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Psychophysical estimates of nonlinear cochlear processing in younger and older listeners

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Abstract

The primary goal of this project was to compare the performance of younger and older listeners on a number of psychophysical measures thought to be influenced by nonlinear cochlear processing. Younger (mean of 25.6 years) and older (mean of 63.8 years) listeners with normal hearing were matched (within 5 dB) according to their quiet thresholds at the two test frequencies of 1200 and 2400 Hz. They were similarly matched at the adjacent octave frequencies of 600 and 4800 Hz (within 5 dB at one and 9 dB at the other). Performance was compared on measures of auditory filter shape, psychophysical suppression, and growth of forward masking. There was no difference between the two age groups on these psychophysical estimates reflecting nonlinear processing, suggesting that aging *per se* does not affect the cochlear nonlinearity, at least for the ages sampled here. The results did, however, consistently demonstrate an age-related increase in the susceptibility to forward masking.

I. INTRODUCTION

Older listeners often experience poorer speech intelligibility than younger listeners, particularly in the presence of noise (e.g., Plomp and Mimpen, 1979; Duquesnoy and Plomp, 1980). Age-related hearing loss is the most likely cause of the difficulties in speech recognition exhibited by older listeners. The articulation index (AI), more recently referred to as the speech intelligibility index (SII), predicts that speech intelligibility performance will systematically decrease as increasing segments of the speech spectrum become inaudible to the listener (ANSI, 1997). Recent studies, however, have shown that substantial threshold elevation need not be present for older listeners to exhibit significant performance deficits on measures of speech intelligibility (Dubno *et al.*, 2002, 2003).

Aside from the effects of reduced audibility on speech recognition is the relationship between suprathreshold processing, especially temporal resolution, and aging. Temporal resolution has been found to be impaired in older listeners both with and without clinically significant hearing loss (e.g., Humes and Christopherson, 1991; Gordon-Salant and Fitzgibbons, 1999; Schneider *et al.*, 1994; Snell, 1997). Although impaired temporal resolution likely contributes to age-related deficits in speech intelligibility, it cannot account entirely for the reduced intelligibility (e.g., Humes and Christopherson, 1991).

Another potential contributor to reduced speech understanding among older listeners is a reduced cochlear nonlinearity. Nonlinear cochlear processing is responsible for, among other things, high sensitivity, sharp tuning, and enhanced spectral contrasts via suppression. It is well known that healthy outer hair cells (OHCs) are responsible for this nonlinearity (e.g., Liberman

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and Dodds, 1984). Several studies have examined the effects of aging on OHC function using evoked otoacoustic emissions (OAEs). Examining distortion product otoacoustic emissions (DPOAEs) as an index of outer hair cell (OHC) functioning, McFadden *et al.* (1997a) reported significant differences between younger and older chinchillas in terms of DPOAE thresholds and amplitudes. Similar findings have also been observed in the CBA mouse (Parham *et al.*, 1999). These comparisons between the younger and older animals, however, may not have isolated changes in aging alone, because the older animals had auditory thresholds that were higher than the thresholds for the younger animals (McFadden *et al.*, 1997a; Parham *et al.*, 1999). Thus, it is possible that elevated thresholds may have influenced the results.

McFadden *et al.* (1997b) conducted another study examining suprathreshold measures of auditory functioning as a function of age in the chinchilla auditory system. All testing was completed at frequencies (1) that were within the limits of normal hearing in even the aged chinchillas and (2) where no significant age differences in quiet thresholds were observed. They obtained measures of frequency selectivity, including evoked potential tuning curves and DPOAEs following acoustic overstimulation. Results showed that the evoked potential tuning curves measured from the aged animals were more broadly tuned than those measured from the young, control animals. Inasmuch as we can attribute broadened tuning to a loss of OHC-driven nonlinearity (e.g., Liberman and Dodds, 1984), one may conclude that the older animals exhibited a decrease in cochlear nonlinearity independent of hearing loss. In addition, the post-acoustic-overstimulation DPOAE data showed that the older animals had a greater initial reduction in DPOAE amplitude following the noise, as well as a greater overall reduction in DPOAE amplitude with time. Thus it appears that the ability of the OHCs to recover following intense acoustic stimulation is reduced in older as compared to younger animals. These age-induced changes were observed in the absence of hearing loss in the frequency range tested.

Research examining DPOAEs (Dorn *et al.*, 1998) and transient-evoked otoacoustic emissions (TEOAEs) (e.g., Satoh *et al.*, 1998) in humans has revealed findings similar to the animal studies. Specifically, older subjects have been shown to exhibit higher OAE thresholds and lower amplitudes than younger subjects. A potentially critical problem with the interpretation of these OAE studies in humans is that no attempt has been made to match younger and older subjects on the basis of auditory thresholds. Simply requiring that thresholds not exceed 15 or 20 dB HL could yield comparisons between subjects with threshold differences of 20 dB or more in a range considered *clinically normal*.

Aside from the issue of potentially elevated thresholds in older subjects, another difficulty with the interpretation of all OAE data is that significant changes in middle ear stiffness have been found in aged mice (Doan *et al.*, 1996). Thus, one cannot discount middle ear changes as contributing to the age-related changes in OAEs. However, in support of compromised OHC functioning are reports of histopathologic changes in aged cochleae, particularly in the stria vascularis which plays a critical role in maintaining OHC function (e.g., McFadden *et al.*, 1997a).

