J Am Acad Audiol 17:582–597 (2006)

Amplitude-Modulated Auditory Steady-State Responses in Younger and Older Listeners

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Abstract

The primary purpose of this investigation was to determine whether temporal coding in the auditory system was the same for younger and older listeners. Temporal coding was assessed by amplitude-modulated auditory steady-state responses (AM ASSRs) as a physiologic measure of phase-locking capability. The secondary purpose of this study was to determine whether AM ASSRs were related to behavioral speech understanding ability. AM ASSRs showed that the ability of the auditory system to phase lock to a temporally altered signal is dependent on modulation rate, carrier frequency, and age of the listener. Specifically, the interaction of frequency and age showed that younger listeners had more phase locking than old listeners at 500 Hz. The number of phase-locked responses for the 500 Hz carrier frequency was significantly correlated to word-recognition performance. In conclusion, the effect of aging on temporal processing, as measured by phase locking with AM ASSRs, was found for low-frequency stimuli where phase locking in the auditory system should be optimal. The exploration, and use, of electrophysiologic responses to measure auditory timing analysis in humans has the potential to facilitate the understanding of speech perception difficulties in older listeners.

Key Words: Aging, ASSR, auditory evoked potentials, auditory temporal processing, phase locking, speech perception

Abbreviations: AEP = auditory evoked potential; AM = amplitude modulation; ASSR = auditory steady-state response; ERP = event related potential; FFT = Fourier frequency transformation; FM = frequency modulation; HP = high predictability sentences; LP = low predictability sentences; MMSE = Mini-Mental State Exam; SPIN = speech perception in noise; TMTF = temporal modulation transfer function

Sumario

El propósito primario de esta investigación fue determinar si la codificación temporal del sistema auditivo era la misma para oyentes jóvenes y viejos. La codificación temporal fue evaluada con respuestas auditivas de estado estable por modulación de la amplitud (AM ASSR), como una medida fisiológica con capacidad de bloqueo de fase. El propósito secundario de este estudio fue determinar si los AM ASSR se relacionaban con la capacidad de entender el lenguaje conductual. Los AM ASSR mostraron que la capacidad del sistema auditivo de hacer bloqueo de fase ante una señal temporalmente alterada es

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Paper presented at the annual meeting of the American Speech-Language-Hearing Association, Chicago, IL, November 2003.

dependiente de la tasa de modulación, de la frecuencia portadora y de la edad del sujeto. Específicamente, la interacción de frecuencia y edad demostró que los oyentes jóvenes tenían mejor bloqueo de fase que los más viejos a 500 Hz. El número de respuestas con bloqueo de fase para la frecuencia portadora de 500 Hz correlacionó significativamente con el desempeño en reconocimiento de palabras. En conclusión, el efecto del envejecimiento sobre el procesamiento temporal, medido por bloqueo de fase con AM ASSR, se encontró para estímulos de baja frecuencia, donde el bloqueo de fase del sistema auditivo debería ser óptimo. La exploración y el uso de respuestas electrofisiológicas para medir el análisis auditivo del tiempo en humanos tienen el potencial de facilitar la comprensión sobre las dificultades de percepción del lenguaje en oyentes más viejos.

Palabras Clave: Envejecimiento, ASSR, potenciales evocados auditivos, procesamiento auditivo temporal, cierre de fase, percepción del lenguaje

Abreviaturas: AEP = potenciales evocados auditivos; AM = modulación de la amplitud; ASSR = respuestas auditivas de estado estable; ERP = potenciales relacionados con el evento; FFT = transformación de la frecuencia de Fourier; FM = modulación de la frecuencia; HP = frases de alta predictibilidad; LP = frases de baja predictibilidad; MMSE = Examen Estatal Mini Mental; SPIN = Percepción del Lenguaje en Ruido; TMTF = función de transferencia de modulación temporal

