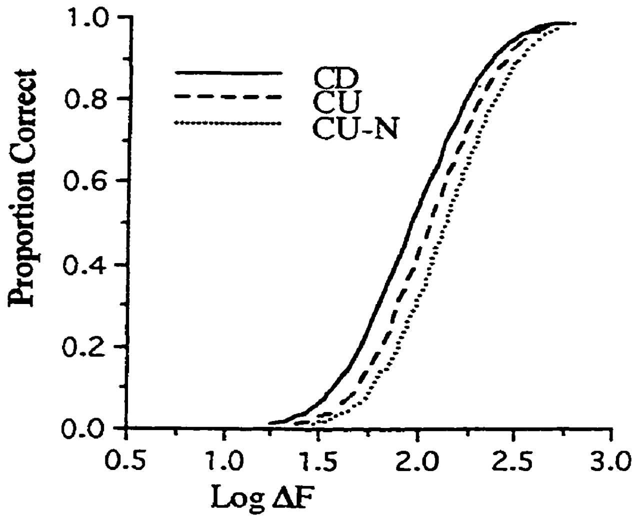
F. Converging Signals (45-54 yrs) (High Freq)



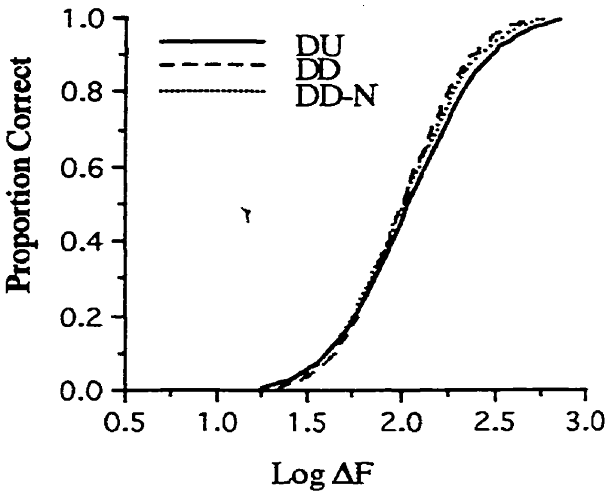
G. Diverging Signals (55-64 yrs) (High Freq)



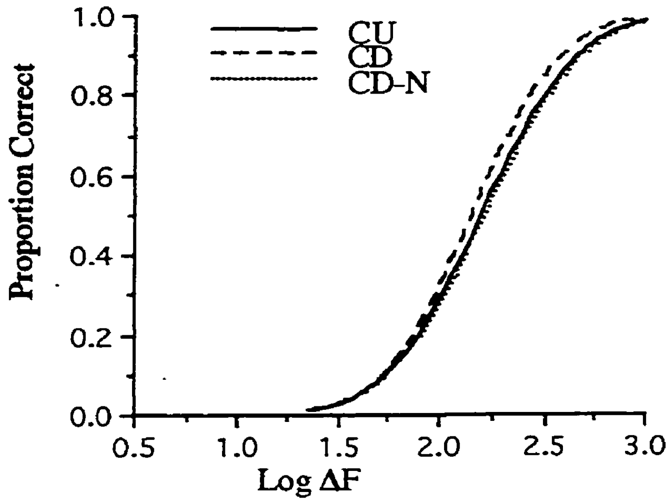
H. Converging Signals (55-64 yrs) (High Freq)



I. Diverging Signals (65-74 yrs) (High Freq)



J. Converging Signals (65-75 yrs) (High Freq)



ANCOVA with PTA2 as a covariate with two levels of endpoint frequency (converging and diverging) and two levels of transition direction (upward and downward) was conducted on the slope values of the high frequency region. The main effects for age and transition direction were not significant, ($p=.212$; $p=.069$ respectively). The main effect of endpoint frequency was significant, [$F(1,136)=10.34$, $p<.001$]. The only significant two way interaction was age group by transition direction, [$F(4,136)=3.45$, $p<.01$]. Simple main effects were performed to assess age effects for transition direction. For signals with a downward transition direction, there was a significant effect for endpoint frequency (i.e., whether the signals diverged to varying offset frequencies or converged to a common offset frequency), [$F(1,136)=4.75$, $p<.01$].

A series of ANOVAs were conducted on the downward signals to investigate the impact of endpoint frequency for each age group. The effect of whether the signals converged or diverged to offset frequencies was significant for the 65-75 year olds, [$F(1,37)=5.4$, $p<.01$]; and, for the 45-54 year olds, [$F(1,24)=6.42$, $p<.01$]. For each of these two age groups the slopes were significantly shallower for the converging series of signals than for the diverging series of signals. For the 65-75 year olds, the mean for DD signals was 4.104 probits/log Hz and 2.794 probits/log Hz for the CD series. For the 45-54 year olds, the slope for the DD signals was 4.874 probits/log Hz and 3.167 probits/log Hz for the CD series. No other age group showed any significant effects for the endpoint frequency for signals which had a downward trajectory of the transition.

For signals with an upward trajectory there was a different pattern of age effects noted. There were significant main effects for whether the signal converged on a common offset frequency or diverged to varying offset frequencies for only the 35-44 year olds , [$F(1,28)=9.07$, $p<.01$], and for the 20-34 year olds, [$F(1,28)=5.24$, $p<.01$]. For both of these age groups, the slopes for the diverging series of signals was steeper than for the converging series. For the 20-34 year olds the mean for diverging signals was 3.756 probits/log Hz and 3.024 probits/log Hz for the converging series. For the 35-44 year olds the diverging series had a slope of 3.649 probits/log Hz; the converging series had a slope of 3.121 probits/log Hz. For the other three age groups, there was no effect on the slope of the function for whether the signals had a diverging or converging endpoint frequency for the series with an upward trajectory.

For signals in noise, there were no significant differences in the slopes for CU signals, however for DD signals, slopes were significantly shallower for the 45-54 year olds, [$F(1,28)=6.15$,$p<.01$], and for the 65-75 year olds [$F(1,28)=13.4$,$p<.01$].

v. Effect of Listening Condition: Quiet versus Noise Background

a. Low Frequency Region

ANCOVAs (PTA2 was a covariate) with 2 levels of listening condition (quiet versus noise) and 2 levels of signal type (converging versus diverging) with age as a grouping factor were computed on CU and DD signals. Main effects for age [$F(4,137)=9.39$, $p<.01$], background [$F(1,137)=31.01$, $p<.001$], and signal type [$F(1,137)=34.71$, $p<.01$] were significant. The only significant interaction was for signal type and listening condition [$F(1,137)=13.00$, $p<.01$]. Post Hoc analysis revealed significant differences for DD signals for the 35-44 year olds (panel C figure 8) and the 45-54 year olds (panel E figure 8). Therefore, noise significantly increased thresholds for 35-44 year olds (ΔF difference = 8.656 Hz), but significantly decreased thresholds for 45-54 year olds (ΔF difference = -5.67 Hz respectively).

b. High Frequency Region

At the higher frequency region, ANCOVAs showed significant main effects for age group, [$F(4,132)=6.25$, $p<.0001$] but not for the signal type. The two way interaction between age group and signal type was significant, [$F(4, 136)=5.60$, $p<.001$]. Oneway ANOVAs showed that there were no significant differences across the age groups for the differences in quiet and noise presentation for the converging signals, ($p=.8519$); however, there was a significant effect for age in the differences in the diverging series of signals, [$F(4,136)=5.9663$, $p<.001$]. In this series of signals, only the 45-54 year olds (panel E figure 10) showed significant effects for background presentation relative to all other age groups except the eldest listeners. In other words, the 45-54 year olds showed a greater impact for background presentation on diverging downward signals

(ΔF difference= -26.983) than did the 20-34 year olds (ΔF difference=9.424 Hz), the 35-44 year olds (14.696 Hz), and the 55-64 year olds (ΔF difference=20.027 Hz). ΔF difference scores for 65-75 year olds are not significantly different from each other.

Interim Discussion

A. Effect of age

There are several age-related effects that are noted in frequency glide discrimination. The most notable is that among a population of 'clinically normal hearing' listeners, there are significant effects in discrimination for suprathreshold signals in all 12 glide conditions for listeners aged 65 and over. The robustness of the effect given the variety of signal conditions is striking. These results are important for several reasons. First, the differences cannot be attributed to differences in absolute sensitivity. Though all individuals had normal thresholds, there was considerable variation in range of hearing thresholds; however, the range of frequencies tested encompassed frequencies for which absolute sensitivity was very similar (see Table 4). Second, this age effect is frequency dependent. At the low frequency region, the eldest listeners showed significantly higher thresholds relative to the youngest listeners, consistent with reports on age and frequency discrimination (He, Dubno, and Mills, 1998), but the proportionate increase in thresholds is quite large. Thresholds for the eldest group of listeners ranged from an increase of 25% for DD signals to a 30% increase for DU signals relative to the youngest group (Table 7, 50.92 Hz compared to 35.63 Hz). At the higher frequency region, the effect is even more dramatic. Thresholds for discriminating CD signals were

56% higher than thresholds for the youngest group (Table 8, 171 Hz compared to 115 Hz). This means that at the low frequency region, converging signals had to change at .93 Hz/ms (Appendix B) compared to a .68 Hz/ms change for the young listeners. At the high frequency region, the 65 year and older individuals needed a signal which changed more than twice as fast than that for the younger group (4.33 Hz/ms compared to 1.89 Hz/ms). There are few direct comparisons in the literature on glide discrimination and age, but the values reported here are comparable to the formant-like signals that Elliot, Hammer, Scholl, and Wasowicz (1989) used. In their study, thresholds for discriminating an upward sweeping formant-like glide for the elderly were 1.5 times faster than the thresholds (in Hz/ms) for the younger group. Hearing sensitivity in this study though was normal only to 2.0 kHz, so that may have contributed to their findings. Abel, Krever, and Alberti, (1990) compared ΔF values between young and aged listeners and found that the elderly showed poorer frequency discrimination regardless of hearing status.

This same series of signals, also had the most effect on the slopes of the psychometric functions. Though threshold values were consistently higher, for older listeners, slopes of psychometric functions were not necessarily steeper. For the low frequency region, (Figure 9), signals which converged upward on a common offset frequency showed the most dramatic effect on the slopes of the elderly (Panel J. Figure 10). Diverging signals showed no differences regardless of whether the signal glided up, down, or was presented in noise (Panel I Figure 10).

For all groups as well, discrimination of frequency glides was not a function of detecting increments or decrements in frequency onset or offsets. Diverging down signals required detecting a frequency decrement in offset frequency while converging up signals required detection of a frequency decrement in onset frequency. Porter, Cullen, Collins, and Jackson (1991) argued that increments in glide rate would be discriminated better than decrements in glide rate. The hypothesis being that given a particular reference variation, (i.e., a particular rate of change in a standard) that physical increases in the size of this variation will produce a larger change in the resulting excitation envelope than an equivalent physical decrease. Both DD and CU signals which traversed the same frequency extent required just such a discrimination. The robustness of the enhanced discrimination by all age groups for signals which varied in terminal frequencies does not support Porter et al.'s (1991), hypothesis. Therefore, 'rate cues' are not the sole basis of discrimination. At the low frequency region, the most salient cue for glide discrimination appears to be final frequency pitch. Signals of varying offset frequencies (DD and DU) have significantly lower thresholds for all age groups. This argument does not differentiate between situations where listeners are tracking a moving pitch, or whether sensory memory makes the final pitch the most salient.

Because the perception of changes in sequences of signals depends upon a comparison process between the incoming stimulus and the neural representations of the previously presented process (Alain & Woods, 1999), the age-related effect may reflect either impaired sensory memory or impairments in the comparison process itself. The robust finding of an age-related effect of the eldest listeners relative to the youngest listeners in a normal hearing population for all signal conditions is suggestive of a less precise internal representation of the signal among the aged. The lack of a significant temporal order effect of the stimuli (standard first versus standard second in a pair) does not refute this argument. If signals are internally compromised among the aged, then the suppressive effects will operate equally on each. Mismatch negativity (MMN) studies showing an age-related decline in MMN amplitude (Alain & Woods, 1999), and neuroimaging studies showing reduced brain activation in prefrontal and temporal cortex (Grady, et al., 1997) together suggest the possibility of a decline in the frontrotemporal network. This is suggestive of a decrease among the aged in activation of auditory cortical areas under the influence of a distributed cortical circuit that includes the tempoparietal region and the prefrontal cortex.

Within each age group, there was no effect for the direction of the transition at the low frequency region. As discussed in the introduction, the data on asymmetric discrimination of short duration glides is mixed (Madden & Fire, 1997; Moore & Sek, 1998). No age group exhibited preferentially better discrimination for an upward glide versus a downward glide. This is in contrast to the asymmetric peak / trough findings of Demany and Clement (1998) who reported this to be a stable phenomenon across the range of frequencies which were used in this study. It is reasonable to postulate that tracking a linear sweep 'perceptually' involves different processes than tracking the 'height' of a modulated signal. Indeed thresholds for discrimination can be rank ordered in terms of ease as discriminating a tone, detecting a modulation, and discriminating modulations (Horst, 1985). If psychoacoustic cues are based on spectral resolution, the 'fine structure' of the signal which maybe tracked in a glide. However, if the fine temporal structure of the signal is being tracked, then the auditory channels at the low frequency region which have poorer temporal resolving capabilities should not readily demonstrate a clear distinction for an upward or a downward glide. Conversely, glides in the higher frequency region should be able to more readily process the trajectory of a glide.

At the high frequency region, there is an effect for the direction of the glide, but this is dependent upon the type of signal used and the age of the listener. For the youngest group of listeners, there is no effect for direction of the signal. The most significant differences in discrimination appear at age 40 and up. In general, signals which converged up are more difficult than signals which converged down, and in particular for listeners aged 40 and over. Changes in auditory processing at about age 40 have been reported previously (Alain & Woods, 1999; Snell, 1997, Snell, 1999). For glides in noise, the youngest group of listeners showed higher thresholds for converging versus diverging signals. If more perceptual 'weight' is provided by the end of the signal, this would suggest that psychophysically, the pitch or timbre cues are not strong enough to provide reliable discrimination beyond age 40 and that for younger listeners this effect is manifest only in noise. Implicit in this argument is that signals which diverge to various offset frequencies should always be discriminated better than signals which converge to a common offset frequency, but the data do not support this argument.

B. Effect of Noise

The effect of noise was dependent not only on age but also on stimulus parameters. Because elderly listeners often report difficulty in discerning signals under noisy listening conditions it was expected that the presence of background noise might have a negative impact on perception for the elderly listeners. At neither frequency region were the results for the eldest listening group significantly different in noise versus quiet listening conditions, though there is an overall elevation in thresholds relative to younger listeners. Therefore, processing of 'cues' to discriminate frequency glides is elevated in aging listeners, but not differentially impacted by noise. The significant effect for 55 plus year olds, but not for 65 plus year olds for signals at the high frequency region could indicate the onset of a decline in auditory ability followed by a compensation for this in later years. The decrease in thresholds for the 45 plus year olds in noise relative to a quiet condition is not readily explainable. Frisina, Walton, and Karcich (1994) reported that units in DCN can enhance the coding of AM responses relative to quiet in the presence of background noise, but for S/N ratios of +14 or +19 dB and at high signal levels of 75 dB SPL which were larger than the parameters of this study.

C. Relationship to ERB

Various psychophysical phenomenon concerning the detection of changes in signal features can be understood in the general framework of an excitation-pattern (EP) model (Zwicker, 1970; Moore & Sek, 1994). The EP of a tone is its representation in a bank of tonotopically organized auditory filters and is "...assumed by EP models to be reflected by the tone's masking pattern" (Demany & Clement, 1997). That is, the EP is a reflection of the activity in several overlapping filters. Zwicker (1970) generalized the mechanisms for frequency discrimination in an EP model where frequency changes can be perceived by changes in the output of a single filter. Moore and Sek (1995) have advanced the argument that if discrimination is below the phase locking capabilities of auditory fibers, then thresholds should be based on 'place' cues and be a constant proportion of the ERB. If it is assumed that in the process of glide discrimination, a listener compares signals by comparing the differences between their start and endpoints, the accuracy with which this change can be measured would be determined by the resolution of the location of these points along the basilar membrane. This in turn would be a function of the slope of the excitation pattern, which in turn is determined by the bandwidth of the auditory filters centered at and just below the test frequency (Moore & Sek, 1995).