There are a number of psychophysical measures that are thought to depend upon normally functioning OHCs, including frequency selectivity and the nonlinear phenomena of suppression and basilar membrane compression. If age affects OHC function, then one might expect to see differences between younger and older listeners on these measures. For example, if OHCs are compromised by aging, auditory filters (AFs) should be broader in older than in younger listeners. However, the research on the effects of age on AF shapes is equivocal. Patterson *et al.* (1982) found that older subjects exhibited wider AF bandwidths for all signal frequencies tested (even for those frequencies where age-related threshold differences were minimal), whereas others have not (Peters and Moore, 1992; Sommers and Humes, 1993; Peters and Hall, 1994; Sommers and Gehr, 1998). The generalizability of these results to the

nature of the cochlear nonlinearity in older listeners may be limited. For example, Peters and Moore (1992) completed all testing at signal frequencies below 1000 Hz, where nonlinear cochlear processing may be less frequency selective than at higher frequencies (Plack and Drga., 2003), and thus where the effects of age may be less clear. Further, a potential problem with all of these studies is that the filter shapes have been derived with the assumption that the masker level determines the shape of the filter. Rosen and Baker (1994) and Rosen *et al.* (1998) have shown that the AF shape is more likely determined by signal level. Thus, it may be more appropriate either to analyze results using a fixed masker level differently [using the PolyFit procedure (Rosen and Baker, 1994)] or to employ a fixed, low-level signal (Oxenham and Shera, 2003).

If advanced age adversely affects OHCs, then one would expect to observe less suppression in older than in younger listeners. Few have examined the relationship between psychophysical suppression and aging. However, what research has been done suggests that suppression is reduced in older listeners (Sommers and Gehr, 1998; Dubno and Ahlstrom, 2001b, c). However, Dubno and Ahlstrom (2001b, c) included older normal-hearing listeners whose audiometric thresholds were higher than those of the younger normal-hearing listeners. Thus, as of yet, there is not a clear picture of the relationship between aging and suppression, independent of hearing loss.

The growth of response of the basilar membrane is highly compressive for a tone equal to or near the characteristic frequency (CF) of the measurement site (e.g., Ruggero *et al.*, 1997), although it is linear for a tone much lower in frequency than CF (though this may not be the case at low CFs—see Plack *et al.*, 2004; Lopez-Poveda *et al.*, 2005; Williams and Bacon, 2005). One way to estimate basilar membrane compression psychophysically is with a masking experiment, in which the masker frequency (f_m) is well below the signal frequency (f_s) (for a recent review, see Oxenham and Bacon, 2004). In young listeners with normal hearing, the masking function has a slope quite different from 1.0 (i.e., from linearity), being much greater than 1.0 when signal level is plotted as a function of masker level (e.g., Bacon *et al.*, 1998) and much less than 1.0 when masker level is plotted as a function of signal level (e.g., Oxenham and Plack, 1997). The slope of the masking function is linear, or at least closer to linear, when the OHCs are compromised by either permanent (Oxenham and Plack, 1997) or temporary aspirin-induced hearing loss (Hicks and Bacon, 2000). If age adversely affects OHCs, then the masking functions in older listeners would be expected to be more linear than they are in younger listeners. There are, however, no published data examining the effects of age on masking functions designed to estimate basilar membrane compression.

Psychophysical studies examining nonlinear cochlear processing in normal-hearing listeners following a course of aspirin ingestion have demonstrated broader AFs, reduced or eliminated two-tone suppression, and less compression on psychophysical masking experiments where $f_m < f_s$ (Hicks and Bacon, 1999, 2000). These effects were observed even for frequencies where minimal shifts in quiet threshold were observed (as low as 5 dB). Thus, it appears that even mild disturbances of OHC function (Hicks and Bacon, 1999, 2000)—that may or may not yield a significant elevation of quiet threshold—can translate to significant functional effects on psychophysical measures of auditory function. It follows that subtle changes in active cochlear mechanics that may be attributable to age might also yield considerable functional deficits on measures of nonlinear cochlear processing.

In summary, although there is histopathological and physiological evidence that aging adversely affects OHC functioning, possibly independent of hearing loss, there have been few studies designed to examine the relationship between aging and psychophysical estimates of nonlinear processing. Further, the collective results of these studies are equivocal. There is a need for such studies given the importance of normally functioning OHCs on the perception

of sound, and the fact that many older listeners often experience more difficulty understanding speech than would be expected from their pure-tone hearing loss. Thus, the goal of this project was to compare the performance of younger and older listeners on three psychophysical measures thought to depend upon normally functioning OHCs, to determine whether an age-related decline in nonlinear cochlear processing exists.

II. METHODS

A. Subjects

All three experiments were designed to examine measures at two signal frequencies, 1200 and 2400 Hz. These frequencies were chosen so that it was possible to obtain older subjects with normal hearing in the range of frequencies from one octave below to one octave above f_s . The reason that hearing was required to be normal above the test frequency is that the cochlear location of the nonlinearity 1 ranges from $\frac{1}{3}$ to $\frac{1}{2}$ of an octave above that of the cochlear place corresponding to the CF of the test stimulus (e.g., Davis, 1983). Thus, it is important to control for hearing thresholds located above the signal frequencies. The reason for controlling hearing thresholds below the test frequency was to control audibility of maskers that were lower in frequency than the signal.