Older persons have a higher risk of hearing loss (Cruickshanks et al, 2003) and greater difficulty understanding speech (Wiley et al, 1998; Versfeld and Dreschler, 2002) than younger persons do, even when they have similar hearing sensitivity (Dubno et al, 1984). Systematic study of speech understanding in younger and older listeners, matched both on age and on hearing sensitivity, has suggested that poor temporal processing may underlie speech understanding deficits in older listeners (Fitzgibbons and Gordon-Salant, 1996; Tremblay et al, 2004) . Temporal processing has been measured with distorted or degraded stimuli to emphasize the differences in timing analysis ability between younger and older listeners (Frisina and Frisina, 1997). The key to understanding an age-related decline in auditory temporal processing is to understand the functional effects of aging in the underlying neural response to auditory stimuli (Snell and Frisina, 2000; Tremblay et al, 2004). The change in neural timing, as hypothesized from neural changes associated with aging, should be related to poorer temporal processing in older listeners (Walton et al, 1997; Walton et al, 1998; Frisina, 2001).

In order to improve our current knowledge of auditory behavior and neural function, it might be useful to determine whether physiologic deterioration in auditory processing can be measured in older listeners. Auditory evoked potentials (AEPs) can be used to measure neural responses without complications from attention and cognition (Fisher et al, 2000; Wingfield, 1996). Different levels in the auditory system can be investigated with similar steady-state signals by changing the rate of modulation of that signal (Herdman et al, 2002; Herdman et al, 2004).

The processing of temporally altered stimuli can be assessed in older listeners with AEPs to stimuli that mimic the temporal and spectral complexities of speech signals, albeit in a limited manner (Eggermont, 1994). The electrophysiologic method of amplitude-modulated auditory steady-state responses (AM ASSRs) can be used to measure the ability of the auditory system to phase lock to the stimulus (Rickards and Clark, 1982). The stimulus consists of a pure-tone modulated at a specific rate and at a specific depth of modulation. In other words, there is a carrier frequency, a modulation rate, and a modulation depth (i.e., % modulation) for each AM signal. AM ASSRs can be recorded in younger and older listeners to determine whether or not neural responses are different for older listeners (Aoyagi et al, 1994; Boettcher et al, 2001).

Only recently have investigators begun to study suprathreshold responses to steady-state stimuli. In a study of aging, Boettcher et al (2001) measured AM ASSRs at the carrier frequencies of 520 and 4000 Hz modulated at 40 Hz from 0–100% modulation depth presented at 65 dB SPL. The methodology used in the Boettcher study introduced the concept of AM ASSRs to assess the physiologic mechanisms underlying temporal coding in older listeners for a 40 Hz modulation rate. Significant differences in hearing thresholds for high frequencies existed between listeners with normal hearing and listeners with either hearing loss or masked normal hearing suggesting that differences in AM ASSR amplitude were due to audibility, not age. No effects of age were found, but the modulation rate of 40 Hz is the most robust response in adult listeners, and the sample sizes of six and seven for the older groups may have been too small to find existing differences in phase-locking ability given the degree of variability in the response amplitudes.

In another investigation of AM ASSRs, Dimitrijevic et al (2001) measured ASSRs to AM and FM (frequency-modulated) stimuli at presentation levels of 20–70 dB SPL and word recognition in adults with normal hearing. AM and FM signals were presented separately and in combination with AM depth at 50 or 100% and FM depth at 20%. Each type of stimulus was presented at the carrier frequencies of 750, 1500, 3000, and 4000 Hz with frequency modulations from approximately 78–95 Hz. Higher depths of modulation and lower carrier frequencies evoked the most robust responses. The AM condition alone evoked larger response amplitudes than the combined AM and FM signals, and the FM response to the combined signal was stronger when AM was 50% modulated as opposed to 100% modulated. Word-recognition scores (W-22 and NU-6 word lists) in quiet improved as ASSR amplitude increased, or detectability of a response increased, to combined AM and FM signals; however, presentation level may have been responsible for this significant correlation.