The width of the ERB for the center frequencies of both frequency region were computed based upon Moore and Glasberg's (1990) equation $ERB = 24.7(4.37F + 1)$, (equation 2). The ERB for the CF at the low frequency region is 133 Hz, and the ERB for the high frequency region is 314.5 Hz. Threshold values were expressed in Hz/ ERB for each signal condition at each frequency region. As the extent of the signal was variable within each signal condition (to keep duration and either the endpoint or the starting frequency constant), signals are not a constant proportion of the ERB. However, the standard signals in the low frequency region spanned .38 ERB, and the standard in the high frequency region spanned .48 ERB. When thresholds were expressed as Hz/ERB the proportions ranged from fairly constant at .3 for the 20-44 year olds across conditions and frequency regions. However, values for the 45-74 year olds ranged from .3 to .5 within each signal type for each group. These values are higher than the values of Moore and Sek (1998) and Madden and Fire (1997) for their 50 ms signals with a transition span of .5 ERBs at 2 kHz for the youngest groups of listeners. The proportions are considerably higher for the eldest group of listeners. The increase in the proportions in this study could be a reflection of experience. In the studies by Moore and Sek (1998) and Madden and Fire (1997) listeners were practiced for 10-15 hours before data collection. Therefore, their values probably represent asymptotic performance of discrimination.

In summary, these data do not support models of glide discrimination which predict an enhancement for an upward sweep, nor do they support models of cochlear dispersion cues based on an increment in frequency targets. The most parsimonious explanation is that listeners in this study were relying on terminal frequency pitch cues for discrimination. However, the $\Delta F/F$ values are quite large, Weber fraction equivalents of the values in Tables 7 and 8 range from .3 to .6 which are considerably larger than $\Delta F/F$ values for equivalent pure tones (Wier, Jesteadt, and Green,1977) or for glide detection (Dooley & Moore, 1988).

Study Two: Gap Detection Thresholds

Purpose

As discussed in the introduction, tasks revealing auditory temporal phenomenon are important in understanding changes in perception among an aging population. A simple gap detection in broadband noise task was employed to evaluate the temporal discrimination performance of listeners on an elemental level. This methodology removes aspects of the frequency domain from discrimination and serves as a metric of purely temporal discrimination.

Participants (Described in Section II)

Stimuli

Stimuli for the gap detection stimuli were generated in real time using EXPERIMENTER software, an array processor (TDT QAP1), and played out through a 16 bit D-to-A converter (TDT QDA1, sampling frequency = 40 kHz). Stimulus levels were controlled by a programmable attenuator (PA4), fed to a headphone buffer (HB5), output through a Packard Bell computer and fed monauraly to Kros Pro/4x Headphones. Presentation level of all stimuli was 65 dB SPL. The noise bands had a center frequency of 5000 Hz and a bandwidth of 10,000 Hz. Each of these signals was digitally filtered with offband attenuation rates of 96 dB/oct. Signals were 200 ms in duration and a gap ranging in duration from 0-20 ms was centrally placed in the signal.

Procedure

A three interval forced choice procedure was used. Each trial consisted of three noisebands separated by a 200 ms ISI. The gap could appear with equal probability in any of the three noise bands and always appeared in one signal. To prevent the use of overall duration as being used as a cue, the duration of the stimuli was held at 200 ms regardless of the length of the gap. The listener's task was to press a button on the keyboard corresponding to the signal that contained the gap. After each response, feedback as to whether the response was correct or incorrect was provided on the screen. Response time was opened and subsequent trials were not run until a response was received. After a response was recorded, subsequent trials began after a 500 ms interval.

Thresholds were measured by an adaptive updown, three interval, three alternative forced choice paradigm which converges on the 79% point on the psychometric function (cf. Levitt, 1971). Adaptive procedures refer to those paradigms where the level of a variable at which a particular stimulus is presented is determined by how the listener responded to previous stimuli. A predetermined suprathreshold level is initially used and as the listener responds correctly three times in a row the variable under study is made more difficult. If the response is incorrect, the level of the variable is increased until the response is again correct for three trials in a row.

The run began with a 20 ms gap centrally placed in the signal. The initial step size for the first 3 reversals was 3 ms. After this the step size was reduced arithmetically to the smallest value of 0 ms. For this investigation, 60 trials were used and thresholds were determined from the average of the last 14 reversals. All responses were recorded and stored on the computer.

Results

Table 11 shows the means and standard deviations of the gap detection thresholds as a function of each age group. As can be seen, thresholds show an age-related increase with this difference becoming larger for the older listeners. A oneway ANOVA was conducted on the gap detection thresholds. There was a significant effect for group, [$F(4,138) = 26.749$, $p < .00001$]. Follow up Scheffe's contrasts were used to determine significant group differences. At $p < .01$, the two youngest age groups (20-40 years) were not significantly different from each other, but were significantly different from all other age groups.

Table 11. Mean Gap Detection Thresholds and Standard Errors in ms for each Age Group. Percentage Increases in Thresholds Relative to the Youngest Age Group are shown in the Final Column.

		Value (ms)	
Age Group (years)	Mean (ms)	Std. Error	% increase relative to 20 yr olds
20-34	2.52	.10	
35-44	2.61	.11	4
45-54	2.94	.11	17
55-64	3.55	.16	42
65-75	4.99	.19	98

Table 11. Group thresholds in ms for each age group. Standard Errors of the mean are shown in parentheses. The final column is the percentage increase in threshold referenced to the youngest age group.

Figure 13 shows a comparison of the present findings for only the young listeners and the eldest group. As can be seen, the present findings fall within the range of previous works, (note: results from Diveyi & Haupt, 1997 are estimated from their Figure 3.).

Figure 13. Comparison of thresholds for only the youngest and the eldest groups with published results.

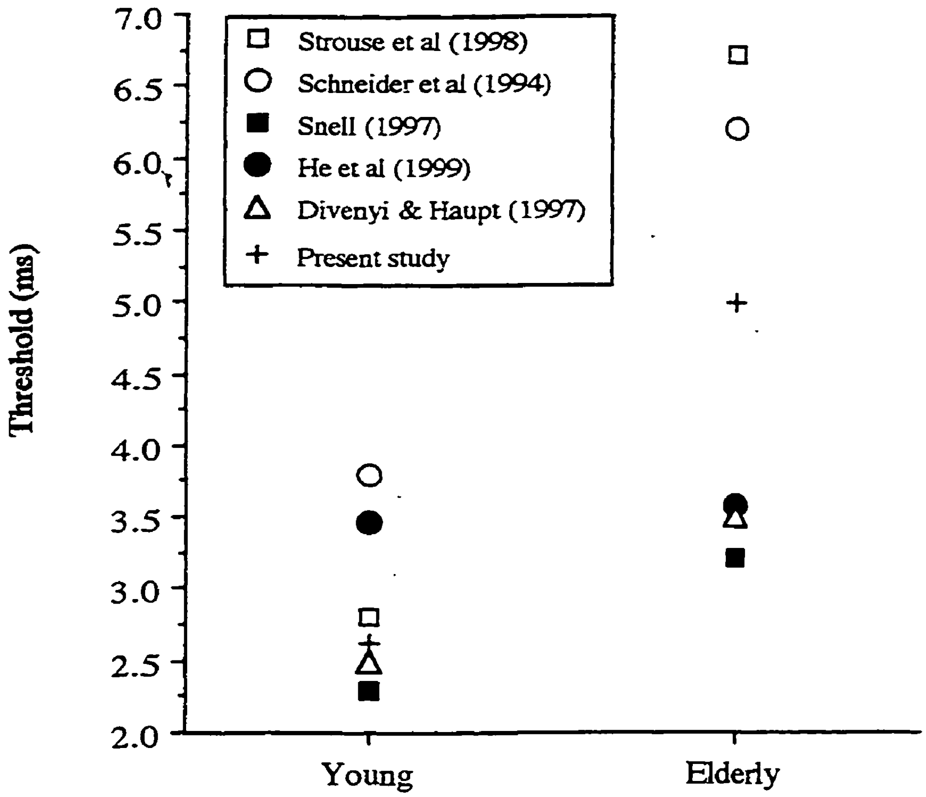
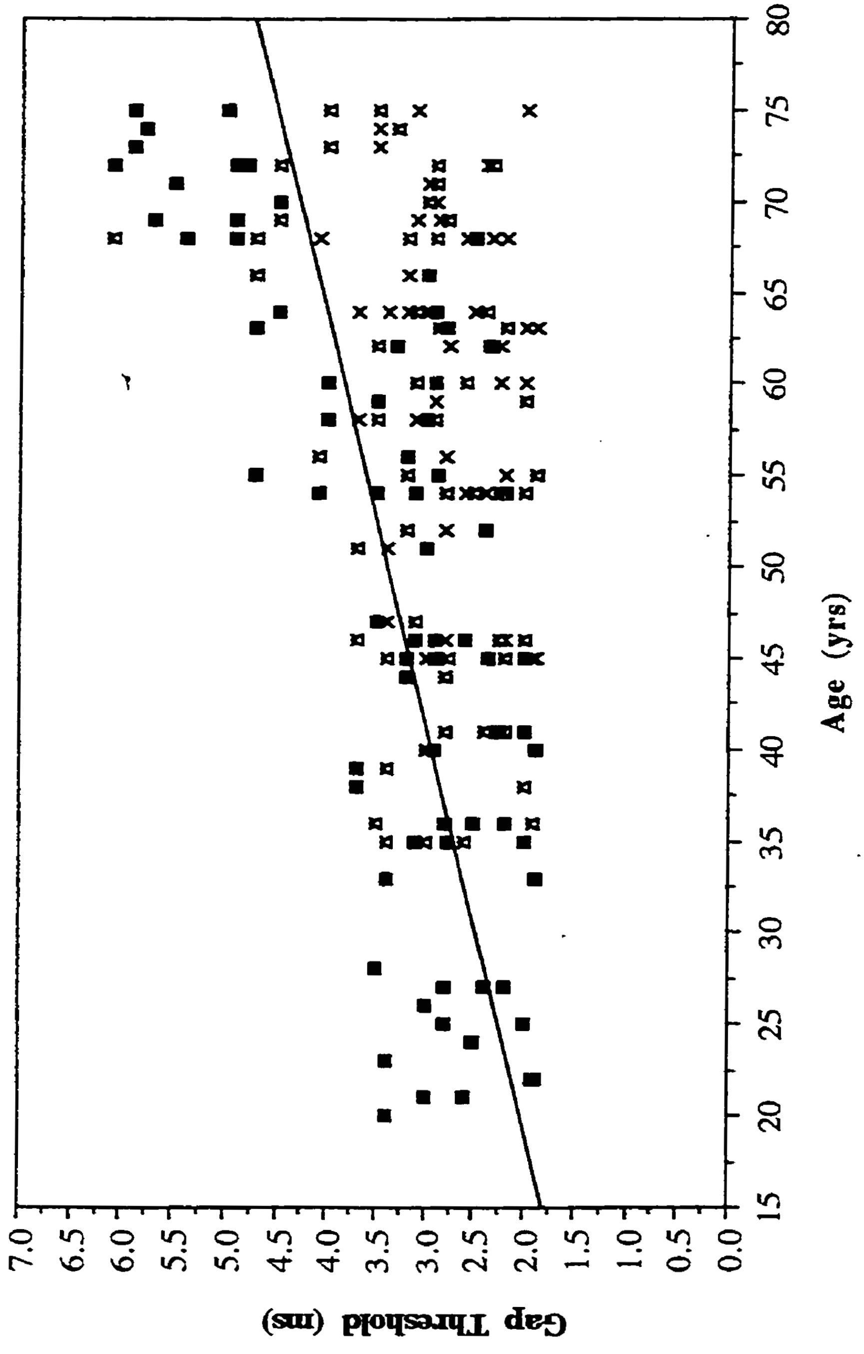


Figure 14. Scatterplot of individual gap thresholds. Note the overlap among the young and old. Best fit regression line is also shown.



Interim Discussion

Consistent with previously reported findings by Moore, Peters and Glasberg (1992), Snell (1997) He et al. (1999), this study also observed a large overlap of data between the young and the aged listeners. The interesting finding is, that on average, beyond age 50 gap detection thresholds begin to significantly increase. Though there are few studies to serve for direct comparison, an examination of the individual data in Snell (1997) showed that among her 'young' group of listeners, thresholds appeared to increase around age 40. The percentage increase in gap thresholds is not a monotonic function of age. Using the 20 year old group as a baseline reference, thresholds are unchanged for 30 year olds increasing by only 4%, but for the 40 year olds, the increase is 17% and dramatically increases with each subsequent decade (Table 11).

It is unlikely that the age increase noted in gap detection studies with broadband noise is influenced by characteristics of the auditory filters at either the high or low frequency regions. Broadband noise will affect the whole cohlear partition and not just specific points. Plomp (1964) argued that temporal resolution is limited by the decay of sensation produced by the first part of the stimulus, which would fill in the gap. A change in the decay of neural response could therefore by a factor that limits temporal resolution with age. Zhang, Salvi, and Saunders (1990) investigated neural correlates of gap detection in auditory nerve fiber responses from chinchilla and found an inverse relationship between CF of the unit and the decay in neural response. According to Zhang et al., the peristimulus-time histogram showed an abrupt drop followed by a sharp increase and that the modulation was a function of gap length. As the gap length increased, the firing rate during the gap systematically decreased until a gap of 10 ms where it decreased to below the spontaneous rate. Also, the firing rate at the onset of the second part of the noise increased with increasing gap length. Therefore, it is possible that the onset response at the end of the gap begins to be compromised beyond age 40.

Study Three: Simplified Psychophysical Tuning Curves

Purpose

As discussed in the introduction, frequency selectivity refers to the range of frequencies over which information is combined and can be characterized by a series of overlapping auditory filters with differing bandwidths (BW). Auditory filters can be characterized by parameters that define the slopes of the filter and the bandwidth at a particular point on the function. Typically values of the 3-dB BW or the 10 dB BW, (the frequency difference where the filter function has decreased by either 3dB or 10dB from its maximum value), (Holube, Kinkel & Kollmeier, 1998; Rosen, 1997; Kollmeier & Holube, 1992) or by the equivalent rectangular bandwidth (ERB), (Moore, Vickers, Plack & Oxenham, 1999; Glasberg & Moore, 1990; Wright, 1996). Estimates of 3dB BW are typically about 10% of the center frequency (Bacon & Moore, 1986; Moore et al., 1984) while values for the 10dB BW can range from 30% in simultaneous masking to 16% in forward masking (Bacon & Moore, 1986).

The Q10 dB value is a parameter which represents the frequency difference where the filter function has decreased by 10 dB from its maximum value and larger Q values represent a narrower filter (Kollmeier & Holube, 1992; Bacon & Moore, 1986). This parameter has the advantage that only the central part of the filter function is taken into account, and therefore measures of the low frequency 'tail' region of the filter would be independent of this measure (Kollmeier & Holube, 1992).

Alterations in the frequency-analyzing capability of the peripheral auditory system have been assumed to account for the abnormal speech discrimination observed in some elderly listeners, and have shown changes in both filter bandwidth and filter shape

(Sommers & Gehr, 1998; Matschke, 1991; Moore & Glasberg, 1986). Although some studies have shown that the width of the auditory filter has been shown to correlate with threshold elevation (Lutman, Gatehouse & Worthington, 1991), other studies have found that the auditory bandwidth is independent of audiometric loss (Festen & Plomp, 1983). Therefore, even in a clinically normal population, differences in frequency selectivity may be apparent.

Psychophysical tuning curves (PTCs) were determined by keeping the level and frequency of a signal fixed and finding the level of a narrow-band (NB) masker required to mask the signal as a function of masker frequency. Frequency selectivity was measured with a forward masking paradigm to avoid confounds of spectral interactions with the signal and the masker (Nelson 1991; 1989). To produce an abbreviated measurement of the PTC, three measures below the probe tone, and three measures above the probe tone were obtained (Florentine; 1990; Zwicker & Schorn 1978).

Participants (Described in Section II)

Stimuli

Tuning curves were measured monaurally in the right ear for 0.5 kHz and 4.0 kHz probes. Stimuli were generated in real time using EXPERIMENTER software, an array processor (TDT QAP1), and played out through a 16 bit D-to-A converter (TDT QDA1, sampling frequency = 40 kHz). Stimulus levels were controlled by a programmable attenuator (PA4), fed to a headphone buffer (HB5), output through a Packard Bell computer and fed monaurally to Koss Pro Headphones with a flat frequency response to 6 kHz.

For each tuning curve, threshold of the probe tone (Fp) was determined in the absence of any masker. Fp was then set to 15 dB above this level and the level of various narrowband (NB) maskers required to mask the tone was determined. The CFs of the NB maskers were 0.43, 0.78. 0.92. 1.08, 1.23, and 1.48 times Fp. For a 0.5 kHz Fp, the bandwidth of the masker noise was 85 Hz with center frequencies of .215, .39, .46, .54, .615, and .74 kHz. For a 4.0 kHz Fp, BW of the masker was 710 Hz, with CFs of 1.72, 3.12, 3.68, 4.32, 4.92, and 5.92 kHz.