Nine younger and nine older subjects with normal hearing were recruited from Arizona State University and the surrounding communities. With the exception of the ninth younger/older subject pair, the same subjects in each group completed all three experiments. The subjects included in the *younger* age category were 30 years of age or younger and the *older* subjects were 60 years of age or older. All older listeners were considered as “high functioning” with respect to mental alertness and intellect. For example, one of the older listeners was a graduate student in the Audiology program, one was a practicing oral surgeon, one was a retired college professor fluent in multiple languages, three were retired school teachers, and one was a recently retired engineer. The other two were both retired from a business-like working environment. The mean age of the younger subject group was 25.6 years with a range of 19 to 30 years. The mean age of the older subject group was 63.8 years with a range of 60 to 75 years. The criterion for inclusion was hearing thresholds ≤ 15 dB HL at audiometric test frequencies from 250 to 6000 Hz. The younger and older subjects were matched according to their quiet thresholds for 200-ms signals. The original criterion required less than a 5-dB difference in quiet thresholds at 600, 1200, 2400, and 4800 Hz. Given the difficulty in obtaining older subjects with normal hearing and then matching a younger subject to those thresholds, however, the criterion was relaxed such that quiet thresholds needed to match within 5 dB for the two test frequencies (1200 and 2400 Hz) and one of the other two frequencies, but that differences of up to 9 dB were acceptable at the fourth frequency. The subjects were classified such that younger subject 1 (Y1) was matched to older subject 1 (O1), and so on. Figure 1 displays the individual and mean quiet thresholds for the 200-ms signals for all subjects enrolled in the study. The thresholds for the 1200- and 2400-Hz signals are also given in Table I, along with thresholds for 10- and 20-ms signals at those frequencies.

With the exception of subject Y8 (the first author), all subjects were paid an hourly wage for their participation. Subjects Y3, Y6, and Y8 were experienced listeners in psychoacoustic experiments similar to those in the present study. Regardless of past listening experience, all subjects were provided with training prior to data collection (specifics are given below).

B. General procedures

Thresholds for all experiments were measured in an adaptive, two-interval, forced-choice paradigm with a decision rule to track 79.4% correct (Levitt, 1971). That is, after three consecutive correct responses, the task was made more difficult and after one incorrect

response, the task was made easier. Each reported threshold is based on at least three runs typically obtained over at least two different test sessions. For any given experiment, test sessions lasted approximately 2 h. Subjects were typically scheduled for one to two sessions per week. On average, subjects were able to complete data collection in approximately four to five sessions (including training). Since all three experiments involved forward masking, which some subjects may find somewhat difficult, all subjects were trained for at least 1.5 h on conditions from experiment 1, with an average training time of approximately 2.5 h. Data collection commenced once threshold estimates appeared stable.

Tonal stimuli were generated and produced digitally at a 20-kHz sampling rate. The noise masker in experiments 1 and 2 was produced by an analog random noise generator (General Radio 1381). All gated stimuli were shaped with $\cos^2$ rise/fall times. In all three experiments, the sinusoidal signal was output through one channel of a 16-bit digital-to-analog converter (DAC), whereas the masker was output through the second channel of the DAC (TDT DA1). The output of each channel was low-pass filtered at 8 kHz (Kemo, VBF.25.01, 135 dB/oct), attenuated by separate programmable attenuators (Wilsonics PATT), ultimately added together, and routed monaurally to one channel of Sony MDR-7506 stereo headphones via a headphone buffer (TDT HB6). To avoid electrical crosstalk, the headphone of the nontest ear was disconnected by means of a custom-made switchbox.

Subjects were tested in a double-walled, sound-attenuating booth. The interstimulus interval was 500 ms. The observation intervals were indicated by lights on a response box. For experiments 1 (AF shapes) and 3 (masking functions), forward-masked thresholds were measured by fixing the signal level and varying the masker level. For experiment 2 (suppression), thresholds were measured by fixing the level of the masker and varying the level of the signal. The maximum level for the dynamically varying stimulus was 95 dB SPL for tonal stimuli and 45 dB SPL (spectrum level) for the notched-noise stimuli. During a run, it was permissible for the threshold track to reach the ceiling value; however, if the tracking procedure called for a higher level, that run was discarded. If two runs for a particular condition were discarded on this basis, it was concluded that a masked threshold for that individual condition could not be achieved.

The tonal signal was presented randomly in one of two intervals. Subjects responded by pressing a button on the response box corresponding to what they believed to be the signal interval. Visual correct-answer feedback was provided. A run consisted of 50 trials. The first two (or three) reversals were discarded and the threshold estimate was determined using the average signal or masker level at the remaining even number of reversal points. All threshold estimates are based on the average of at least six reversals. If a run produced an estimate based on the average of less than six reversals, that particular run was discarded. The initial step size of 5 dB was decreased to 2 dB after the second reversal. On the rare occasion that an estimate had a standard deviation greater than 5 dB, that run was discarded. All reported thresholds represent the mean of at least three estimates. If the standard deviation of the mean of those estimates was greater than 3 dB, one additional run was completed and averaged. Out of the 738 thresholds obtained, 697 (94.4%) had standard deviations less than 3 dB and 540 (73.2%) had standard deviations less than 2 dB.