In summary, ASSRs have been used to estimate hearing sensitivity in a broad range of listeners and for a broad range of stimulus characteristics. The best carrier frequencies are low frequency (e.g., 500 Hz), where neural phase locking is the most robust, and the strongest and most often occurring responses are for higher modulation depths (e.g., 80–100%). The most appropriate modulation rate depends on the level of the auditory system under investigation (i.e., as the rate decreases, more cortical potentials are involved in the response), so it is necessary to measure ASSRs at each level for a complete evaluation of the auditory system. ASSRs have only been measured in a small group of older listeners and at only one modulation rate, so differences between younger and older listeners under less than ideal modulation rates and depths have yet to be determined.

The primary purpose of this investigation was to use AM ASSRs to determine if temporal processing, as measured by ASSRs, is different in younger and older adults. ASSRs were chosen because their phase-locking ability serves as a measure of temporal processing. The ASSRs are thought to be dominated by neurons at several levels of the auditory system from the periphery to the cortex (Rickards and Clark, 1982; Kuwada et al, 2002), thus allowing observations at these different levels. A further advantage is that they are a physiologic response that minimizes effects from fluctuating listener attention, and they are measured with an objective routine that eliminates examiner bias.

The secondary purpose of this investigation was to determine if temporal processing, as measured with the ASSR, is related to behavioral measures of speech understanding. The speech measures were the revised Speech in Noise test (R-SPIN) in the low predictability mode, which has been shown to differentiate listeners with varying speech recognition abilities (Schum and Matthews, 1992; Pichora-Fuller et al, 1995).

MATERIALS AND METHODS

Two protocols were used to address the purposes, each with different criteria for subject selection. The general methods are discussed first, followed by the specific protocols that addressed the primary and secondary purposes.

General Methods

AM ASSRs

The purpose of recording AM ASSRs to tap temporal processing was threefold. First, ASSRs do not require the listener to respond behaviorally, so responses from listeners were not altered by attention. Second, phase coherence analysis of the steady-state response provided an objective determination of whether auditory neurons followed the stimulus or not. Third, AM ASSRs can be recorded from different levels in the auditory system, from the lower brainstem to the cortex, by manipulating the rate of modulation.

Evoked potential recordings were obtained for each listener using a steady-state evoked-potential-based evoked response audiometer (ERA Systems Pty Ltd) connected to a personal computer (Gateway 2000 P5-60). Electrodes led from the listener's scalp to an AD620 Analog Devices instrument amplifier interfaced with the evoked response system and computer that controlled stimulus generation and data acquisition. Gold cup electrodes were attached to the high forehead (Fz) (noninverting), mastoid of test ear (A1 or A2) (inverting), and mastoid of the nontest ear (A2 or A1) (ground) with impedances of ≤7 kohms (ERA Systems User Guide, 2000). EEG activity was sampled at 44.1 kHz and filtered from 3–5000 Hz. The stimulus level was held constant at 70 dB SPL for all AM ASSR tests and for each listener. Calibration of the stimulus included pre- and poststudy level and attenuator linearity as well as prestudy visual calibration of the amplitude-modulated signals via FFT (Fourier frequency transformation) and spectrogram analysis.

Stimuli consisted of sinusoidally amplitude-modulated pure tones presented through an ER-3A insert earphone. The modulation rates of 20, 40, and 90 Hz were manipulated for each of the two sinusoidal carrier frequencies of 500 and 2000 Hz. The carrier frequencies were chosen to tap low-frequency coding where phase locking should be the strongest (Rose et al, 1967) and higher frequency coding that should not be greatly affected by presbycusis in the older listeners. Both frequencies are also important speech frequencies (Studebaker et al, 1987; DePaolis et al, 1996). Modulation depths were 100, 80, 50, and 20%, chosen to provide a range of challenges to the auditory system from easy (i.e., 100%) to hard (i.e., 20%) in terms of neural phase-locking ability (Kuwada et al, 1986).

For each listener, phase locking was determined by an automated detection algorithm based on known statistical properties of background (EEG) noise and on the statistical properties of the ASSR. Phase coherence squared (PC^2) values were used to determine if the phase of the response was randomly distributed or not (i.e., in phase with the stimulus). Phase coherence squared values are obtained from samples, or subaverages, and were calculated by the ERA software as follows:

$$PC^2 = \frac{\{(\Sigma \sin)^2 + (\Sigma \cos)^2\}}{(\text{\# of samples})^2}$$

The phase coherence squared values can range from zero to one (i.e., phases are randomly distributed, or phases are identical in all samples, respectively).