Procedure

Each measurement consisted of three signals with an ISI of 250 ms. The masker signals were 200 ms in duration; the probe tone, 20 ms in duration. Rise/fall times on both the maskers and probe tone were 5 ms. The probe occurred 2 ms after the offset of the masker frequency. In order to avoid listeners determining the appropriate interval based upon time cues, the duration of the masker in the interval without the probe tone was randomly roved between 200 ms and 230 ms. Though there was a gap of 2 ms between the masker and the probe, there will be excitation on the Basilar Membrane after the termination of a signal (Glasberg & Moore, 1994). If auditory filters ring for 6-10 periods, this means that at 0.5 kHz each period is 2 ms and the filters will ring for 12-20 ms. At 4.0 kHz, since each period is 0.25 ms, the filters will ring for 1.5-2.5 ms. However, forward masking still can be considered to an advantageous method of measuring selectivity.

Each masker frequency was tested in a single block of 60 trials using an adaptive staircase algorithm (Levitt, 1971) in which the level of the probe tone was kept constant and the level of the masker was varied. The probe tone was set at 15 dB sensation level

(SL) above threshold, and the level of the masker bands were varied. At the beginning of a block, the masker was set at 20 dB SPL below the signal and was increased in various steps for each correct response. Initial step sizes in the level of the masker were set to 6 dB for the first 5 reversals and then reduced to 3 dB for the rest of the reversals. Specifically, dependent upon the response, the masker either increased or decreased by 6 dB for the first 5 reversals, and then changed by either plus or minus 3 dB for subsequent trials. Masker levels for the last 15 reversals were averaged to estimate threshold.

Each trial consisted of three signals separated with an ISI of 250 ms. One of the signals was the narrow band noise followed by the probe tone. The other two signals were the masking noise alone. The probe was presented with equal probability in any of the signal intervals, but was present in one interval on all trials. Listeners depressed a key on the computer keyboard corresponding to the interval containing the probe. Immediately after responding, feedback was provided on the screen indicating whether the response was correct or incorrect. Response time was open ended and subsequent trials were not begun until a response was received. After a response was recorded, subsequent trials began after a 500 ms interval.

Results

At both frequency regions, four metrics were determined to quantify each tuning curve; slope of the 'tail'; slope on the low frequency side of the probe (LF slope); slope on the high frequency side of the probe (HF slope); and the Q10 dB value. Tuning curve slopes were fitted on a frequency-ratio scale and then transformed to dB/octave slopes using the probe frequency (Fp) as the octave reference for the high frequency slope (S_{hf})

and low frequency slope (S_{lf}) (Figure 15). For the tail region, the masker CF at the end of the tail served as the octave reference frequency. For calculating this value, .39 kHz was the octave reference for the tail for a 0.5 kHz probe; for a 4.0 kHz, the octave reference for the tail was 3.1 kHz. Q10 dB bandwidth (BW) estimates were derived from Slf and Shf interpolations of BW 10 dB above the value of the level of the tip and dividing Fp by BW. That is,

$$Q_{10} = Fp \,/\, Q_{10}BW \qquad (5)$$

Scatterplots of individual responses are shown in Figure 16 for a PTC at 0.5 kHz for each age group (panels A to E), and Figure 17 for a PTC at 4.0 kHz for each age group (Panels A to E). For clarity, only the responses at the measures used in the calculation of the slopes are shown. Therefore, Figure 16 shows responses at .215 kHz, .39 kHz, tip at 0.5 kHz, and .74 kHz. The mean regression lines are displayed as well. In Figure 17, responses to 1.72 kHz, 3.68 kHz, tip a 4.0 kHz, and 5.92 kHz are shown. The solid line represents the mean regression line for the tail, Slf, and Shf. For some listeners in each age group, the probe tone was audible even when the masker was set at maximum level. In this situation, the level of 120 dB was used in the analyses, these ranges are indicated by an arrow in each panel. Tables 12 and 13 shows the group mean dB/octave changes for the tail, LF slope, and HF slope for the tuning curves for Fp of 0.5 kHz and 4.0 kHz respectively.

Figure 15. Idealized psychophysical tuning curve illustrating the tuning curve metrics. Frequency of the probe is expresssed on a log scale. Slopes were expressed in dB/octave with the probe used as an octave reference for the high and low slopes and the masker frequency of the junction of the tail and the low frequency slope used as an octave reference for the tail.

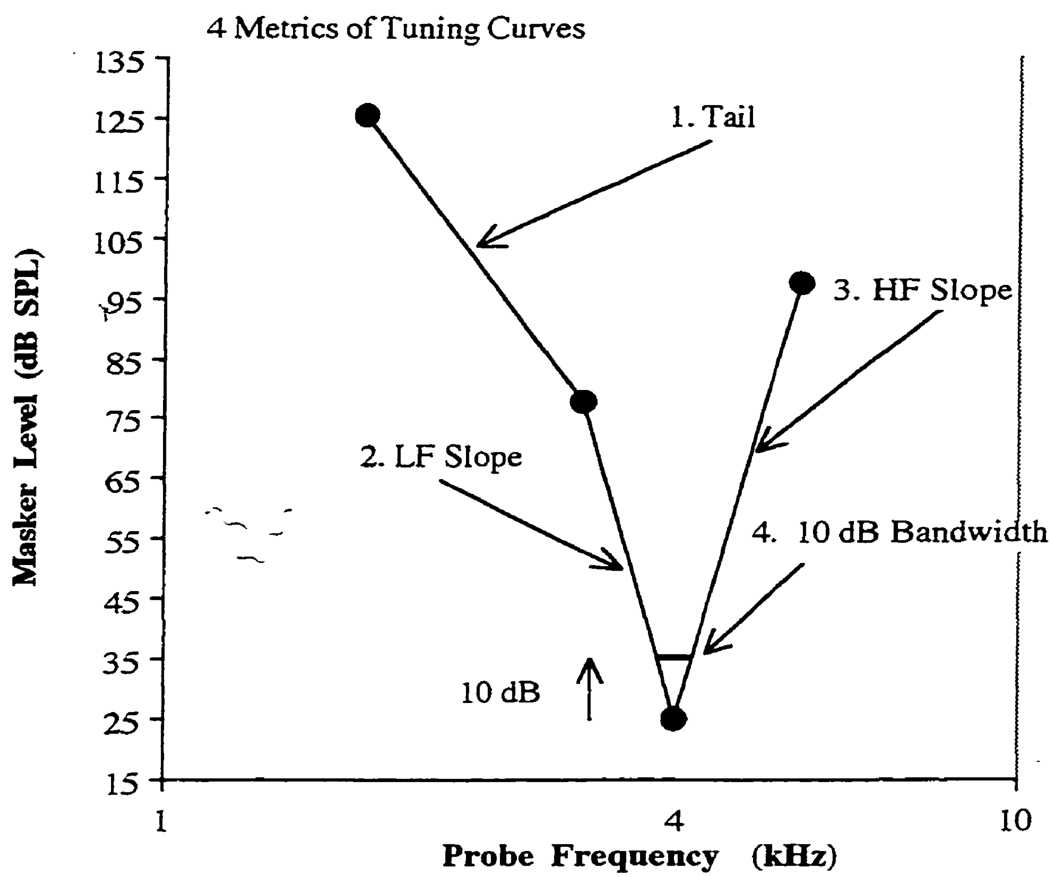
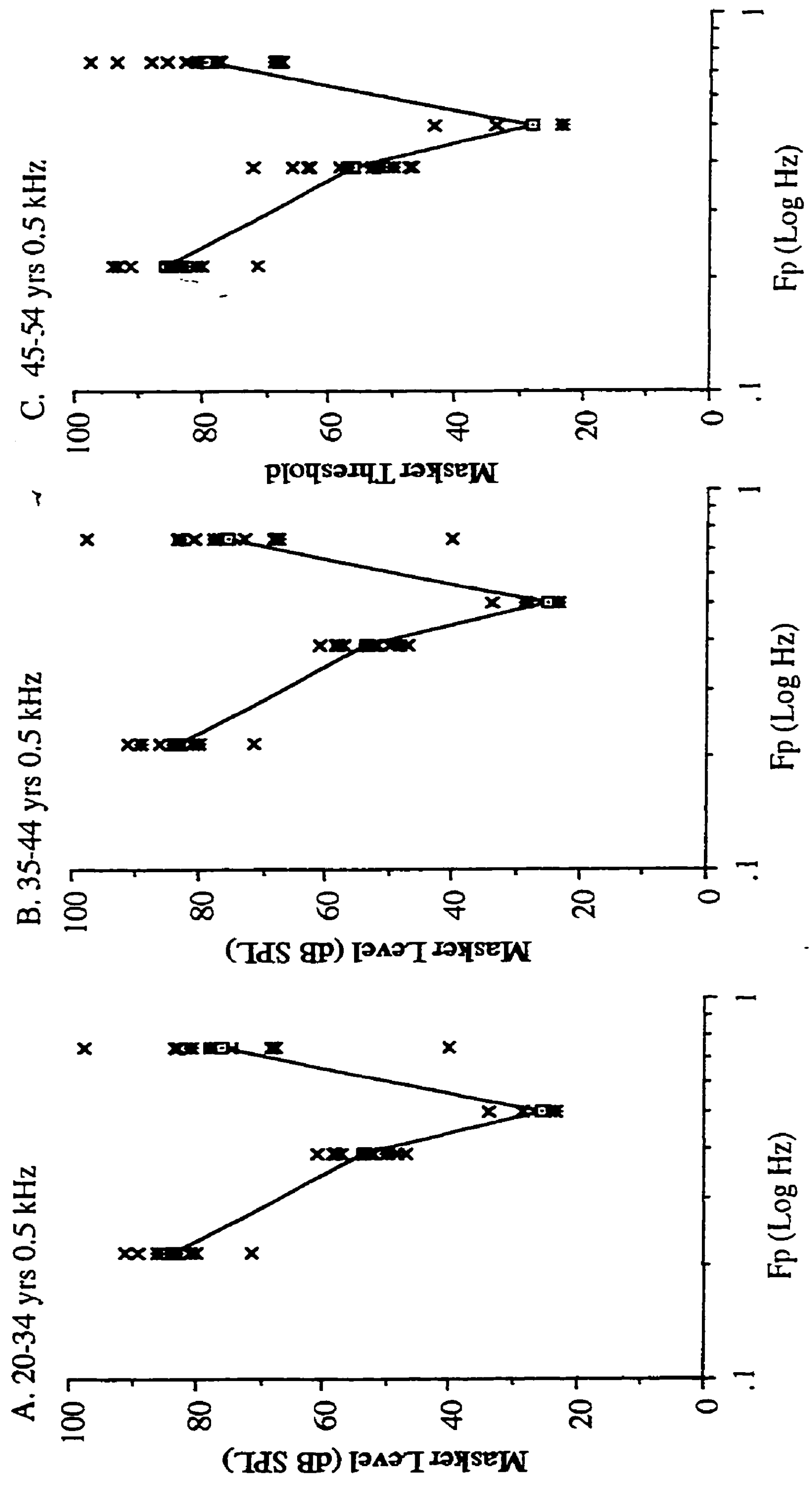

4 Metrics of Tuning Curves
Masker Level (dB SPL)
135
125
115
105
95
85
75
65
55
45
35
25
15
1. Tail
2. LF Slope
3. HF Slope
4. 10 dB Bandwidth
10 dB
1
4
10
Probe Frequency (kHz)

Figure 16. Tuning curve measurements at a probe of 0.5 kHz for each age group with frequency plotted on a log scale. Scatterplots of individual responses in each age group are shown only for the octave frequency measurements used in the calculation of the slopes for the tail, the low frequency region, and the high frequency region.


A. 20-34 yrs 0.5 kHz
B. 35-44 yrs 0.5 kHz
C. 45-54 yrs 0.5 kHz
Masker Level (dB SPL)
Masker Level (dB SPL)
Masker Threshold
100
80
60
40
20
0
.1
1
Fp (Log Hz)
Fp (Log Hz)
Fp (Log Hz)

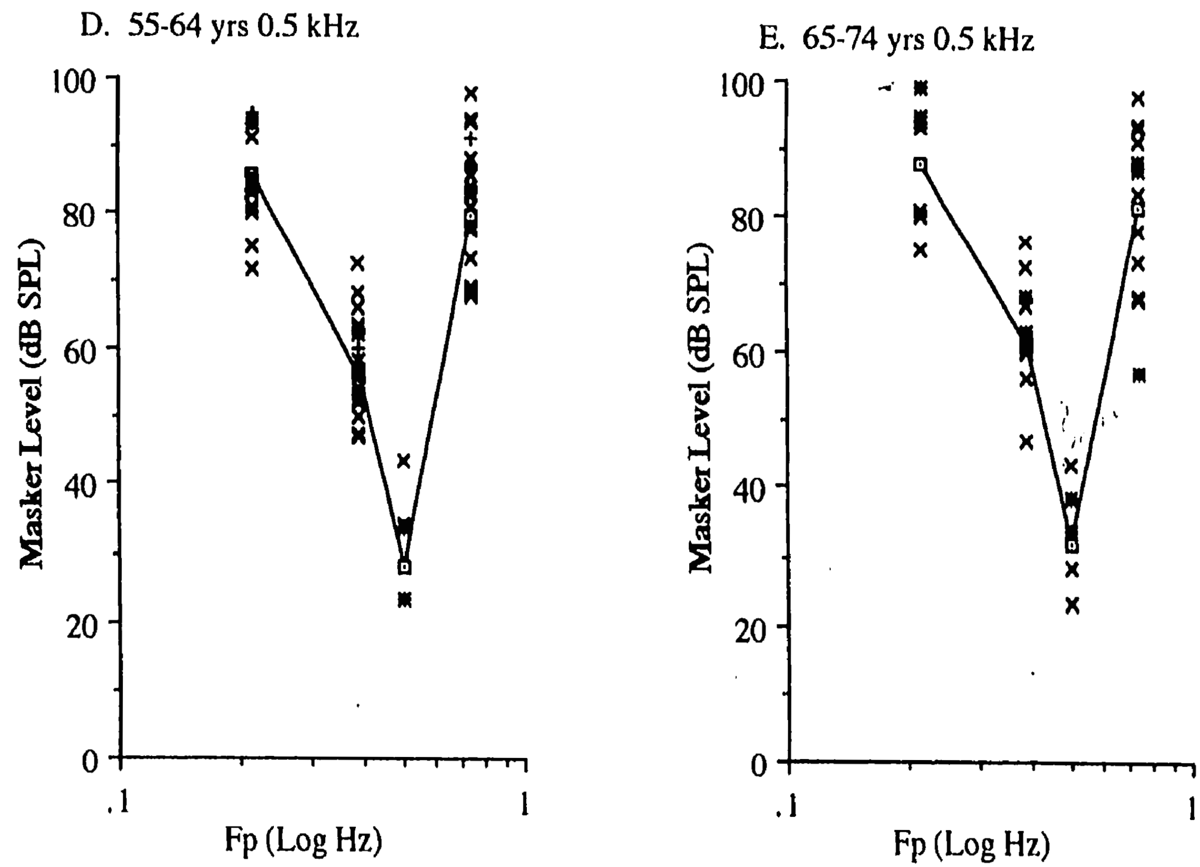
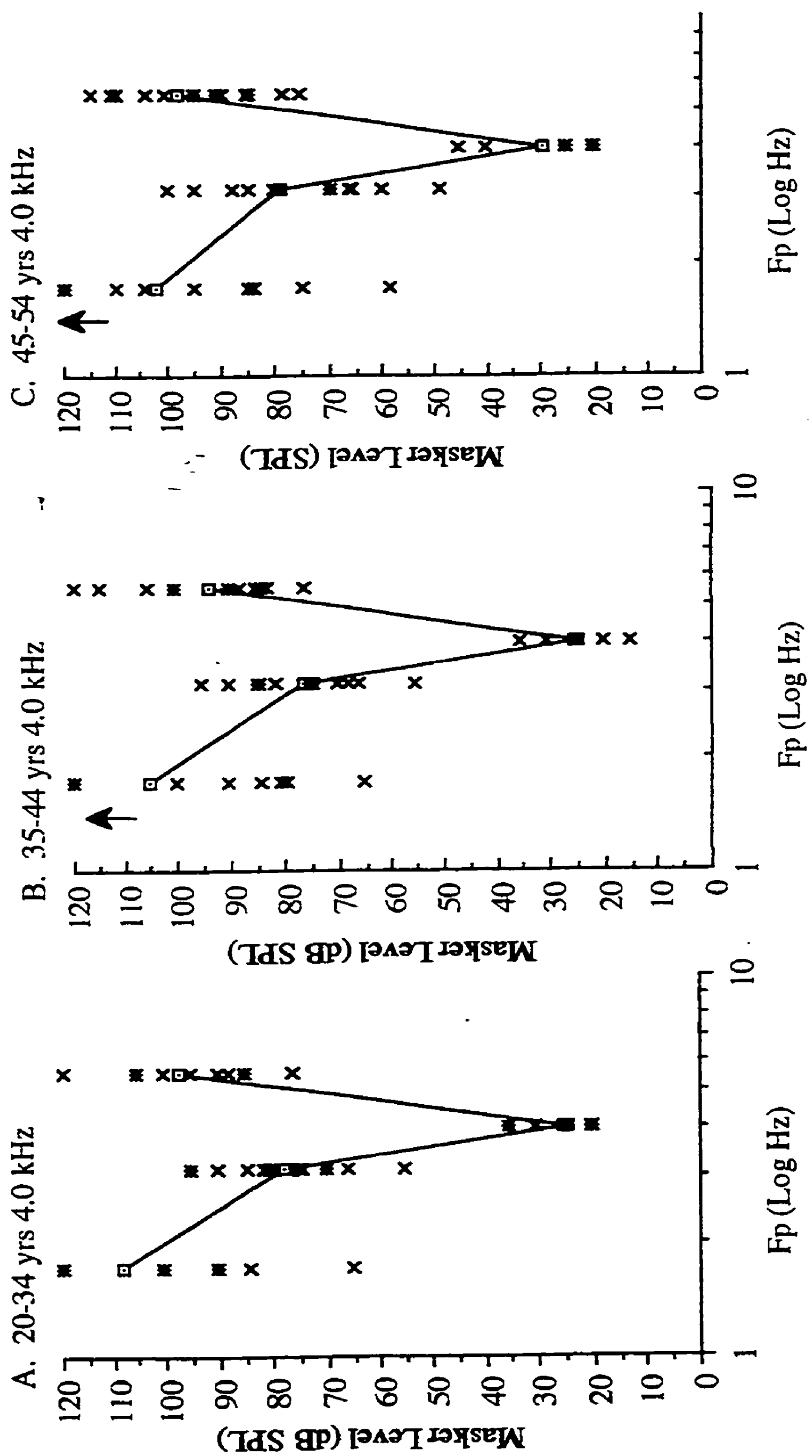
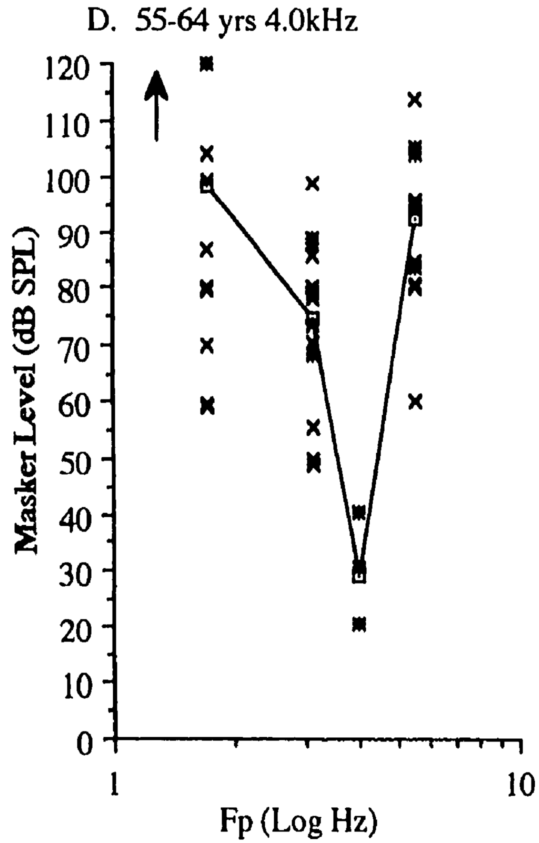