III. EXPERIMENT 1: AUDITORY FILTER (AF) SHAPE

A. Stimuli and conditions

AF shapes were derived using the notched-noise method (Patterson *et al.*, 1982) in a forward-masking paradigm to avoid any masking by suppression. This would be of critical importance given that psychophysical suppression—which would effectively broaden AF bandwidth—may be influenced by age independent of hearing loss. The notched-noise maskers were

produced by low-pass filtering (Kemo VBF 25.01, 135 dB/oct) random noise from two independent analog noise generators (General Radio 1381) and multiplying each low-pass noise by a sinusoid (HP 8904 A synthesizer). This method produced a noise masker that was comprised of two noise bands each having a bandwidth that was twice the cutoff frequency of the low-pass filter and a center frequency that was equivalent to the sinusoidal frequency.

Each band of noise ($0.4f_s$ wide) was placed symmetrically or asymmetrically around f_s . Given that it is possible to obtain accurate (and time-efficient) estimates of the AF shape with just five notch widths (e.g., Stone *et al.*, 1992), the following five notch widths, expressed as a proportion of f_s , were used: symmetric—0.0 (no notch), 0.1, and $0.2 f_s$; asymmetric—closer edge $0.1 f_s$, farther edge $0.2 f_s$ (in one case the lower frequency band was closer, and in the other the higher frequency band was closer).¹ The signal was fixed at a level of 10 dB sensation level (SL), and the masker level was varied adaptively. The masker and signal were 300 and 20 ms in duration, respectively. All durations include a 10-ms $\cos^2$ rise/fall time. The onset of the signal was delayed 5 ms following the offset of the masker to minimize confusion effects (Neff, 1985).

B. Results and discussion

Figures 2 and 3 display the masker spectrum levels required to mask the 10-dB-SL signal for the younger (filled circles) and older (unfilled circles) subjects at 1200 and 2400 Hz, respectively. The data for the asymmetrical conditions are offset slightly relative to the symmetrical conditions, and not connected by a line. For both f_s , the masker level at threshold generally increased with increasing notch width. The masker levels at threshold, however, were generally lower for the older subjects, indicating a greater susceptibility to forward masking. A two-way repeated-measures analysis of variance (ANOVA) of masker levels at threshold for the 1200-Hz signal condition revealed no effect of age [$F(1,16)=2.4$, $p=0.14$], a significant effect of notch width [$F(1,4)=225.1$, $p<0.001$], and no interaction between age and notch width [$F(1,16)=3.3$, $p=0.06$]. The same analysis was computed for 2400 Hz revealing a significant effect of age [$F(1,16)=11.7$, $p=0.004$], a significant effect of notch width [$F(1,4)=222.6$, $p<0.001$], and no interaction between age and notch width [$F(1,16)=1.4$, $p=0.24$]. Comparing average thresholds (collapsed across notch width) across the age groups, the masker levels at threshold were 5.3 dB lower for the older listeners at 1200 Hz and 9.4 dB lower for the older listeners at 2400 Hz. Thus, although the age effect did not reach significance at 1200 Hz, there is still a trend for masker levels at threshold to be lower for the older listeners—indicating a greater susceptibility to forward masking for the older listeners.

Although the subjects were carefully matched for quiet thresholds using 200-ms signals, subject pairs were not matched as well for the 20-ms signals (see Table I). The group mean thresholds for the 20-ms thresholds, however, were closely matched. Moreover, a two-way repeated-measures ANOVA revealed no significant effect of age [$F(1,16)=2.0$, $p=0.17$] or frequency [$F(1,16)=2.5$, $p=0.13$] on the 20-ms thresholds. Thus, the differences in masker levels between the groups in Figs. 2 and 3 cannot be accounted for by differences in quiet thresholds for the 20-ms signal.

The masker levels at threshold were used to derive filter shapes using the roex (p,k) model (Patterson *et al.*, 1982). The parameter p represents the slope of the filter skirts, and k represents the processing efficiency—or the signal-to-masker ratio at threshold. This model set the upper and lower skirts of the filter symmetrically about f_s . The results of the fitting procedure are displayed in Table II.

¹The notch widths used in this experiment were not as wide as those used by Stone *et al.* (1992) because the signal could not be masked by some subjects at the maximum masker level at the wider notch widths.

The equivalent rectangular bandwidth [(ERB_n), Glasberg and Moore, 1990] values are similar for the younger and older subject pairs. These values, however, are generally lower than most reported in the literature. There are several possible reasons for this finding. First, many of the ERB_n values in the literature were obtained in simultaneous masking and at masker spectrum levels in the range of 40 to 60 dB SPL. Given that AF bandwidths are broader in simultaneous masking (Sommers and Gehr, 1998) and at high levels (e.g., Hicks and Bacon, 1999), it is reasonable to assume that the narrower bandwidths in the current study are a result of the forward-masking paradigm and the relatively low signal and masker levels employed. Consistent with this are the recent results of Oxenham and SHERA (2003), who used a 10-dB-SL signal in a forward-masking paradigm and observed AF bandwidths similar to those reported here.

A two-way repeated-measures ANOVA revealed no effect of age [$F(1,16)=3.1$, $p=0.1$] and a significant effect of frequency on the ERB_n values [$F(1,16)=119.6$, $p<0.001$]. There was no interaction between age and frequency [$F(1,16)=0.4$, $p=0.6$]. Thus, there was no difference between the younger and older subjects in terms of frequency selectivity as measured here.