The probability of detecting a false positive was preset by the ERA software to $p < .002$. Calibration included pre- and poststudy level and attenuator linearity as well as prestudy visual calibration of the amplitude-modulated signals via FFT and spectrogram analysis.

Subjects

The present study was approved by the College of Letters and Science Human Subject Committee at the University of Wisconsin-Madison. Participants were recruited from local senior centers by way of posted advertisement and by word of mouth. Listeners were ≤41 years of age or ≥63 years of age and native speakers of English. The average years of education for the younger (M = 17.75 years, SD = 2.1) and older (M = 17.15 years, SD = 5.7) listeners were similar. Listeners were screened for cognitive, auditory, and medical conditions that may have confounded experimental test results. The mini mental state exam (MMSE; Folstein et al, 1975) was administered to determine if a listener was at risk for cognitive dysfunction. Criterion was a score of 24 or higher on the MMSE. The average score on the MMSE was 29.1 for the younger listeners and 29.6 for the older listeners; all scores were well above the criterion for suspected cognitive dysfunction (i.e., 24). A brief case history was obtained to determine if previous or current otic disease or neurological disorder required that the listener be excluded from the study.

All subjects were tested with admittance measures and pure-tone audiometry. Tympanometric measures were within normal limits for younger (Roup et al, 1998) and older listeners (Wiley et al, 1996). Pure-tone thresholds were obtained using a clinical audiometer (Grason-Stadler, model GSI 61) with TDH-50P earphones calibrated according to ANSI 3.6 (ANSI, 1996) specifications for a Type 2 audiometer. All testing was conducted in a sound-treated booth (Industrial Acoustics Company, 1200 Series) that met the ANSI 3.1 (ANSI, 1991) standard for ambient noise levels for audiometric test rooms.

Protocol 1. To determine if temporal processing differed in younger and older people, Protocol 1 involved 11 young listeners paired with 11 older listeners. The criteria for pairing listeners were matched thresholds within 10 dB for 500, 1000, and 2000 Hz, the frequency range that included all test frequencies. The younger listeners had a mean age of 29.6 years and included eight women. The older listeners had a mean age 69.9 years and included six women. The comparison of hearing thresholds between younger and older paired listeners has been provided in Table 1. A paired samples t-test (Serlin and Marascuilo, 1988) revealed that thresholds were not significantly different at the frequencies of 500, 1000, and 2000 Hz; however, significant differences were found at 250 Hz and 4000 Hz. Possible effects of the significant differences in threshold between younger and older listeners have been included in the discussion. A Friedman test (Serlin and Marascuilo, 1988) was conducted to evaluate the differences in the median number of phase-locked responses for the main factors of age, modulation rate, and carrier frequency and the interactions. Follow-up pairwise comparisons were conducted using the Wilcoxen test controlling for Type I errors across these comparisons at the 0.05 level using the least significant difference (LSD) procedure (Serlin and Marascuilo, 1988).

Statistical analyses were conducted to determine if the phase locking capability of the auditory system was different between younger and older listeners by taking into account modulation rate, carrier frequency, and the interaction of age by rate and by frequency. A Friedman test (Serlin and Marascuilo, 1988) was conducted to evaluate the differences in the number of phase-locked responses as a function of age, modulation rate, and carrier frequency. The difference in phase locking was calculated by counting the number of phase locked responses in each sample, ranking these differences according to absolute magnitude, and then performing the significance test. If there was no difference in phase locking capability between samples, then the sum of the ranks should be zero; however, if consistent differences existed, then the sum of the ranks should be far from zero. Follow-up pairwise comparisons were conducted using the Wilcoxen test controlling for Type I errors across these comparisons at the .05 level using the least significant difference (LSD) procedure.