D. 55-64 yrs 0.5 kHz
Masker Level (dB SPL)
Fp (Log Hz)
E. 65-74 yrs 0.5 kHz
Masker Level (dB SPL)
Fp (Log Hz)

Figure 17. Tuning curve measurements at a probe of 4.0 kHz for each age group with frequency plotted on a log scale. Scatterplots of individual responses in each age group are shown only for the octave frequency measurements used in the calculation of the slopes for the tail, the low frequency region, and the high frequency region. Arrows indicate cases where the probe tone was still audible at the maximum level of the masker (120 dB).


A. 20-34 yrs 4.0 kHz
B. 35-44 yrs 4.0 kHz
C. 45-54 yrs 4.0 kHz
Masker Level (dB SPL)
Masker Level (dB SPL)
Masker Level (SPL)
120
110
100
90
80
70
60
50
40
30
20
10
0
1
10
Fp (Log Hz)
Fp (Log Hz)
Fp (Log Hz)


D. 55-64 yrs 4.0kHz
Masker Level (dB SPL)
120
110
100
90
80
70
60
50
40
30
20
10
0
1
10
Fp (Log Hz)

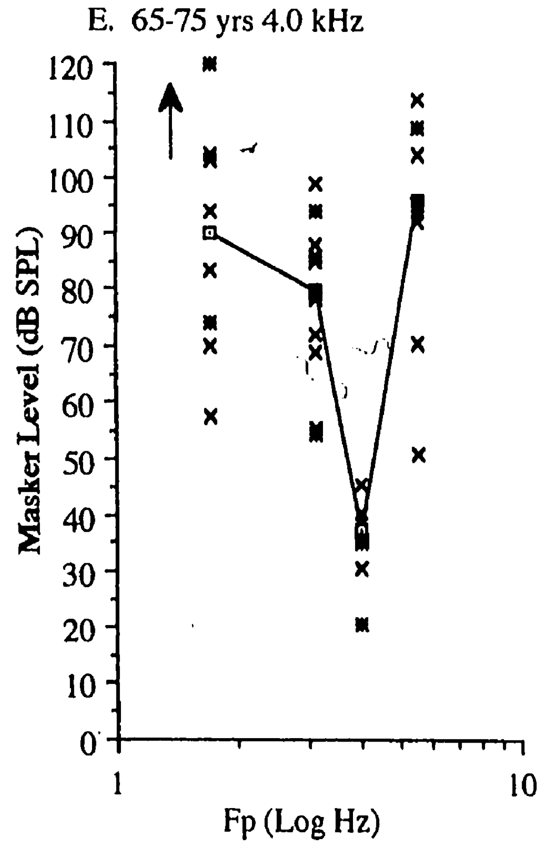

E. 65-75 yrs 4.0 kHz
Masker Level (dB SPL)
120
110
100
90
80
70
60
50
40
30
20
10
0
1
10
Fp (Log Hz)

Table 12. PTC measures for a Fp of 0.5 kHz. The metric for the Tail, Slf and Shf are in dB/octave. Q10 is the frequency normalized bandwidth. Standard errors are shown in parentheses.

		Tuning Curve Components		
Age Group (years)	**Tail**	**S_{lf}**	**S_{hf}**	**Q_{10}**
20-34	67.8 (.89)	- 102.58 (.74)	126.7 (2.28)	6.9 (.67)
35-44	67.47 (.82)	-102.13 (.69)	127.54 (2.28)	6.9 (.56)
45-54	67 (1.54)	-106.55 (1.48)	126.59 (1.83)	6.7 (1.28)
55-64	65.28 (1.17)	-108.1 (1.22)	130.23 (1.6)	6.67 (.99)
65-75	60.89 (1.79)	-107.39 (1.6)	132.8 (2.17)	5. (1.32)

Table 12. Tuning curve characteristics for a probe of 0.5 kHz. Values for Slf and Shf are expressed in dB/oct referenced to 0.5 kHz. Tail values are in dB/oct referenced to the .39 CF masker frequency.

Table 13. PTC measures for Fp of 4.0 kHz. The metric for the Tail, Slf and Shf are in dB/octave. Q10 is the frequency normalized bandwidth. Standard errors are shown in parentheses.

Tuning Curve Components

Age Group (years)	**Tail**	S_{lf}	S_{hf}	Q_{10}
20-34	68.16 (3.44)	- 241.21 (1.98)	144.17 (3.5)	10.67 (1.002)
35-44	69.95 (3.62	-232.64 (1.8)	143.69 (3.7)	9.14 (1.004)
44-54	52.6 (4.12)	-233.34 (3.13)	144.59 (2.94)	9.14 (2.04)
55-64	54.95 (4.51)	-235.73 (2.72)	139.3 (2.48)	9.15 (1.73)
65-75	22.72 (6.05	-189.94 (2.61)	125.45 (3.05)	7.11 (1.16)

Table 13. Tuning curve characteristics for a probe of 4.0 kHz. Values for Slf and Shf are expressed in dB/oct referenced to 4.0 kHz. Tail values are in dB/oct referenced to the 3.1 CF masker frequency.

Results

PTC metrics were analyzed separately at each frequency region with Factorial ANOVAs. At 0.5 kHz there were no significant group differences noted for any of the four metrics of frequency selectivity at an alpha level of .01. At 4.0 kHz, there were significant effects for tail , [$F(4,138) = 6.46$, $p < .001$], Slf [$F(4,138 = 3.4$, $p < .01$], and for Shf [$F(4, 138) = 4.82$, $p < .01$]. Follow up analyses showed that for listeners aged 65 and over, both measures of Slf and Shf were significantly shallower relative to all other listeners. By contrast, slopes of the tail regions were significantly shallower for listeners aged 44-64 ($p < .01$) and for listeners aged 65 and over ($p < .01$). Measures of the tip of the filter, Q10, were significantly smaller for only individuals aged 65 and over (larger Q values mean a more narrowly tuned filter).

At 0.5 kHz, 10dB BW estimates ranged from 15% (for 20-69 years of age) to 20% (for 70 plus years) consistent with values previously reported (Bacon & Moore, 1986). Q10 dB values at 0.5 kHz ranged from 5 – 6.7 and are slightly larger than values reported previously by Moore, Glasberg and, Roberts, (1984) (4.5 – 5.6 from their Table 2) but are also larger than those reported in other studies where estimates range from 3.3 to 4.5 (Kollmeier & Holube, 1992). At 4.0 kHz, 10dB BW estimates ranged from 9% - 11% (20-64 years) to 14% (65-75 years). Previous reports of Q10 values at 4.0 kHz have ranged from 6.3 – 6.9 (Florentine, 1992; Florentine, Buus, Scharf & Zwicker, 1980) to 10.67 (Moore, Glasberg & Roberts, 1984).

Interim Discussion

The lack of observed differences in PTC measures at 0.5 kHz is consistent with previous findings that frequency selectivity at low frequency regions is not impacted unless noticeable findings of hearing loss are seen (Lutman, 1991; Moore & Glasberg, 1986). There is a remarkable consistency in measures of the slopes of the functions at 0.5 kHz, however for a probe of 4.0 kHz, changes are quite pronounced on the low frequency side of the function. These changes are very gradual through to the 5th decade, but then accelerate. The slopes of the functions can be taken as a measure of the 'width' of the filter, and an increase in this is particularly noted at 4.0 kHz for listeners aged 60 and over despite peripheral hearing sensitivity being clinically normal (Table 13). Measures of the tail region show a decrease in the slope of the function by about 24 dB per octave; while the low frequency slopes (Slf) decrease by about 46 dB per octave.

The selectivity of the filter as estimated from the Q values shows consistent values with those previously reported, but again shows a tendency for an age-related increase. Relative to 20 year olds, listeners aged 65 and over show about a 5% increase in the bandwidth of the filter measured at 10dB above the tip at the higher frequency of 4.0 kHz. Taken together, the above findings indicate age-related changes in frequency selectivity are not a linear function of age.

Even though auditory thresholds were within clinically normal values, there was variation among the listeners, and one explanation for the results is a change in absolute threshold, and is seen as an elevation of the tip in the function at 4.0 kHz, (figure 17 panel E). However, no significant correlations (either zero order or partial) between any of the audiometric frequencies, PTA1, or PTA2 (see Table 5) were found ($p > .05$ in all cases). An examination of the individual slopes and pure tone thresholds showed that some elderly listeners with hearing levels as low as 5 dB HL showed very shallow tail slopes, and conversely, listeners with hearing levels as high as 18 dB HL showed very steep tail slopes. Therefore, auditory threshold is not a tenable explanation.

Alternatively, a possible explanation for these findings could be the suppressive effects of the masker. Filter shapes measured in young normal hearing listeners show sharper tuning when measured with a forward masking procedure than with a simultaneous masking procedure (Sommers & Gehr, 1998; Moore & Glasberg, 1986). The suppression hypothesis states that the improvement in the detection of a tone probe is because the temporal discontinuity between the masker and the tone allows for suppression to reduce the effective level of the masker without altering the excitation arising from the probe tone (Wright, 1996; Houtgast, 1972).

There are few studies available on age-related effects of suppression. Moore and Glasberg (1986) reported no differences in forward or simultaneous masking with aged listeners. Sommers and Gehr (1998) reported no differences in either the low-frequency or high-frequency filter skirts among 7 elderly listeners (66-75 years) all of whom had clinically normal hearing. In both of these studies, forward masking did not sharpen the skirt of the filter. Based upon their findings and the findings of the present study it is possible that age-related <u>declines</u> in auditory suppression may be present in this study. For young normal hearing listeners, the amount of suppression is greatest when the suppressor is in the range of 1.1-1.2 times the probe frequency (Houtgast, 1974), which means that the maskers above the probe in this study will serve to sharpen the high-frequency slopes. Explanations based upon auditory suppression are most consistent with the empirical findings (Sommers & Gehr, 1998). Though suppression areas exist below the probe frequency, (Wright, 1996; Houtgast, 1972), their effectiveness is less than that of suppressors greater than the probe. The greater change in the low-frequency slopes at

4.0 kHz among the elderly could be indicative of a generalized change in suppression at this frequency region which is less noticeable on the high-frequency slope. However, there is tremendous variability among the measures at the low frequency region where among all age groups, the probe was clearly audible for listeners at the maximum level. This has been noted among listeners with cochlear pathology (Florentine, 1990) but in such situations is a result of an increased SL presentation of the probe. There was no specific pattern among the individuals relating presentation level of the probe and masker level.

Though this study did not examine growth of masking functions, or compare simultaneous and forward masking procedures, the findings are indicative of no changes in at the low frequency regions, but a tendency for a decrease in auditory processing at the higher frequencies. What is of interest is the 'rate' of change. As measured with forward masking, changes are very gradual through the first six decades and then accelerate.

Study Four: Phoneme Identification

Purpose

A central question in speech perception focuses on the relation between psychoacoustic abilities and phonemic decisions, and a general trend is that as temporal acuity and frequency selectivity decrease, speech recognition errors increase (Dubno & Schaefer, 1992) but attempts to correlate speech recognition errors have produced mixed results. Some studies have reported that age, independent of hearing loss is a significant factor (Gelfand, Piper & Silman, 1986) while others have shown that age alone does not impair performance, but depends upon the nature of the task (Gordon-Salant & Fitzgibbons 1995; Gelfand, Ross & Miller, 1988). Given that the human brain can recognize phonetic information when broadly filtered (Turner et al.,1997) it could also be that phonetic categorization is a task which is dependent upon basic auditory abilities such as gap detection. Therefore, measures of stimuli classified 'mainly' (though not exclusively) on spectral cues, such as stop consonants, and temporal cues, such as voiced-voiceless consonants were obtained.

Participants. Described in Section II.

Stimuli

Two continua of signals representing a stop consonant series that went from /ba/ to /da/ to /ga/, and a voiced-voiceless series that went from /ba/ to /pa/ were generated on a Macintosh II computer using an adaptation of Klatt's parallel/cascade synthesizer program (KLYSN). Parameter values for the exemplars of the /ba/-/da/-/ga/ continuum of 14 stop consonant vowel (S1-S14) were patterned after previously published guidelines (Elliott, Busse & Bailet, 1985; Van Tasell, Hagen, Koblas & Penner, 1982). Total duration of the stimuli was 350 ms long. Three 'base' stimuli (S1, S8, and S14) were exemplars of /ba/, /da/ and /ga/ respectively. Onset frequencies of stimuli that fell between the base stimuli were interpolated in equal steps. Spectral values for F2 and F3 onset are given in Table 14 .