IV. EXPERIMENT 2: SUPPRESSION

A. Stimuli and conditions

It is possible to measure suppression with a band-widening procedure. As the bandwidth of the noise masker is increased beyond a critical band, the noise components outside the critical band may suppress those within the critical band, resulting in a decrease in forward masking (e.g., Houtgast, 1974). Using several different band-widening methods, Dubno and Ahlstrom (2001a, b) have shown that fixing the upper cutoff frequency of the masker and subsequently increasing the bandwidth below that cutoff produces the greatest amount of suppression. Thus, experiment 2 used a similar band-widening procedure. Forward-masked thresholds were obtained as a function of masker bandwidth. The noise masker was produced by low-pass filtering (Kemo VBF 25.01, 135 dB/oct) random noise (General Radio 1381) and multiplying that noise by a sinusoid (HP 8904 A synthesizer).

The masker had an initial bandwidth of one ERB_n, and was centered at the signal frequency.² Six masker band-widths, increasing in 2-ERB_n steps relative to the lower frequency edge of the 1-ERB_n masker, were tested for each f_s . Table III displays the six bandwidths used for each f_s , as well as the frequency ranges of each masker bandwidth. The masker and signal were 300 and 20 ms in duration, respectively (including 10-ms $\cos^2$ rise/fall times). The signal onset was delayed 5 ms following the offset of the masker in an attempt to minimize confusion effects (Neff, 1985). The masker level was fixed at a spectrum level of 45 dB SPL, and the signal level was varied adaptively. This relatively high masker level was chosen because suppression tends to increase with level and it was shown previously to reveal differences in suppression between younger and older listeners (Dubno and Ahlstrom, 2001a,b).

B. Results and discussion

Figure 4 displays the results for the younger (filled symbols) and older (unfilled symbols) listeners. Circles represent thresholds for the 1200-Hz signal and triangles represent the thresholds for the 2400-Hz signal. For the majority of the conditions, the thresholds for the older subjects were higher than those of the younger subjects. This trend for greater forward masking was also observed in experiment 1.

²The individual ERB_n values obtained for each subject in experiment 1 were not used for this experiment because this experiment was conducted at a much higher level (masker spectrum level of 45 dB SPL) than that of experiment 1 (signal level of 10 dB SL). Past research has shown that the width of the auditory filter increases with level (Hicks and Bacon, 1999). Thus, the initial 1-ERB_n condition (in experiment 2) was based on estimates with moderate-level maskers provided by Glasberg and Moore (1990).

A reduction in threshold with increasing masker bandwidth beyond the 1-ERB_n condition provides evidence of suppression. The maximum amount of suppression for each subject was calculated by subtracting the lowest threshold (usually at the widest BW) from the threshold for the 1-ERB_n condition (see Table IV). On average, the amount of suppression exhibited by the younger and older listeners was essentially equivalent. The average amount of maximum suppression for the younger subjects was 21.7 dB at 1200 Hz and 23.1 dB at 2400 Hz. The average amount of maximum suppression for the older subjects was 21.3 dB at 1200 Hz and 20.9 dB at 2400 Hz. A two-way repeated-measures ANOVA revealed that there was no significant effect of age [$F(1,14)=0.4, p=0.5$] on the amount of maximum suppression, nor was there a significant effect of frequency [$F(1,14)=0.07, p=0.8$] or an interaction between age and frequency [$F(1,14)=0.4, p=0.5$]. However, statistical analysis performed on the thresholds revealed an effect of age [$F(1,14)=19.8, p<0.001$], with no effect of frequency [$F(1,14)=0.5, p=0.5$] and no interaction between age and frequency [$F(1,14)=0.03, p=0.9$]. The effect of age resulted from the thresholds being 9.1 dB higher, on average, for the older subjects.

Dubno *et al.* (2003) observed 3 to 7 dB higher forward-masked thresholds in their older listeners compared to their younger listeners, although the two groups revealed similar amounts of masking. In the present study, the older subjects exhibited higher forward-masked thresholds (9.1 dB on average) and greater amounts of forward masking (7 dB on average) than their younger counterparts.

V. EXPERIMENT 3: MASKING FUNCTIONS ($f_m < f_s$)

A. Stimuli and conditions

Masking functions were measured for tonal maskers and signals. The signal level was fixed from 40 to 90 dB SPL (or the highest level possible such that the level of the masker did not exceed 95 dB SPL), in 5-dB steps. The masker level was varied adaptively. The corresponding f_m was 3 ERBs below each f_s . Thus, the f_m was 806 Hz for the 1200-Hz signal and 1675 Hz for the 2400-Hz signal. The masker duration was 300 ms and the signal duration was 10 ms (including 10- and 5-ms $\cos^2$ rise/fall times for the masker and signal, respectively). A delay of 5 ms between the masker offset and the signal onset was incorporated to minimize any temporal overlap between the masker and signal due to ringing in the auditory filter (see Oxenham and Plack, 1997) and confusion effects (Neff, 1985). To reduce the possibility of off-frequency listening, a high-pass noise, with a cutoff frequency of $1.12f_s$, was presented continuously at a spectrum level that was 55 dB below the level of the signal (Oxenham and Plack, 1997).