Protocol 2. Twenty-eight listeners who had hearing thresholds ≤20dB HL from 250–2000 Hz served as listeners. This set included 16 younger listeners (mean age 29.0 years) and 12 older listeners (mean age 69.6 years), and included the 22 listeners from Protocol 1. Twelve of the 16 younger listeners were women, and 6 of the 12 older listeners were women. In addition to the ASSR measures described

Table 1. Individual Thresholds (dB HL) for Each Pair of Listeners for Octave Frequencies 250–4000 Hz

	250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz	
	Young	Old	Young	Old	Young	Old	Young	Old	Young	Old
Pair 1	5	15	5	0	5	15	5	10	15	45
Pair 2	10	30	5	15	0	0	-5	5	10	20
Pair 3	5	5	5	10	0	10	5	10	0	20
Pair 4	-5	5	-5	5	0	10	-10	15	-5	20
Pair 5	0	10	0	15	0	10	0	15	0	15
Pair 6	0	10	-5	5	0	5	0	0	5	10
Pair 7	0	15	0	15	-5	15	-5	0	0	10
Pair 8	15	15	20	10	15	15	10	0	20	35
Pair 9	5	5	0	0	0	10	0	10	15	45
Pair 10	10	10	5	10	5	10	0	10	20	15
Pair 11	15	15	10	0	15	0	20	10	10	65
t	-2.714*		-1.480		-2.204		-1.921		-3.970*	
p	0.022		0.170		0.052		0.084		0.033	

Note: Paired samples t-test analysis results are listed for each test frequency (t = test statistic for t-test, p = p-value, * = significant differences).

above, these listeners also had word-recognition performance measured with two lists of the R-SPIN test for a total of 100 sentences consisting of 50 sentences with linguistic cues (i.e., HP [high predictability] sentences) and 50 sentences without linguistic cues (i.e., LP [low predictability] sentences). Word recognition for the R-SPIN-HP was used to rule out any gross neural pathology in the listeners and for comparison of this older group with older groups described in the literature. Word-recognition performance on the R-SPIN-LP was used for correlation with the ASSR because the difficulty of the task was expected to elicit a range of word-recognition performance for the older listeners, thus demonstrating reduced word-recognition ability in difficult listening situations (Pichora-Fuller et al, 1995). The correlation coefficients (SPSS 11.5) were computed for the total number of phase-locked responses at 500 Hz and at 2000 Hz with the total percent correct for the R-SPIN-LP test. Type I error rate was held at $p \leq 0.05$ for the experiment.

Statistical analysis was conducted to determine if the differences in the mean percent correct scores were significant. The word-recognition data were skewed positively (i.e., toward 100% correct) and required a rationalized arcsine transformation to be performed prior to data analysis (see Studebaker, 1985). A two-way repeated

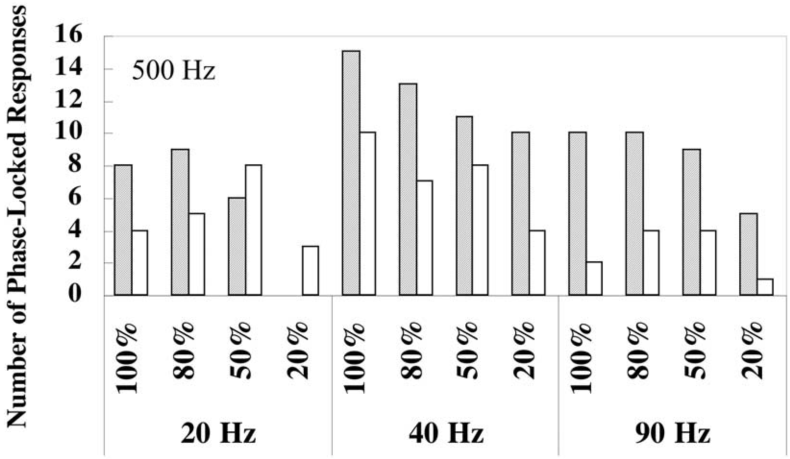

Figure 1. Number of phase-locked responses (ordinate) by modulation rate across modulation depth (abscissa) is shown for the 500 Hz carrier frequency for each listener pair for each of the 12 AM ASSR tests. The filled bars represent the younger listeners, and the open bars represent the older listeners. The maximum number of responses is 16.