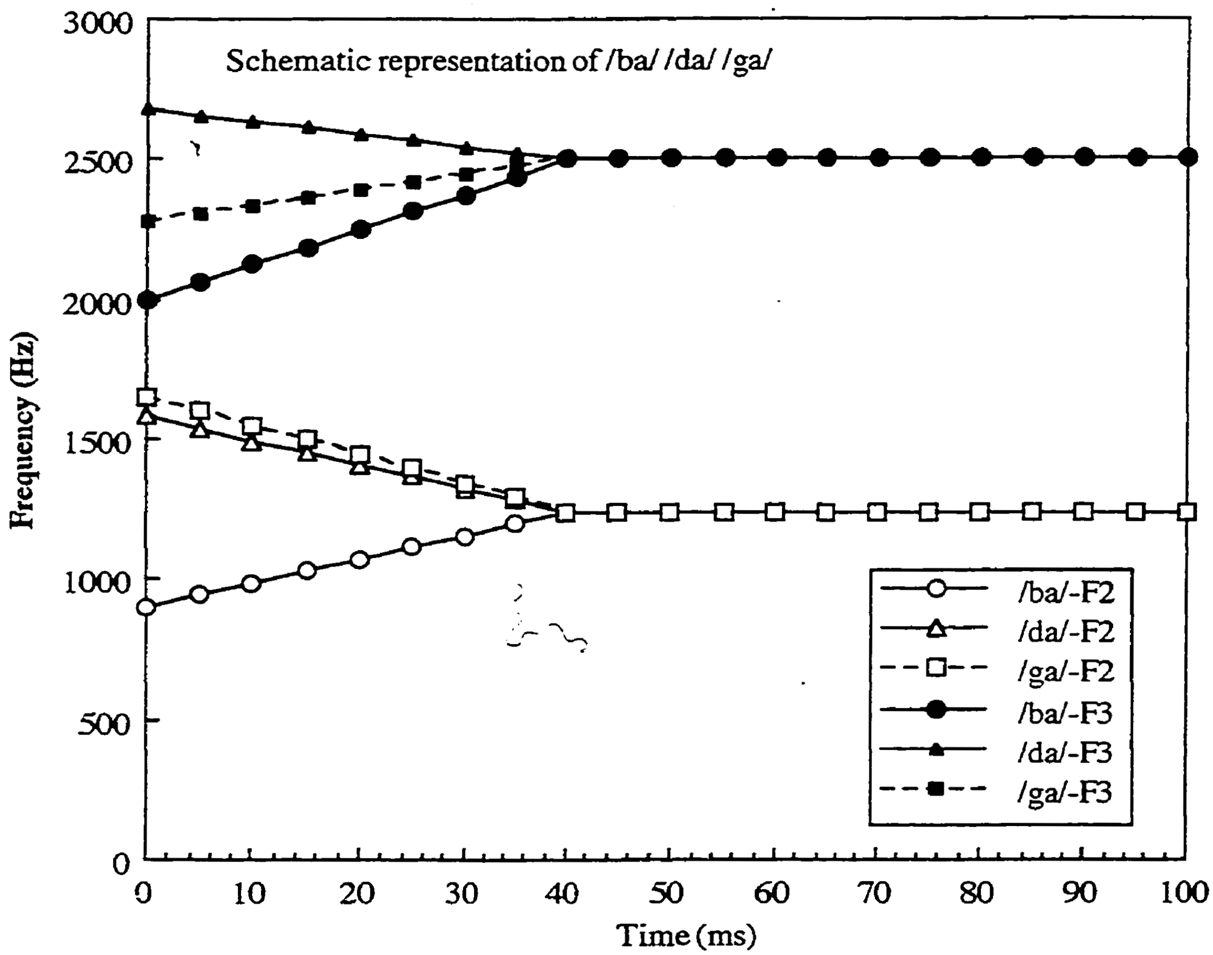
Table 14 . Frequency Onset Values, in Hz. for Stop Consonant Stimuli.

	Frequency Values (onset frequencies)					
Stimulus	Formant transition			Vowel steady state		
	F1	F2	F3	F1	F2	F3
S1	200	900	2000	720	1240	2500
S2	200	1010	2110	720	1240	2500
S3	200	1120	2220	720	1240	2500
S4	200	1240	2340	720	1240	2500
S5	200	1350	2450	720	1240	2500
S6	200	1470	2570	720	1240	2500
S7	200	1580	2680	720	1240	2500
S8	200	1700	2800	720	1240	2500
S9	200	1680	2630	720	1240	2500
S10	200	1670	2460	720	1240	2500
S11	200	1650	2280	720	1240	2500
S12	200	1640	2100	720	1240	2500
S13	200	1620	1920	720	1240	2500
S14	200	1610	1750	720	1240	2500

Table 14. Onset frequencies of F1, F2, and F3 for the 14 stimuli in the stop consonant continuum. Stimulus S1 corresponds to /ba/, stimulus S8 corresponds to /da/, and stimulus S14 corresponds to /ga/. F2 and F3 transition duration was held constant at 40 ms.

Figure 18 shows the schematic representation of the formant transition changes which created the continuum from /ba/-/da/-/ga/. Voice onset time (VOT) was 5 ms for S1 to S4; 10 ms for S5-S10, and 15 ms for S11-S14. F1 transition duration also varied across the continuum (Van Tassell et al., 1982). The duration of the F1 transition was 15 ms for S1-S2; 20 ms for S3-S5; 25 ms for S6-S7; 30 ms for S8-S9; 35 ms for S10-S12; and, 40 ms for S13-14. The formant transition durations for all other formants were 40 ms in duration. The fundamental frequency was set at 120 Hz and fell to 100 Hz over the last 100 ms of the stimulus.

Figure 18. Schematic representation of /ba/-/da/-/ga/ continuum. Specific parameter values are given in Table 18 for F1, F2, F3 frequency onsets.



The ba-pa continuum was created by taking the /ba/ stimulus from the previous continuum and varying the voice onset time in 5 ms steps. As the only parameter that changed in the continuum was the VOT, the F1, F2 and F3 frequency transitions were held constant at 25 ms in the /ba/-/pa/ continuum. Total duration of the signals was 350 ms including the duration of the VOT. The onset noise burst was 5 ms in duration and low level aspiration noise was present in the period before the onset of voicing. Pilot data in the lab showed that the VOT onset required to identify the signal as a /pa/ instead of /ba/ was on average 23.5 ms and ranged from 20-25.5 ms.

Procedure

After digital storage on the computer, the signals were passed through a Macpanel, fed through a mixer, and low-passed through two filters connected in series with attenuation rates of 48 dB/oct each. The signals were fed to an Industrial Acoustics double walled anechoic chamber, output through Kros Pro/4x headphones, and monaurally presented to the right ear at a presentation level of 60-70 dB SPL. The listener's task was to depress a button corresponding to the perceived identification of the phoneme heard. For the noise condition, cafeteria noise, (produced on digital tape by Auditec of St. Louis), was played out through a Sony Digital Tape Recorder (ES-75) and mixed with the phonemes at the level of the mixer (Sony 48134). The noise was played continuously during the background noise condition.

Results

Stop Consonants

To determine the phonetic boundary (PB50%), the raw data were smoothed with a polynomial line fitting procedure and the 50% change over position was determined.

Voiced/Voiceless Continuum

Responses for the /ba/-/pa/ continuum were fit with probit functions and the PB50% VOT was determined. Figure 19 shows the fitted function to the raw data.

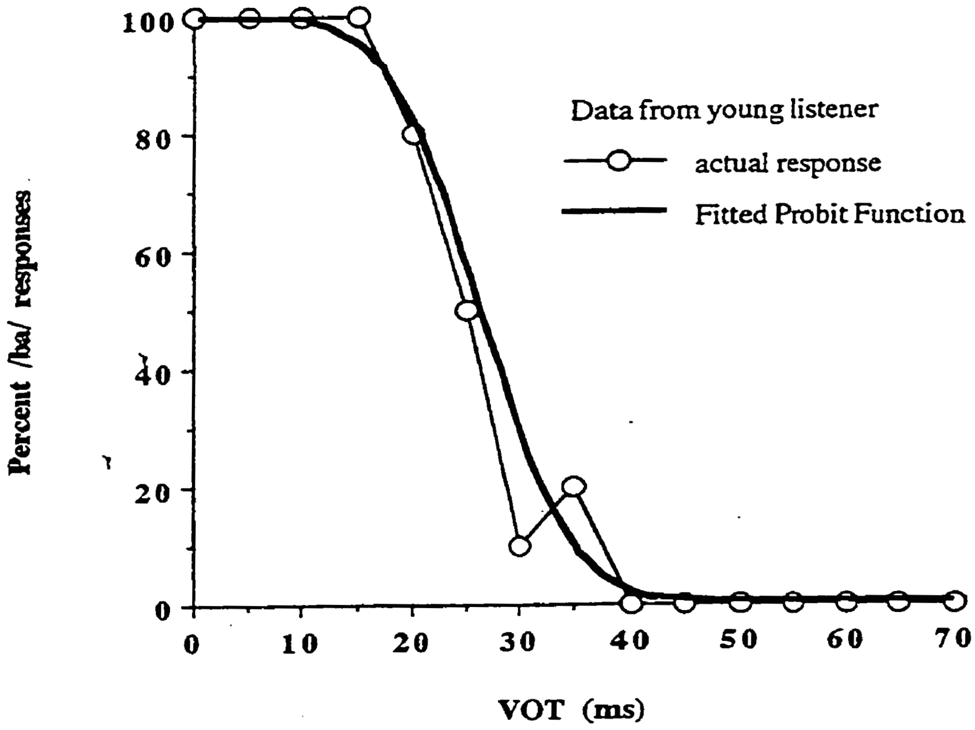
Phonemic Boundaries

Phonemic boundaries (PB50%) and standard deviations for both quiet and noise conditions for each age group are shown in Figure 20. Stimulus numbers for PB50% identification are shown in Table 15 for both the quiet and noise conditions. There is a remarkable consistency across groups for /ba/-/da/ identification, but there appears to be a shift in the phonetic boundary for a /da/-/ga/ discrimination for the elderly. That is, their identification of a stimulus as /ga/ comes later in the continuum.

This was confirmed in a Factorial ANOVA on PB50% values assessed for both the /ba/-/da/ discrimination and for the /da/-/ga/ discrimination in both quiet and noise. There were significant main effects for age group, [$F(4,138) = 18.58$, $p<.0001$], for listening condition (quiet versus noise), [$F(1,138) = 31.16$, $p<.0001$], and for the interaction between age group and listening condition, [$F(4,38) = 11.16$, $p<.0001$]. Post hoc Scheffe's contrasts to follow up the interaction showed that in the quiet condition, the /ba/-/da/ phonetic boundary for 65-75 year olds was significantly higher relative to both 20-34 year olds and 45-54 year olds. In the noise condition, the 65-75 year olds were significantly different from the 20-34 year olds and from the 45-54 year olds. The 55-64 year olds also had a significantly higher phonemic boundary than the 20-34 year olds.

PB50% for the /da/-/ga/ distinction in both quiet and noise was significantly higher for 65-75 year olds relative to 20-54 year olds. Within each group, phonetic boundaries in noise were significantly higher only for 65-75 year olds. Therefore, there is a significant age-related shift in the phonetic identification of stop consonants, and noise is a factor for only the eldest listeners.

Figure 19. An example of the curve fitting for the /ba/-/pa/ responses.



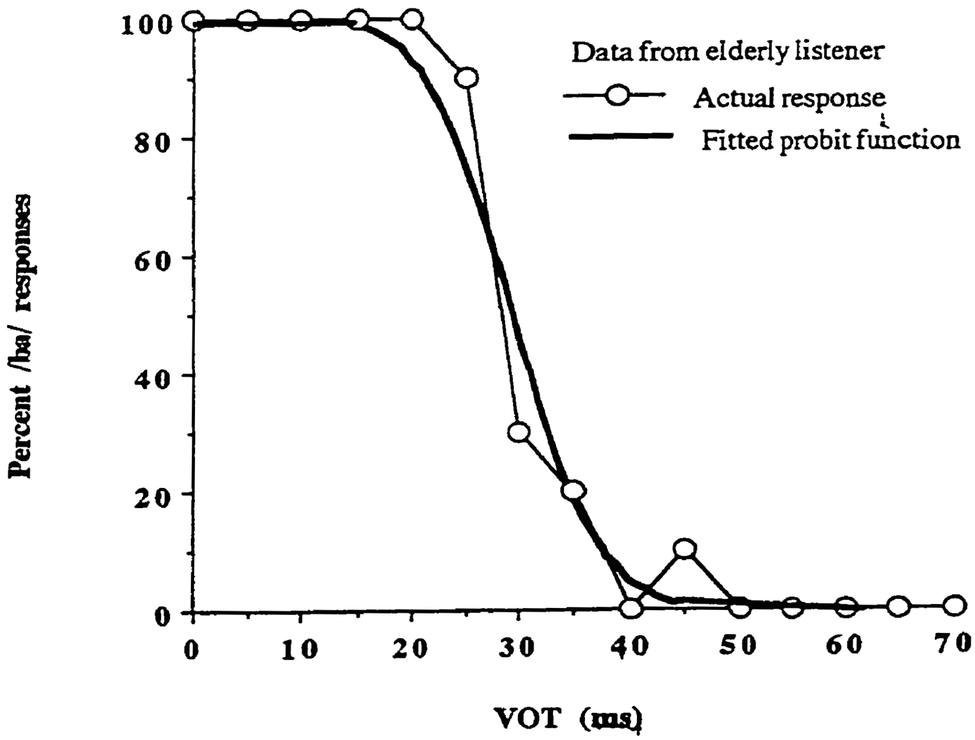


Figure 20. Mean PB50% and standard deviation values for /ba/-da/-/ga/ discrimination for all age groups.

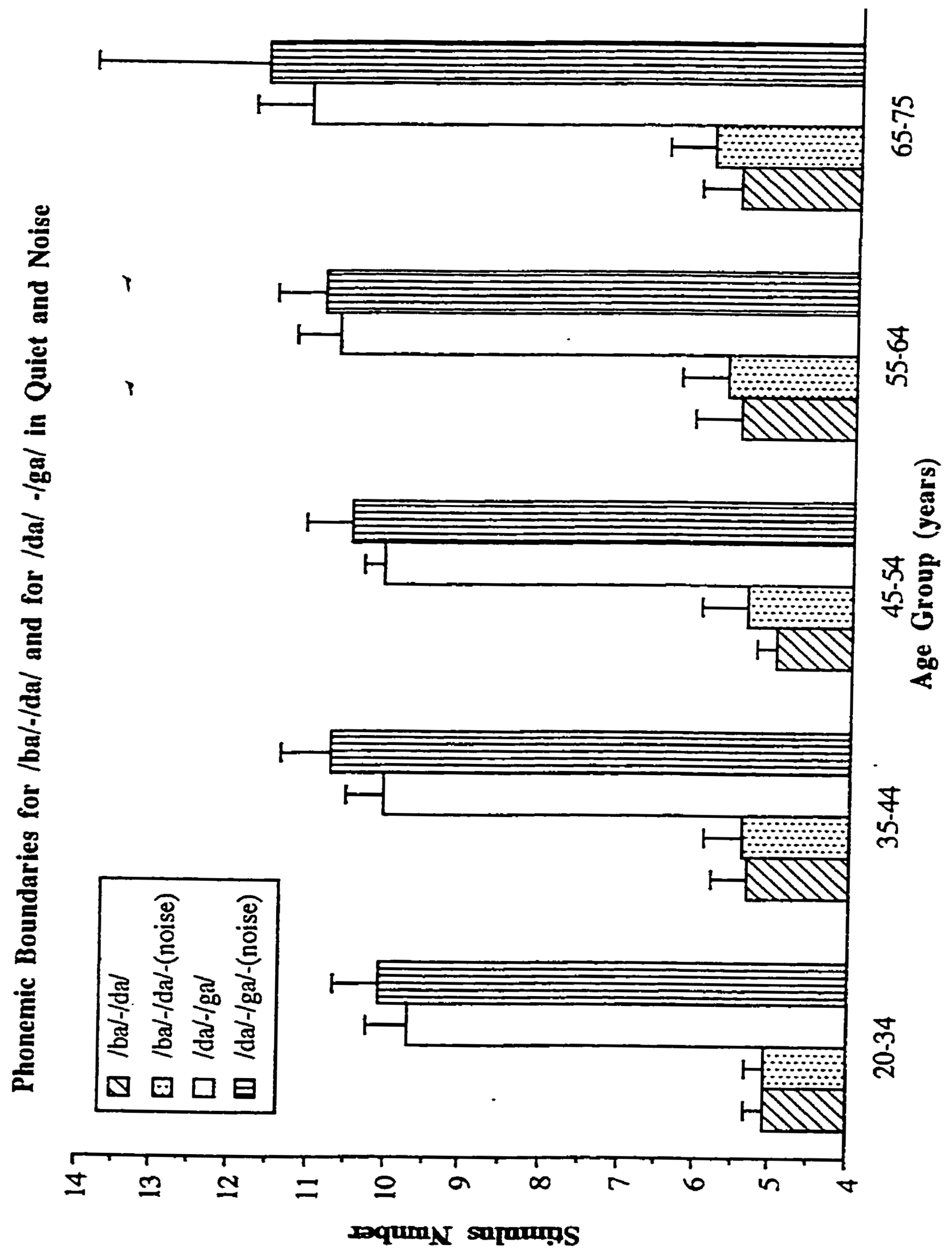
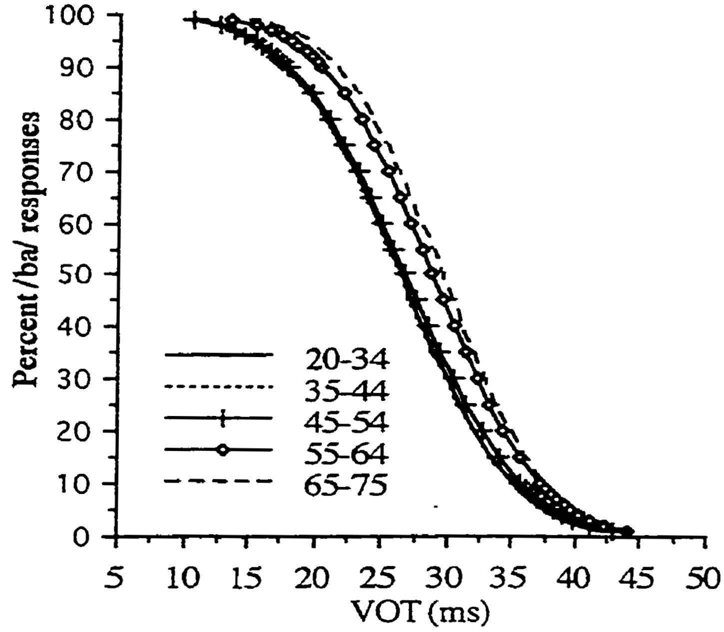


Figure 21. Psychometric functions for /ba/-/pa/ identification for all age groups.