B. Results and discussion

Results are shown in Fig. 5. The filled and unfilled symbols represent the younger and older subjects, respectively. Circles represent the results for the 1200-Hz signal and triangles represent the results for the 2400-Hz signal. Given that the masking functions extended over different signal levels for the different subjects, group mean results were not calculated. To obtain an estimate of compression, the slopes of the masking functions were derived via linear regression analysis for the data points corresponding to signal levels in the range of 50 to 75 dB SPL. All estimates of compression for the masking functions are shown in Table V. These estimates were generally similar across the groups. The average compression estimates at 1200 Hz were 0.46 for both the younger and older listeners, whereas the average compression estimates at 2400 Hz were 0.36 for the younger and 0.40 for the older subjects. These estimates are somewhat less compressive than previously reported physiological (e.g., Ruggero *et al.*, 1997) and psychophysical (e.g., Oxenham and Plack, 1997) estimates of BM compression. One possible reason for this is that the frequency of the masker may not have been placed far enough below the frequency of the signal to evoke a completely linear response at the cochlear

place corresponding to f_s . Physiological (e.g., Ruggero *et al.*, 1997) and psychophysical (e.g., Hicks and Bacon, 2000; Nelson *et al.*, 2001) research has demonstrated that a f_s/f_m ratio of approximately 1.8 may be required to observe maximum compression. In the current study, the masker was 3 ERBs below f_s , resulting in an f_s/f_m ratio of about 1.4 to 1.5. Nevertheless, the estimates of compression reported here provide a reasonable comparison across the age groups. The estimate of compression was not significantly affected by age [$F(1,16)=0.2$, $p=0.6$] or frequency [$F(1,16)=1.4$, $p=0.3$]. There was, however, a significant effect of age on the masker level at threshold, as revealed by a two-way repeated-measures ANOVA [$F(1,16)=9.9$, $p=0.007$]. There was no effect of frequency [$F(1,16)=0.3$, $p=0.6$] and no interaction between age and frequency [$F(1,16)=0.4$, $p=0.6$]. On average, the masker levels at threshold were 5.8 dB lower for the older listeners (see Fig. 5), suggesting a greater susceptibility to forward masking in the older listeners (also see experiments 1 and 2).

VI. GENERAL DISCUSSION

The results of the present study clearly demonstrate that three measures thought to be influenced by OHCs (frequency selectivity, suppression, and compression) were not different in younger and older listeners.³ The lack of an age effect on AF bandwidth is consistent with some past research with similar signal frequencies (e.g., Peters and Moore, 1992; Sommers and Gehr, 1998), though inconsistent with the results of Patterson *et al.* (1982), who demonstrated an effect of age on AF bandwidth across a wide range of signal frequencies.

The lack of an age effect on psychophysical estimates of suppression is in contrast with relatively recent studies in this area. Sommers and Gehr (1998) reported significantly reduced suppression in older listeners. Suppression was quantified as the difference in AF bandwidth (in ERBs) obtained in simultaneous versus forward masking. Although the ERB_n values between the younger and older subjects were not significantly different within a given masking paradigm, the *difference* between the ERB_n values obtained in simultaneous versus forward masking (which can be used as an indirect estimate of suppression) was significantly affected by age. Dubno and Ahlstrom (2001a, b, c) also examined the effects of age on psychophysical suppression. They reported that the older subjects with normal hearing exhibited significantly less suppression than their younger counterparts. The discrepancy in findings between the current study and those of Dubno and Ahlstrom (2001b, c) may relate to how well younger and older subjects were matched in the studies. Dubno and Ahlstrom (2001b, c) included older subjects with clinically normal hearing, but their thresholds were on average 7.5 dB higher than those of the younger subjects (collapsed across frequency).

There are no other data in the literature examining the effects of age on estimates of BM compression. The lack of an age effect observed here, however, is consistent with the other results of the present study.

A consistent finding in the present study was that the older subjects demonstrated greater susceptibility to forward masking than their younger counterparts. There are other reports of age-related increases in forward-masked thresholds (Sommers and Gehr, 1998; Dubno and Ahlstrom, 2001a, b; Dubno *et al.*, 2002, 2003). Indeed, Dubno *et al.* (2002, 2003) reported significantly higher forward-masked thresholds for older subjects with normal hearing;

³Pearson product moment correlations were computed comparing all three metrics of nonlinear cochlear processing as observed in the younger and older listeners—auditory filter bandwidth, suppression, and compression. Given that no age or frequency effects had been found, the correlation analyses were collapsed across subject age and signal frequency. Moreover, ERB_n values were normalized (by dividing by f_s) so that both age and frequency could be factored out of the analysis. No significant correlations were found between any two psychophysical measures of nonlinear cochlear processing. Correlation coefficients and associated p values were $r=0.01$, $p=0.32$ for maximum suppression (in dB) versus normalized ERB_n , $r=-0.30$, $p=0.07$ for compression versus normalized ERB_n , and $r=-0.18$, $p=0.32$ for compression versus maximum suppression (in dB). Thus, no significant correlations were observed for any of the comparisons between the psychophysical estimates of nonlinear cochlear processing.

however, due to the higher quiet thresholds for these listeners, the amount of masking was found to be essentially identical across the age groups. Sommers and Gehr (1998) did not report their subjects' quiet thresholds for the 20-ms signals used for testing so it is unclear whether their older subjects exhibited greater masking. In the present study, the older subjects, on average, exhibited greater amounts of masking as well as greater forward-masked thresholds. Our results are consistent with evidence from vision research showing that older subjects are more susceptible to forward masking by visual noise (e.g., Coyne, 1981).