A. Percent /ba/-responses (quiet)



B. Percent /ba/ responses (noise)

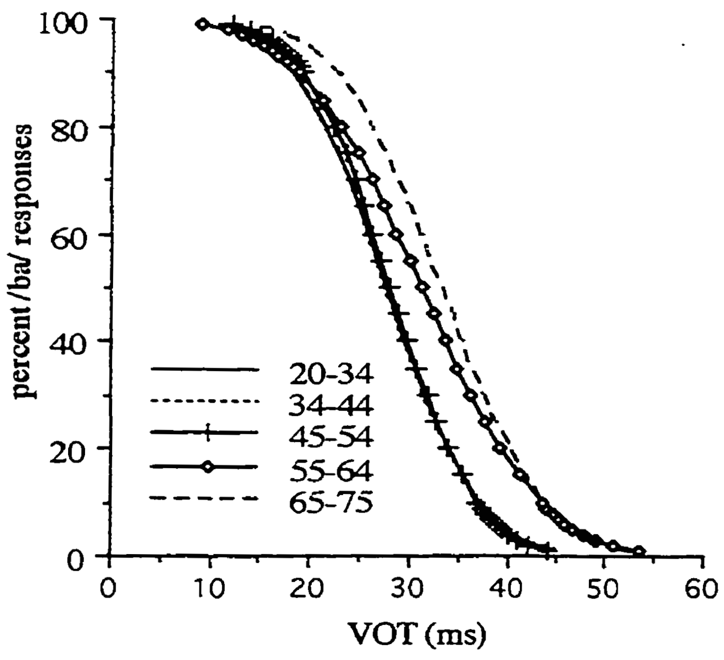


Table 15 . Mean PB50% for **/ba/-/da/-/ga/** discrimination in both quiet and noise listening conditions for each age group. Values indicate stimulus number for 50% identification. Standard errors are shown in parentheses.

	Listening Condition			
	/ba/-/da/		/da/-/ga/	
Age Group	Quiet	Noise	Quiet	Noise
20-34 years	5.05 (.05)	5.06 (.04)	9.7 (.10)	10.08 (.11)
35-44 years	5.33 (.08)	5.467 (.09)	10.06 (.08)	10.7 (.12)
45-54 years	4.97 (.05)	5.350 (.09)	10.1 (.2)	10.5 (.11)
55-64 years	5.48 (.07)	5.777 (.07)	10.7 (.11)	10.8 (.13)
65-75 years	5.56 (.13)	5.920 (.11)	11.1 (.14)	11.6 (.14)

Table 15. Phonemic boundaries for /ba/-/da/ and /da/-ga/ discrimination. Values are the stimulus number.

Response variability

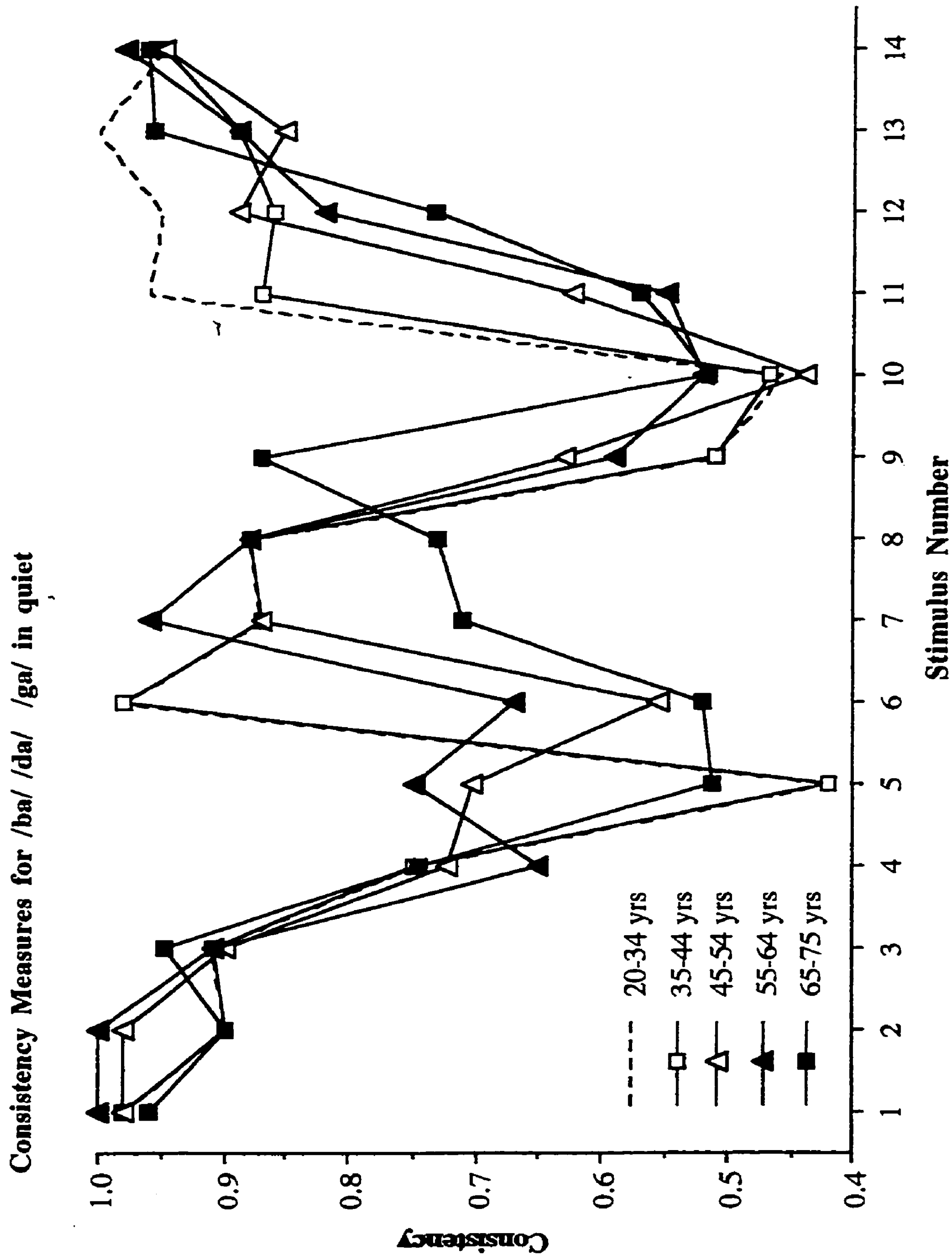
To assess the variability of responses to stimulus perception, each individual's probability score for each stimulus was converted into a measure of consistency based on relative entropy (Slawinski & Fitzgerald, 1998). This measure provides a metric of the uncertainty or randomness in responses and informational 'redundancy'. The metric takes on a value between 1.0 representing perfect consistency in performance and 0.0 which represents complete response diversity in responding. Consistency measures are computed as

$$\text{consistency} = 1 - (\Sigma\ (p_n \log_2 (1/p_n))/\log_2 m) \qquad (6)$$

where "m" is the number of forced responses in a choice task (here m = 3), "n" is the number of stimulus repetitions (here "n" = 10), and pn corresponds to the probability of the response to each stimulus. These analyses are illustrated in Figure 22 for the quiet condition and Figure 23 for the noise condition for all 5 age groups. Consistency measures for all 5 age groups are relatively high for the stimuli designated as /ba/ (stimuli 1 - 3) and are near their maximum value of 1.0 for both quiet and noise conditions, and as expected crossover stimuli (4, 5, and 6) are much lower. An interesting observation of the data is that the consistency measures for the 45-54 year olds and the 55 -64 year olds are much higher for the crossover stimuli than for the other age groups. The 65-75 year olds show a lower degree of consistency across stimuli perceived as /da/ (stimuli 6,7,8, and 9) and a higher phonemic boundary for the perception of /ga/. An examination of the individual confusion matrices revealed that for the elderly listeners the largest number of errors was made in the /da/ versus /ga/ confusions.

The same general pattern of results can be seen in the panel for consistency measures in noise. Consistency measures are close to their maximum value of 1.0 for /ba/ stimuli (stimuli 1, 2, and 3). For the /ga/ stimuli presented in noise there is a sharp separation of the 3 eldest groups (45 years plus). The stimuli designated as /da/ show little effect for age except for the eldest group. However, the perception of stimuli labeled as /ga/ begin to show age effects beginning at age 45 years. The effect of noise is similar in that there is a shift towards higher stimuli as age increases.

Figure 22. Consistency measures for /ba/-/da/-/ga/ identification in quiet. Values of 1.0 are complete consistency. Values of 0.0 are complete response diversity.



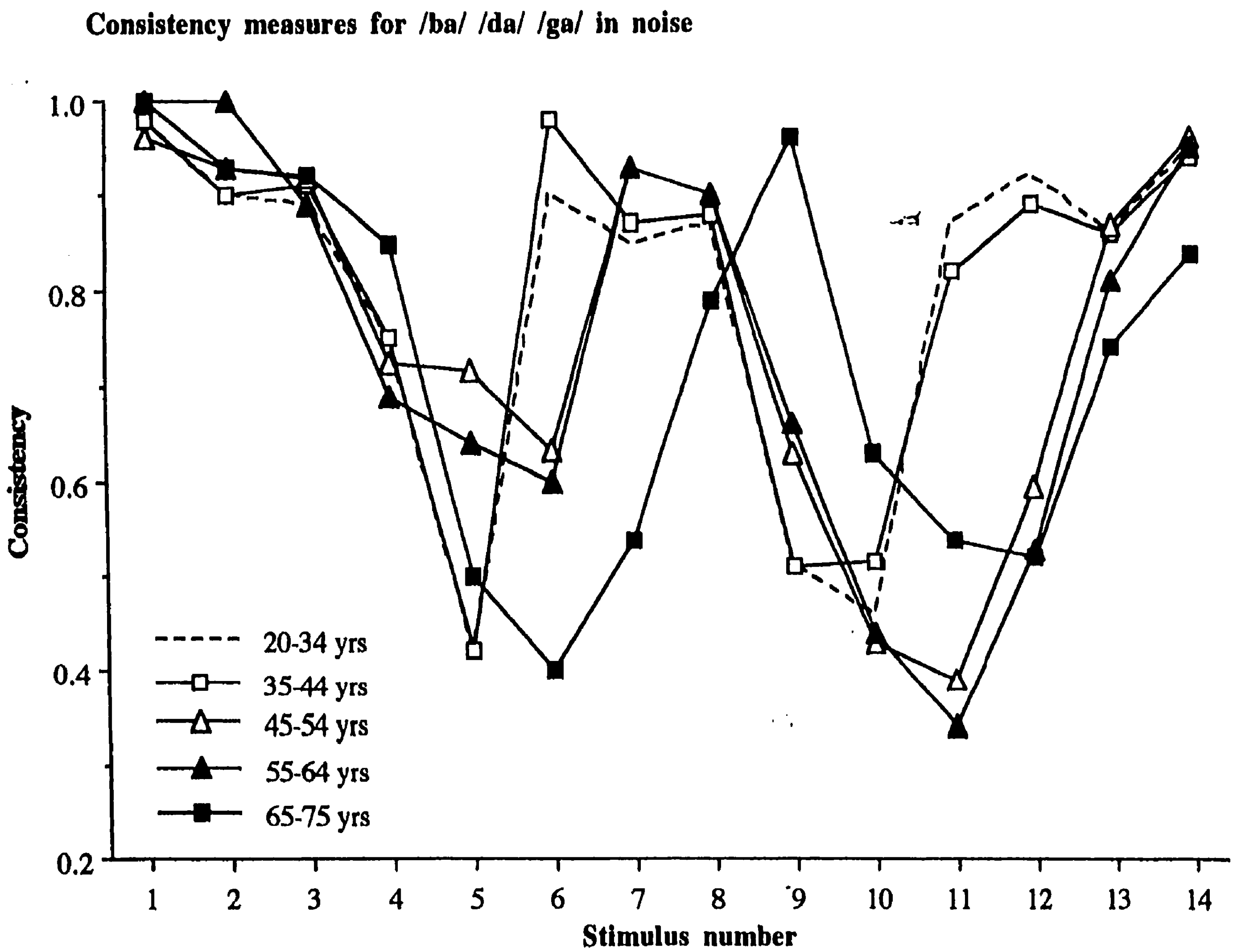


Figure 23. Consistency measures for /ba/-/da/-/ga/ identification in noise. Values of 1.0 are complete consistency. Values of 0.0 are complete response diversity.

Voice Onset Time

Group mean PB50% VOTs and standard errors are shown in Table 16 and represent a strong linear increase with age. Figure 24 shows the scatterplot of individual responses for quiet (open symbols) and noise (filled symbols) with the best fit regression lines as well. The upper line in Figure 24 is for noise and the lower line is for quiet conditions. The equations describing these lines are $Y = 21.7 + 0.11X$ with an r-square of 0.324 for quiet and $Y = 23.3 + 0.12X$ with an r-square value of 0.413. Therefore, VOT discrimination can be described as increasing by approximately 1 ms every decade past 20 years.

Factorial ANOVAs were conducted on the VOT data with two levels of listening conditions (quiet and noise) as a within factor and age group as a between factor. As expected from the pattern in Figure 23, there was a significant main effect for age group [$F(4,138) = 19.21$, $p<.0001$] and for listening condition, [$F(1,138) = 53.21$, $p<.0001$]. The interaction between age group and listening condition was nonsignificant, ($p=.409$). The youngest group had significantly smaller thresholds (M=24.46 ms) than did the two oldest listening groups: (M=28.59 ms for the 55-64 year olds; M=29.53 ms for the 65-75 year olds). The second youngest listening group, 35-44 year olds had significantly smaller thresholds (M=25.67 ms) than only the eldest group. In the noise condition, the eldest listening group had significantly larger thresholds (M=33.14 ms) than did the 20-54 year olds (M=27.35 ms; M=27.29 ms; M=28.84 ms respectively). Among each of the age groups the effect of listening condition was significant. For each age group, thresholds were significantly smaller in quiet conditions than they were in noise. Analysis of the slopes revealed no significant differences for quiet versus noise conditions, nor any group differences ($p<.01$ in all cases). Consistency measures to assess response variability were computed and are shown in Figures 25 and 26.

Table 16. Mean VOT in ms. and standard errors. for each age group.

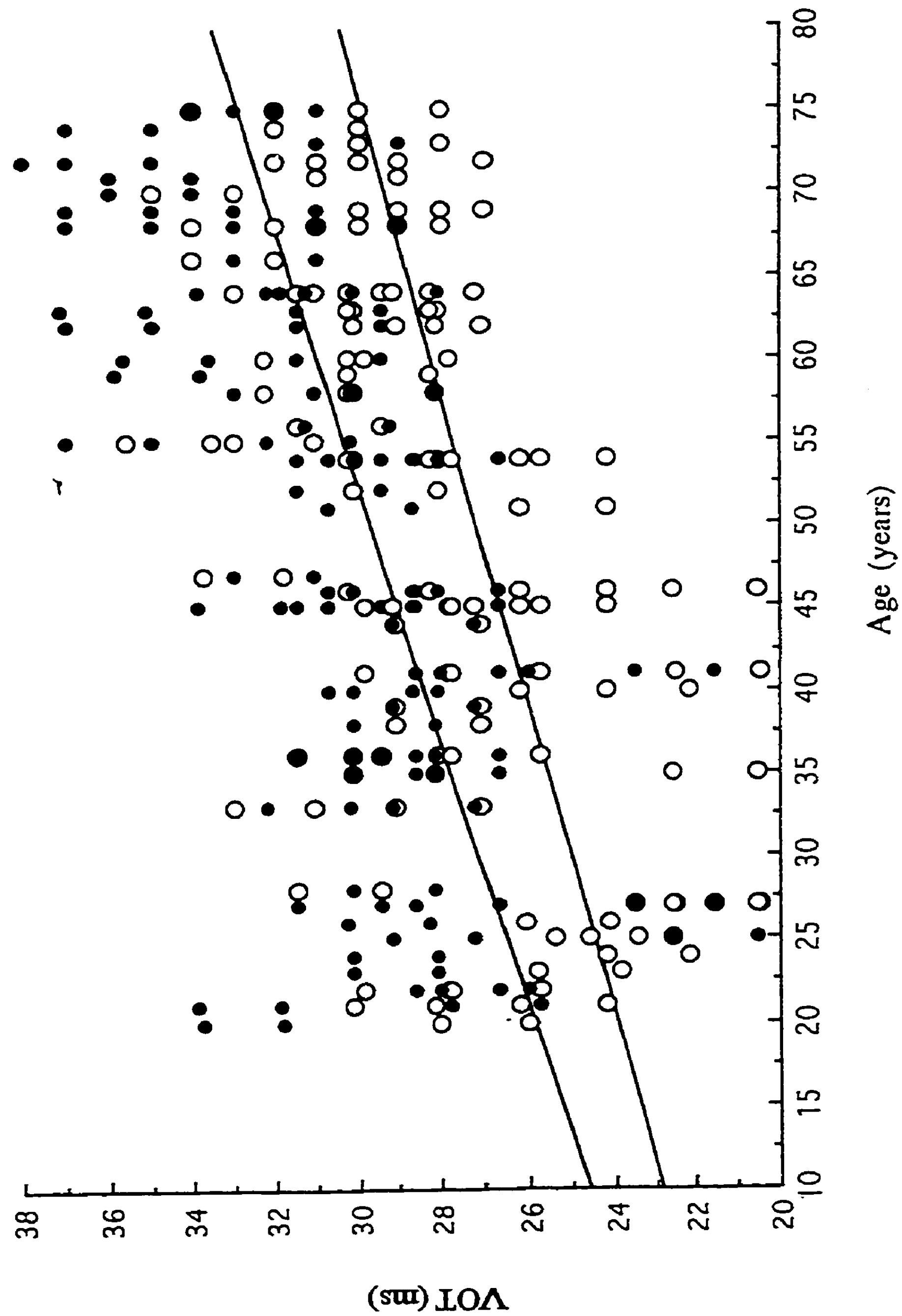
	Listening Condition	
Age Group	Quiet	Noise
20-34 yrs	24.46 (.51)	27.35 (.56)
35-44 yrs	25.67 (.62)	27.29 (.58)
45-54 yrs	26.62 (.58)	28.85 (.23)
55-64 yrs	28.59 (.23)	30.73 (.51)
65-74 yrs	29.53 (.35)	33.14 (.45)

Table 16. Mean VOT response in ms, standard errors are shown in parentheses.

Figure 24. Individual PB50% VOTs for the quiet (open symbols) and noise (filled symbols) conditions.

The upper regression line is for the noise condition, Y = 23.3 + 0.12X, r-square = .41

The lower regression line is for the quiet condition, Y = 21.73 + 0.11X, r-square = .32


VOT (ms)
Age (years)
38
36
34
32
30
28
26
24
22
20
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

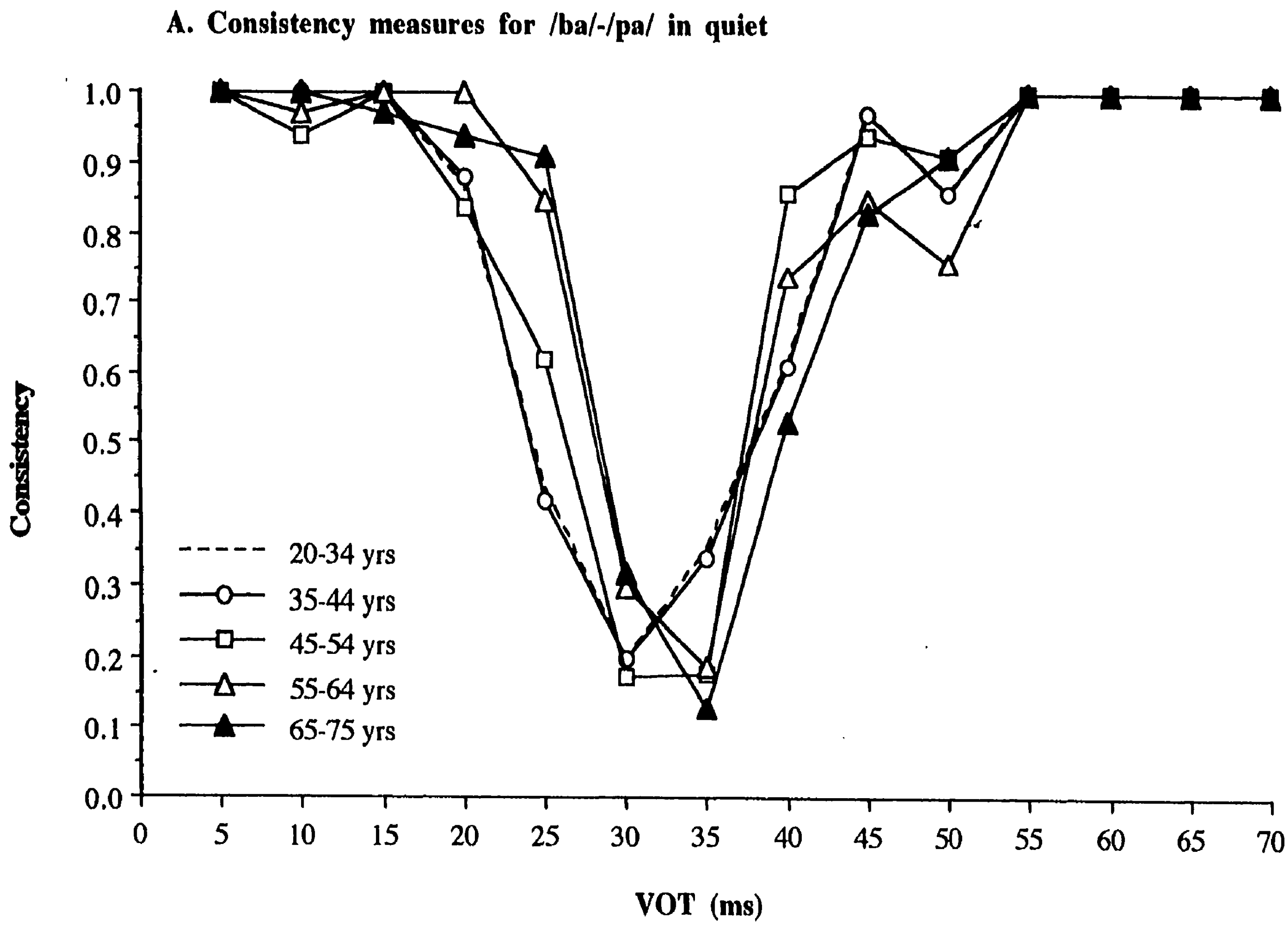
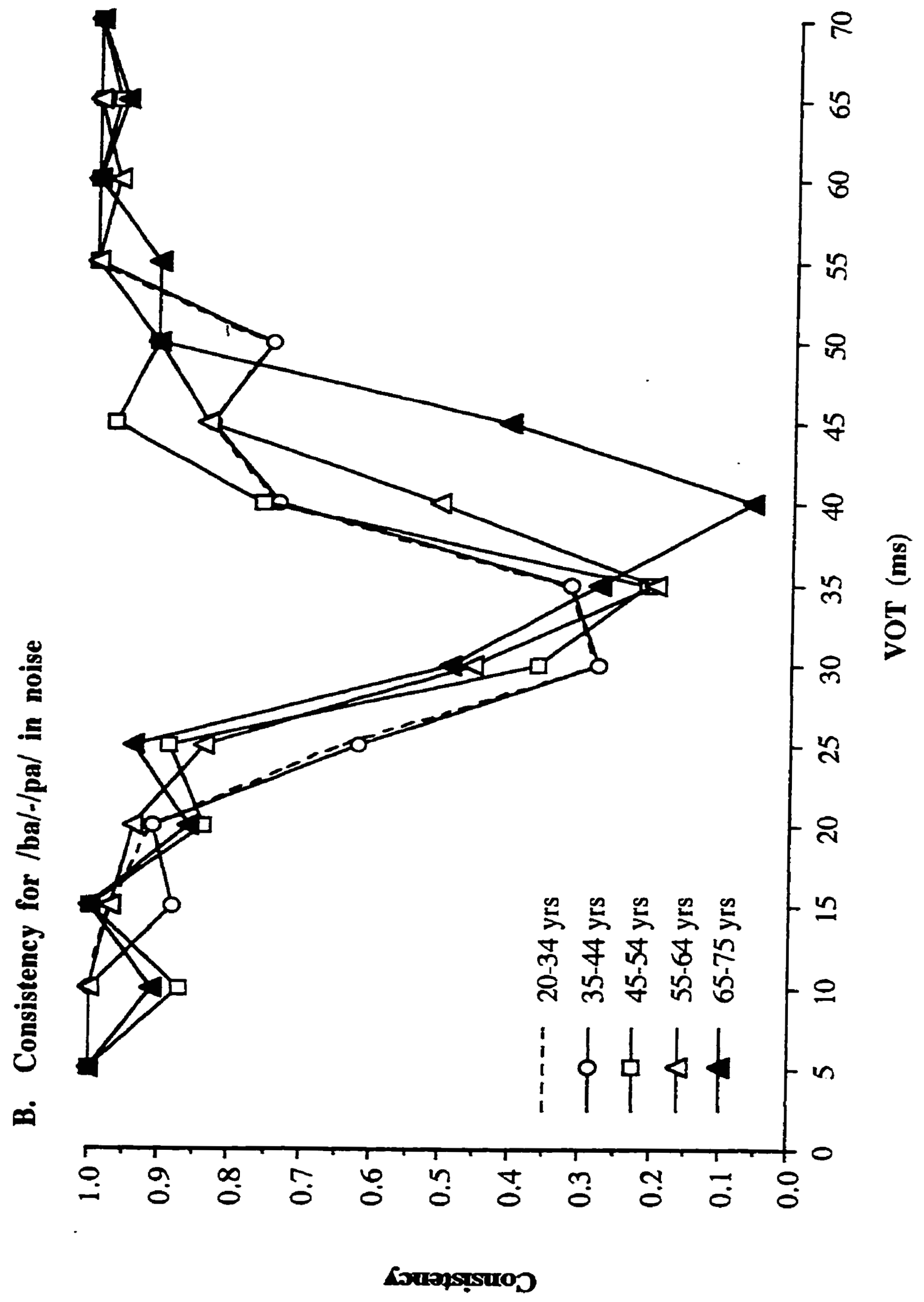


Figure 25. Consistency measures for /ba/-/pa/ discrimination in quiet. Values of 1.0 are complete consistency. Values of 0.0 are complete response diversity.

Figure 26. Consistency measures for /ba/-/pa/ discrimination in noise. Values of 1.0 are complete response consistency. Values of 0.0 are complete response diversity.



Interim Discussion

Results of the present study indicate that elderly listeners have reduced sensitivity to spectral contrasts and to VOT as compared to younger listeners. Shifts in the phonetic boundary for both stop consonant and voiced-voiceless continua are consistent with previous findings (Strouse, Ashmead, Ohde & Grantham, 1998; Gordon-Salant, 1986; Dorman, 1985). Strouse et al., (1998) in a group of listeners rigorously screened for hearing status reported mean VOTs of 27 ms for younger listeners and 32 ms for older which are similar to the 24 ms and 29 ms times in quiet in this study. Though their results were not statistically significant, the difference may be due to the smaller sample in their study.

Examining the measures for consistency showed that for a place distinction, with age there is an attendant confusability across the boundaries. In quiet, (Figure 20) the functions are clearly defined for younger individuals, are spread out for the elderly, and tend to become broad for the middle age group. The finding is even more pronounced in a noisy condition (Figure 21), where the phonetic categories are more clearly defined for the young. The question of whether deficits in temporal processing ability contribute to speech perception is controversial. Reduced temporal processing has been linked to some speech perception errors made by hearing impaired listeners (Stuart & Phillips, 1996; Price & Simon, 1984; Tyler, Woods & Fernandes, 1982), however similar errors have been made by normal hearing listeners as a consequence of changes in temporal relations among phonetic elements (Gelfand,1986). Therefore, it may not be a deficit in phonetic processing, per say, but that the spectral content of the signal has been compromised.

Phonemes can be recognized with an accuracy of 45-to-75% by young listeners with only two modulated filtered frequency channels of information (bandpass filtered below 450 Hz), but this climbs to 85% with four channels (Turner, Chi & Flock 1999; Turner, Souza & Forger, 1995). Thus it seems that transmitting the identity of phonemes requires very little spectral information and that the human brain easily recognizes these patterns.

The linear trend in the data for VOT perception strongly indicates that even in a population who are audiometrically normal, there are changes in temporal acuity. The main effect of noise for the young group of listeners was a suprising result given the findings in the literature (Gordon-Salant & Fitzgibbons, 1995). This raises the possibility that there was some unintended characteristic in the generated stimuli which caused this by lengthening the VOT. A subsequent reanalysis of the spectrum of this continuum revealed no artifacts and therefore this is probably not a tenable possibility. As individual variation is not a negligible source of variance, and is typically noted among aging studies, the possibility that the effects are due to a small number of listeners who had elevated thresholds is also possible. However, since the analysis revealed no outliers nor large group variances, it is more likely that subtle changes in temporal processing are revealed if sample size is sufficient (Snell & Rekhi, 1999).

There was no relationship between VOT discrimination and gap detection thresholds in broadband noise. Pearson correlation coefficients were significant when age was not considered ($r = .52$ for VOT in quiet and $r = .61$ for VOT in noise, $p < .01$). However, this effect was no longer significant for any age group when age was controlled for. Assessing correlations among such a large number of variables must be interpreted cautiously (Pedhazur, 1973), as spurious correlations are to be expected. More importantly, the discrimination of a gap in broadband noise may have no relationship to the ability to identify a voiced-voiceless phoneme (Phillips,Taylor,Hall,Carr & Mossop, 1997; Nelson, Nittrouer & Norton, 1995). Discrimination of VOT requires differences in discontinuity between spectrally different signals with an early onset gap (Phillips et al., 1997). Gap detection in broadband noise in the present study required discrimination between stimuli that were spectrally similar and the gap was centrally placed in the signal.

Section IV. Correlations and Factor Extraction

Given the large number of factors that were measured in this study, data reduction techniques were undertaken to explore the constructs underling the performance on these measures. Variables employed in the psychophysical tests along with age were subjected to a principal components analysis with varimax rotation. The 9 principal components with eigenvalues greater than one and item loadings > or = to +/- .3 are reported in Table 17 as well as the communalities, eigenvalues and the percent of variance accounted for by each factor. The communalities represent the sum of the square of loadings from the factor matrix and, therefore, for age the sum of the square of the coefficients across all 9 factors is .8073. This 9 factor model extracted from the data accounts, therefore, for 81% of the variance in age. Means and standard deviations of the 9 factors are shown in Table 18.

The 9 principal components that were extracted were subjected to a Multivariate Analysis of Variance (MANOVA). The results showed a significant effect for the components (Wilks Lamda = .03491, $p <.0001$). A follow up discriminant function analysis was performed to assess which factors contributed to potential group differences. With 5 groups, there are a maximum of 4 functions which could potentially separate the groups. Table 19 shows the eigenvalues, percent of variance accounted for and the significance associated with each discriminant function accounting for the previous functions. That is, after the first two functions have been removed the significance level is .4438.

Two discriminant functions were calculated with a combined Chi-square (28) = 155.842, $p < .00001$. After removal of the first function, there was still a strong association between groups and predictors, Chi-square (128) = 41.709, $p < .01$. The two discriminant functions accounted for 90% and 6% of the between group variability. Table 20 shows the centroids (means) of the discriminant functions for each of the 5 age groups. Table 21 shows the loading coefficients.

Table 17. Communatlies, eigenvalues and the percent of variance accounted for by each factor.

			Value		
Variable %	Communality	PC	Eigenvalue	% of Variance	Cumm
age	.8073	1	9.067	28.3	28.3
gap	.7096	2	3.211	10.1	38.4
cd-low	.6311	3	2.039	6.4	44.8
cu-low	.5256	4	1.937	6.1	50.9
du-low	.6895	5	1.698	5.3	56.2
dd-low	.7131	6	1.475	4.6	60.8
cu-high	.7364	7	1.297	4.1	64.9
cd-high	.7028	8	1.232	3.9	68.8
dd-high	.6607	9	1.052	3.3	72.1
du-high	.6535				
cu-low-n	.5578				
dd-low-n	.5498				
cu-high-n	.6452				
dd-high-n	.6864				
vot-quiet	.7769				
vot-noise	.7129				
tail- 0.05 kHz	.8846				
Slf- 0.05 kHz	.9168				
Shf- 0.05 kHz	.8064				
tail- 4.0 kHz	.6834				
Slf- 4.0 kHz	.8484				
Shf- 4.0 kHz	.8058				
pb-ba-da	.8012				
pb-da-ga	.8131				
pb-bada-n	.7834				
pb-daga-n	.8195				

Table 17. Communatlies, eigenvalues and the percent of variance accounted for by each factor. Variable labels are the same as those used in the body of the text. Low refers to the low frequency condition, high refers to the high frequency condition. NOTE: pb at the bottom the column stands for phonetic boundary.