The finding of an age-related increase in susceptibility to forward masking is somewhat enigmatic given the lack of an age effect in the estimates of cochlear nonlinearity. It is thought that forward masking is influenced by nonlinear cochlear processing (e.g., Oxenham and Plack, 1997), as revealed within the context of the temporal window model. The temporal window model is one of several popular models describing the temporal resolving capabilities of the auditory system (e.g., Moore *et al.*, 1988; Oxenham, 2001). The model incorporates bandpass filtering, level-dependent, instantaneous compression, a temporal window centered over the signal presentation, and a decision device. The essentially identical compression estimates for the younger and older listeners (Table V) suggest that the elevated forward-masked thresholds in the older subjects are not due to differences in peripheral processing. Thus it would appear that the origin of the aging differences in forward masking may be more centrally located. One possibility is that the temporal window may be wider in the older listeners.

Another possible explanation for the increased forward masking, and one that could co-exist with a broader temporal window, is that the older listeners have poorer auditory processing efficiency. Processing efficiency, which represents one's ability to detect a signal in noise, is calculated as the signal-to-noise ratio at threshold. Auditory processing efficiency is thought to be influenced not only by auditory processing but by general cognitive factors such as attention, memory, and learning (Patterson *et al.*, 1982; Hartley and Moore, 2002). The current study provides some information about the effects of aging on auditory processing efficiency. Comparing the fitting parameters of the derived AFs in the current study, the values of k (which provide an estimate of detection efficiency) were generally higher for the older listeners.⁴ The signal-to-masker ratio required at threshold was on average 9 dB higher for the older listeners than for the younger listeners. A two-way repeated-measures ANOVA computed on the values of k as a function of age and frequency revealed a significant effect of age on k [$F(1,16)=16.3$, $p<0.001$], a significant effect of frequency [$F(1,16)=50.1$, $p<0.001$], and an interaction between age and frequency [$F(1,16)=12.4$, $p=0.003$]. That is, there was a much larger difference in k values between the age groups for 2400 Hz (11.0-dB difference) than for 1200 Hz (7.0-dB difference). This effect of age is not surprising given that, on average, the younger and older listeners had essentially equivalent AF bandwidths, yet the masker levels at threshold were consistently lower for the older listeners. Thus, it is likely that some degree of an age-related deficit in processing efficiency exists.

VII. SUMMARY AND CONCLUSIONS

The goal of this study was to compare the performance of younger and older listeners on three psychophysical measures thought to depend upon normally functioning OHCs, to determine whether an age-related decline in nonlinear cochlear processing exists independent of hearing loss. The first step was to closely match older and younger listeners for quiet thresholds across a broad frequency range. The second step was to examine whether an effect of age could be observed on three psychophysical measures thought to be influenced by nonlinear cochlear

⁴In the context of forward masking, a change in the value of k could reflect a change in processing or a change in temporal window shape. Here, the filters were fitted assuming a rectangular temporal window shape for all listeners. If the window shape differed for the two groups, the differences in k would not necessarily reflect differences in processing efficiency.

processing: (1) AF bandwidth, (2) suppression, and (3) estimates of basilar membrane compression. There were no significant differences between the age groups on any of the metrics. There was, however, a highly consistent and significant effect of age on the susceptibility to forward masking in all three experiments. Given that this was not due to an age-induced reduction in peripheral nonlinear processing, it more likely reflects an age-related change in central processing (Dubno and Schaefer, 1991; Gifford and Bacon, 2004; Henry and Grantham, 2000; Leek and Sommers, 1993; Moore *et al.*, 1997, 1999).

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FIG. 1.
Individual and mean quiet thresholds for a 200-ms signal for the younger (filled symbols) and older (unfilled symbols) listeners.

FIG. 2.

Masker spectrum levels required to mask the 10-dB-SL, 1200-Hz signal for the younger (filled symbols) and older (unfilled symbols) subjects. Thresholds for the asymmetric notch width conditions are offset for clarity.

FIG. 3.
As Fig. 2, but for the 2400-Hz signal.

FIG. 4.

Masked thresholds for the younger (filled symbols) and older (unfilled symbols) listeners for both the 1200-(circles) and 2400-Hz (triangles) signals. The thresholds are plotted as a function of masker bandwidth.

FIG. 5.

Masker levels at threshold for signals ranging from 40 to 55–90 dB SPL for the younger (filled symbols) and older (unfilled symbols) listeners at 1200 (circles) and 2400 Hz (triangles). The reference line in the lower right-hand corner of each panel provides a linear slope reference.

TABLE I

Quiet thresholds (in dB SPL) at 1200 and 2400 Hz for signal durations of 10, 20, and 200 ms. Subject matching was achieved on the basis of the thresholds for the 200-ms signals.

Subject	1200 Hz			2400 Hz		
	10 ms	20 ms	200 ms	10 ms	20 ms	200 ms
Y1	19.6	20.1	15.1	20.1	17.9	3.4
Y2	26.1	26.2	10.2	12.8	12.6	1.5
Y3	15.2	14.9	4.3	28.2	27.8	15.3
Y4	26.0	20.5	8.2	30.4	16.5	7.0
Y5	23.2	16.5	2.4	19.3	13.4	2.9
Y6	24.2	21.5	14.1	19.5	16.0	13.5
Y7	34.3	24.6	14.2	31.3	23.2	10.8
Y8	18.5	17.2	8.1	23.5	21.2	13.5
Y9	23.1	21.4	4.4	25.3	14.2	-0.1
Mean	23.4	20.3	9.0	23.4	18.1	7.5
O1	30.9	27.6	20.0	21.9	19.4	8.4
O2	26.9	23.4	8.5	21.5	15.6	3.5
O3	25.3	23.8	7.0	28.8	24.7	15.5
O4	22.2	15.5	3.8	20.7	17.2	4.4
O5	23.3	20.1	4.3	18.4	13.9	2.3
O6	34.3	30.7	17.0	24.9	23.5	16.7
O7	22.7	20.6	9.4	27.9	26.7	15.1
O8	25.0	22.3	11.2	27.3	21.8	11.7
O9	20.1	19.0	5.4	22.9	17.7	4.2
Mean	25.6	22.6	9.6	23.8	20.1	9.1

TABLE II
ERB_n (Hz), p , k (dB), and rms (dB) values for the individual younger and older subjects (and the mean values) for the 1200- and 2400-Hz tonal signals. The roex (p,k) filter model of Patterson *et al.* (1982) was used to derive the filter shapes. The mean estimates represent filters fitted to the mean thresholds and not the mean of the individual parameters.

Younger subjects					Older subjects				
	ERB _n	p	k	rms		ERB _n	p	k	rms
					1200 Hz				
Y1	91	53	10	5	O1	99	48	14	6
Y2	91	53	4	4	O2	93	52	19	7
Y3	94	51	12	3	O3	97	50	16	4
Y4	116	42	10	2	O4	113	43	18	2
Y5	91	53	10	4	O5	103	47	17	4
Y6	94	51	16	5	O6	131	37	12	2
Y7	90	54	17	5	O7	118	40	16	2
Y8	90	53	9	5	O8	98	49	7	3
Y9	84	57	5	6	O9	141	34	8	4
Mean	91	53	9	3	Mean	108	44	16	3
					2400 Hz				
Y1	193	50	-1	3	O1	202	48	15	4
Y2	216	45	-8	2	O2	194	49	14	5
Y3	246	39	2	2	O3	219	44	11	4
Y4	184	52	2	3	O4	246	39	12	4
Y5	181	53	-2	5	O5	188	51	6	2
Y6	204	47	6	3	O6	182	53	14	4
Y7	241	40	-6	1	O7	252	38	13	3
Y8	236	41	5	3	O8	189	51	3	3
Y9	173	55	-6	5	O9	247	39	5	1
Mean	198	49	-1	2	Mean	226	42	10	3

TABLE III

Masker bandwidths and lower and upper cutoff frequencies of the masker for each signal frequency used for the measurement of suppression (in experiment 2).

Signal frequency (Hz)	
1200 Hz masker BW, spectral range	2400 Hz masker BW, spectral range
134 Hz, 1133–1267 Hz	246 Hz, 2277–2523 Hz
398 Hz, 869–1267 Hz	731 Hz, 1792–2523 Hz
610 Hz, 657–1267 Hz	1122 Hz, 1401–2523 Hz
782 Hz, 485–1267 Hz	1438 Hz, 1085–2523 Hz
920 Hz, 347–1267 Hz	1692 Hz, 831–2523 Hz
1031 Hz, 236–1267 Hz	1897 Hz, 626–2523 Hz

TABLE IV

Individual estimates of maximum suppression. Suppression has been calculated as the difference between the masked threshold for the 1-ERN_n masker and the lowest masked threshold obtained—which typically occurred for the broadest masker bandwidth condition.

Younger subjects	Suppression estimate (dB)		Older subjects	Suppression estimate (dB)
		1200 Hz		
YN1	21.9		ON1	22.5
YN2	22.0		ON2	13.7
YN3	20.8		ON3	18.5
YN4	18.9		ON4	22.9
YN5	22.4		ON5	26.2
YN6	12.0		ON6	21.3
YN7	26.0		ON7	20.0
YN8	29.7		ON8	25.0
Mean	21.7		Mean	21.3
		2400 Hz		
YN1	20.0		ON1	19.1
YN2	29.1		ON2	28.3
YN3	24.9		ON3	23.0
YN4	22.9		ON4	9.7
YN5	20.5		ON5	27.1
YN6	12.7		ON6	21.7
YN7	28.1		ON7	12.5
YN8	26.5		ON8	26.0
Mean	23.1		Mean	20.9

TABLE V

Psychophysical estimates of basilar membrane compression. The compression estimates represent the slope of the function for signal levels ranging from 50 to 75 dB SPL (see text for details).

Younger subjects	Compression estimate		Older subjects	Compression estimate
1200 Hz				
YN1	0.47		ON1	0.56
YN2	0.44		ON2	0.47
YN3	0.50		ON3	0.35
YN4	0.65		ON4	0.11
YN5	0.34		ON5	0.53
YN6	0.50		ON6	0.65
YN7	0.50		ON7	0.49
YN8	0.18		ON8	0.59
YN9	0.55		ON9	0.35
Mean	0.46		Mean	0.46
2400 Hz				
YN1	0.25		ON1	0.20
YN2	0.12		ON2	0.19
YN3	0.80		ON3	0.46
YN4	0.26		ON4	0.22
YN5	0.30		ON5	0.36
YN6	0.64		ON6	0.60
YN7	0.19		ON7	0.45
YN8	0.40		ON8	0.68
YN9	0.30		ON9	0.43
Mean	0.36		Mean	0.40