Table 18. Summary table of means and standard deviations (in parentheses) for the 9 principal components.

	Age Group				
Component	20-34 yrs	35-44 yrs	45-54 yrs	55-64 yrs	65-75 yrs
PC1	-.667 (.484)	-.456 (.627)	.623 (.813)	.190 (1.085)	.739 (.963)
PC2	-.715 (.730)	-.760 (.719)	-.256 (1.101)	.616 (1.077)	.982 (.557)
PC3	-.569 (.856)	.136 (1.151)	.217 (.736)	.217 (.631)	.596 (1.317)
PC4	.185 (.698)	-.063 (1.48)	-.091 (.714)	-.034 (.784)	-.187 (1.267)
PC5	-.028 (.488)	-.179 (.617)	-.239 (.941)	-.604 (1.016)	1.109 (.615)
PC6	.181 (.918)	.179 (1.018)	.239 (.962)	-.016 (1.180)	-.162 (1.101)
PC7	.333 (.909)	.424 (.707)	-.436 (.847)	-.244 (.968)	.321 (1.104)
PC8	-.102 (.593)	.087 (.891)	-.586 (.766)	.337 (.731)	-.139 (1.761)
PC9	.275 (.613)	.177 (.606)	.091 (.741)	.221 (.759)	-.075 (.887)

Table 18. Means and standard deviations for the 9 principle components extracted from the full set of variables.

Table 19. Eigenvalues, percent of variance accounted for, and cannonical correlations.

Function	Value					
	Eigenvalue	% of Variance	Cumm	Cannonical corr	Wilks' Lambda	Sig
1	9.78	90.03	90.03	.9525	.4194	.0012
2	.6871	6.32	96.35	.6382	.7076	.0836
3	.3484	3.21	99.56	.5083	.9541	.6887
4	.0481	.44	100	.2143		

Table 20 . Group centroids. (means of discriminant functions). for each of the age groups on the 4 discriminant functions.

	Discriminant Functions			
Age Group	Function1	Function2	Function3	Function4
20-34 yrs	-3.433	0.644	-0.070	0.296
35-44 yrs	-2.222	0.468	0 .423	-0.333
45-54 yrs	-0.442	-0.723	-0.964	-0.095
55-64 yrs	1.116	-1.082	0.649	0.102
65-75 yrs	5.367	0.871	-0.106	0.022

Table 21. Loading coefficients for the 4 discriminant functions.

	Coefficient			
Variable	Factor 1	Factor 2	Factor 3	Factor 4
DD-high	.751			
CU-N-low	-.590			
DU-high	.570			
CU-high	.53			
DD-N-low				
VOT-noise		.686		
DU-low		.668		
CD-low		.660		
VOT-quiet		.598		
Age		.591		
Gap		.567		
da-gaPB50%	.536			
DD-N-high			.724	
CD-high			.601	
DD-low			.558	
Slf 4.0 kHz				.904
Shf 4.0 kHz				.803
CU-low				.512

Table 21. Loading coefficients greater than +/- .5 on the 4 discriminant functions.

Figure 27. Plot of the five age groups on both discriminant functions.

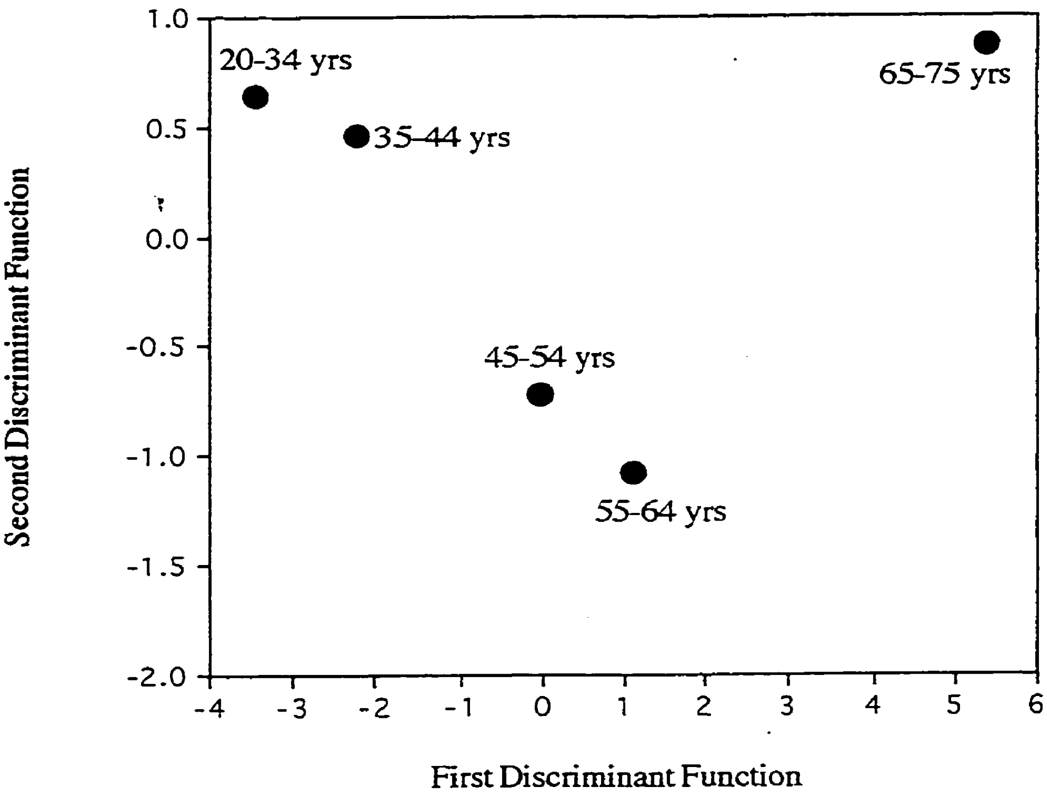


Table 22 . Classification results.

Actual Group	Predicted Group Membership				
	20-34 yrs	35-44yrs	45-54yrs	55-64yrs	65-75yrs
20-34yrs	90.9%	9.1%			
35-44yrs	17.3%	82.7%			
45-54yrs	9.1%	8.2%	73.6%	9.1%	
55-64yrs			16.7%	83.3%	
65-75yrs					100%

Table 22. Classification results for the discriminant functions. Note that all groups are well classified by the functions with the 45-54 year olds showing classifications in all but the eldest group.

Interim Discussion

As can be seen in Figure 27, the first discriminant function appears to separate the five age groups into three clusters: the 20-44 year old; the 45-64 year olds; and, the 65-75 year olds. In other words, it separates the 45-64 year olds from both the two younger groups and the eldest group. The second function again separates the 45-64 year olds from the other age groups. These functions correctly classified 84.82% of age group membership. As can be seen in the classification results of Table 27 , only the very youngest and the very eldest group were correctly classified with a high degree of accuracy. The eldest age group (65-75 years) was correctly classified in 100% of the cases; the youngest (20-34 years), 90.9%. The second eldest group (55-64 years) was correctly classified 83.3% of the time; the 35-44 year olds only 72.7% of the time. The middle group (45-54 years) however was misclassified more than any other group being classified in all other groups except the very eldest group, and correctly classified only 63.6% of the time.

Though identification of components and functions is a somewhat arbitrary and personal thing, it appears from an assessment of the variables that the first discriminant function which separates the eldest age group from the other four is a function which describes high frequency resolution and is inevitably involved with determining the spectro-temporal 'shape' of a stimulus. Therefore, this function can be labeled 'spectral discrimination abilities'. The second function describes an underlying temporal quality to the stimuli and therefore can be labeled 'temporal discrimination abilities'. The third function seems to relate to downward swept signals, and the fourth is related to masking in the high frequencies. Therefore, it appears as if processing of fine structure is useful for discerning differences of an aged auditory system from younger systems. The function which separates the 45-64 year olds reflects that changes in temporal acuity can readily be used to distinguish among a population of listeners.

V. Final Conclusions

The present study found significant age-related changes in auditory processing among a number of different psychoacoustical abilities. These changes were noted on all variables for listeners aged 65 and over despite the presence of clinically normal hearing. More importantly, the finding of significant changes are noted on some dimensions among listeners aged 45 and over. Factor analysis revealed two significant dimensions which differentiated listeners; but one dimension concerned with temporal aspects of changes separates listeners in their 40s and 50s as a distinct subgroup. The classification results also demonstrated that performance of listeners in their 40s and 50s represents an intermediate change in processing between the youngest and the eldest listeners. Indeed, the classification on this group spanned all age ranges. This can be seen on a relatively simple discrimination task of detecting an upward glide centered at about 1 kHz, ΔF values of 45-54 year olds were significantly higher than younger listeners (figure 7). This same effect was also noted at a higher frequency, where ΔF for the same series of signals in a higher frequency region was more difficult for this group, but interestingly not for 55-64 year olds (figure 8 DD and DU signals).

Though the noted age-related changes are robust they are not necessarily linear. Changes in frequency selectivity were suggestive of an initially slow change which accelerates after age 65. Temporal ability as measured by gap detection showed a strong linear trend. The finding of changes in psychoacoustical abilities among individuals aged 45-60 underscores the overused simplified dichotomy of 'elderly' versus 'young' listeners, and shows that auditory changes are a lifelong process. Though, this has received little attention in the literature, Bonfils, Bertrand, and Uziel (1988) found that evoked acoustic emissions thresholds did not vary until the age of 40 and then increased linearly after that among clinically normal hearing listeners. Thus if there are subtle changes in the mechanics of the cochlea, this could manifest itself in changes in auditory processing particularly if the signal is complex.

Despite the linear frequency glides being in the same frequency region as the phonemes, little relationship was found between the discrimination of frequency glide and phonetic perception. Correlational data reduction showed that these abilities did not form an emergent property that reliably discriminated individuals. This supports the findings of Bailey (1999) who reported that discrimination of formant transitions of a stop consonant series was not improved by prior identification of the phoneme. The results of this study show that only certain auditory processes active in simple psychoacoustic tests of frequency glide discrimination (diverging glide signals in quiet) show little relationship to the perception of speech signals.

Frequency selectivity was found to be an auditory ability that did not show changes with age, at least in so far as can be revealed with a forward masking paradigm. It is possible that models of auditory filters which use more parameters in the model such as the roex(p) functions of Patterson et al (1982) may be more appropriate to reveal subtle changes across the life span. Also, the level of the probe in this study was specified relative to individual thresholds, and significant differences may be found as overall stimulus levels are changed. Significant interactions between age and stimulus level have been reported previously (Strouse et al., 1998; Schneider et al., 1994).

Significant findings in temporal acuity have been attributed to the contribution of spectral cues in the detection of temporal gaps (Schneider et al., 1994), however the use of broadband noise in this study was specifically chosen to eliminate such a confound. The linear increase which was found beyond the age of 40, indicates that fundamental auditory abilities undergo changes relatively early. What makes the findings in this study more compelling is that the majority of the elder listeners were female. Gender differences in auditory ability are well documented (Dubno, Lee & Mills, 1997) with elderly females showing significantly smaller thresholds on intensity and discrimination tasks (Dubno et al., 1997). Whether this is a measure of sensory capabilities or response proclivities is uncertain, but physiological differences in the cochlea do exist (Sato, Sando & Takahashi, 1991).

This study clearly demonstrates that even among a population screened for clinically normal hearing, there are significant differences in auditory processing. The fact that these differences arise in midlife is not a new finding, what is significant is that these differences clearly separate middle adults from both younger and older individuals.

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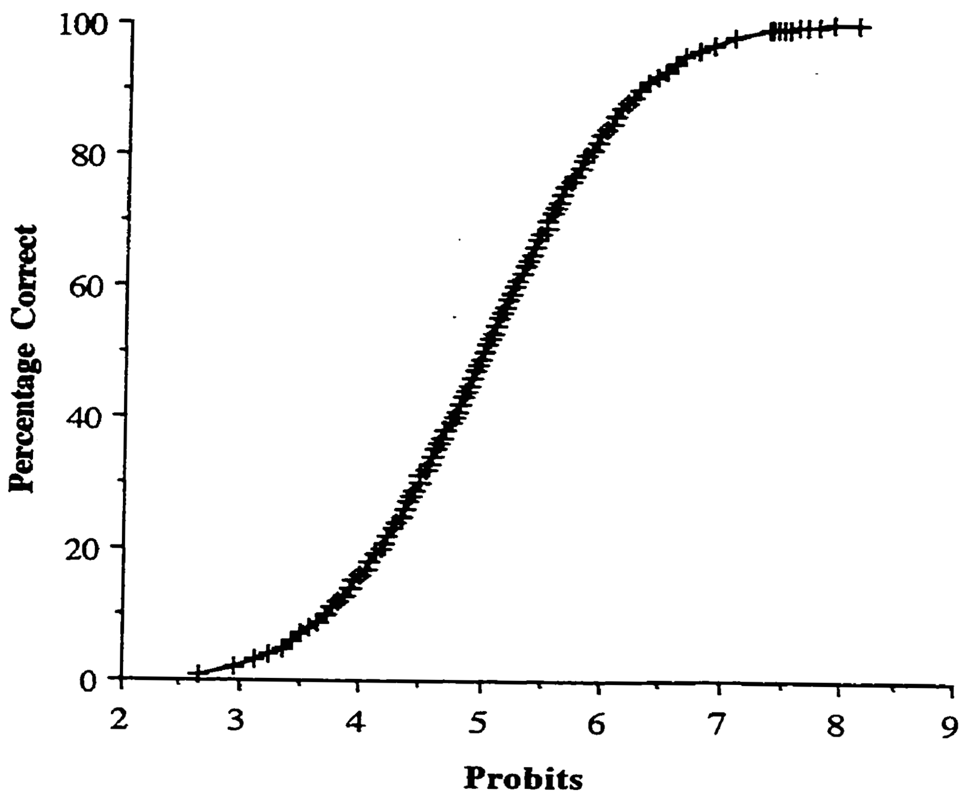
Appendix A. The relationship between percentage correct scores and probits.

Data for each discrimination tasks were transformed into percentage correct scores as a function of the frequency separation between a target stimulus and the standard in each series. Probit regression models can be modeled as a class of generalized linear models in which the response probability function is binomial. In a binary response model for variable Y, the probit regression model has the form:

$$P = \Phi(\beta x)$$

where Φ is the cumulative standard normal distribution.



Appendix B. Thresholds for the glide discrimination tasks at the low frequency region expressed as Hz/ms

<u>Group mean thresholds and standard errors in parenthesis expressed in relative rate of change required for discrimination above the rate of change in the standard signal for the low frequency region glides. Values are expressed in Hz/ms and are normalized to the rate of change in the standard signal.</u>

	Age Group (yrs)				
	20-34	35-44	45-54	55-64	65-75
Signal Condition					
rate-du	.59 (.02)	.60 (.02)	.70 (.03)	.74 (.04)	.85 (.04)
rate-dd	.56 (.02)	.56 (.02)	.77 (.04)	.82 (.03)	.76 (.03)
rate-cu	.68 (.03)	.70 (.03)	.73 (.03)	.78 (.03)	.93 (.04)
rate-cd	.67 (.02)	.70 (.03)	.74 (.02)	.83 (.05)	.95 (.02)
rate-cu-n	.74 (.05)	.91 (.03)	.94 (.03)	.93 (.04)	1.05 (.03)
rate-dd-n	.63 (.02)	.71 (.03)	.69 (.03)	.84 (.04)	.82 (.03)

Mean rate of change in a glide required for discrimination. These values represent the required change in Hz/ms <u>above</u> the change in the standard that was necessary for discrimination. See text for explanation of abbreviations of signal conditions.

Appendix C. Thresholds for the glide discrimination tasks at the high frequency region expressed as Hz/ms

Group mean thresholds and standard errors in parenthesis expressed in relative rate of change required for discrimination above the rate of change in the standard signal (rate) for the **high** frequency region glides.

	Age Group (years)				
	20-34	35-44	45-54	55-64	65-75
Signal Condition					
rate-cd	1.77 (.08)	1.74 (.09)	2.22 (.16)	2.18 (.2)	3.62 (.15)
rate-cu	1.89 (.17)	1.89 (.17)	2.52 (.14)	2.78 (.11)	4.33 (.3)
rate-du	1.92 (.06)	1.98 (.05)	2.18 (.13)	1.96 (.13)	2.85 (.15)
rate-dd	1.70 (.07)	1.68 (.07)	2.01 (.04)	1.79 (.13)	2.49 (.07)
rate-cu-n	2.20 (.14)	2.24 (.12)	2.75 (.2)	3.24 (.16)	4.24 (.17)
rate-dd-n	1.83 (.06)	1.94 (.06)	1.53 (.09)	1.98 (.09)	2.62 (.07)

Group mean threshold and standard error values for the six signal conditions at the high frequency region. Values are expressed in Hz/ms and represent the required change in Hz/ms above the change in the standard that was necessary for discrimination. See text for explanation of abbreviations of signal conditions.