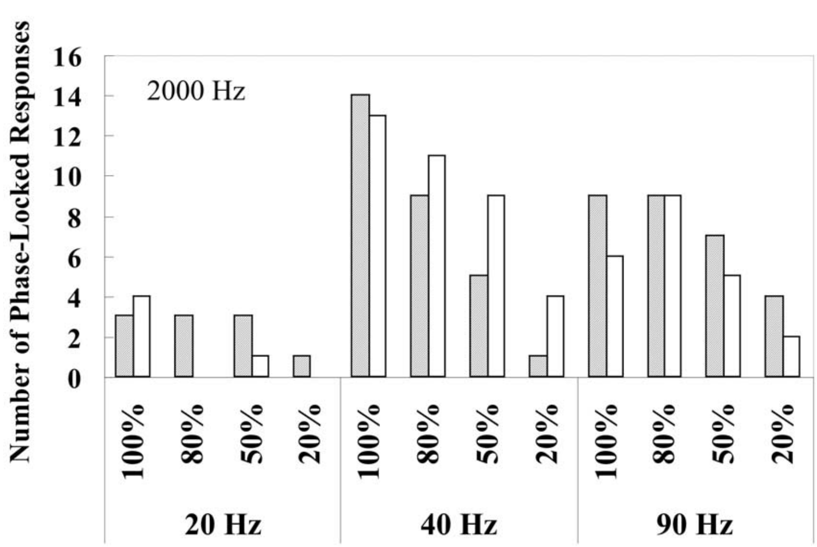

Figure 2. Number of phase-locked responses (ordinate) by modulation rate across modulation depth (abscissa) is shown for the 2000 Hz carrier frequency for each listener pair for each of the 12 AM ASSR tests. The filled bars represent the younger listeners, and the open bars represent the older listeners. The maximum number of responses is 16.

measures ANOVA was conducted to determine if significant differences existed for the two factors of age and word predictability. A post hoc paired samples t-test was conducted to determine how performance on the word-recognition task changed across age of listener. The association between AM ASSRs and word-recognition performance was measured by Kendall's tau-b. This is a nonparametric measure of association based on the number of concordances and discordances in paired observations. Concordance occurs when paired observations vary together, and discordance occurs when paired observations vary differently.

RESULTS

ASSRs in Younger and Older Paired Listeners

Overall, younger and older listeners showed different degrees of phase locking capability dependent on both carrier frequency and rate of modulation. Figures 1 and 2 show the number of responses for each listener pair for all of the stimulus conditions. The maximum number of responses in each figure is 16. Figure 1 illustrates that younger listeners (filled bars) had consistently more phase-locked responses compared to older listeners (open bars) across each modulation rate for the 500 Hz carrier frequency; however, Figure 2 shows that for the 2000 Hz carrier frequency, older listeners (open bars) had the same number of phase locked responses at 20 and 90 Hz modulation rate and more responses at the 40 Hz rate compared to younger listeners (filled bars).

The Friedman omnibus analysis indicated significant differences in the median number of phase-locked responses for the main effects of age, modulation rate, and carrier frequency, as shown in Table 2. The Kendall coefficient of concordance of 0.69 ($p < 0.001$) indicated significant differences among the three factors. For age, the younger group had significantly more responses (135) than the older group (109). For carrier frequency, 500 Hz yielded significantly more responses (133) than did 2000 Hz (111). For modulation rate, the locus of the main effect was attributed to the significantly larger number of responses at 40 Hz (125) compared to 20 Hz (47) and to 90 Hz (72), as seen in Figure 3 and confirmed by the Wilcoxen results shown in Table 2.

Two interactions were significant and were analyzed with the post hoc Wilcoxen pairwise comparisons. The significant age by modulation rate interaction was localized to the significantly larger number of responses of the younger listeners compared to the older listeners at the modulation rate of 90 Hz. Differences in the number of responses at 20 and 40 Hz were not significant (Figure 4 and Table 2).

The interaction of age by frequency was tested by calculating the difference in responses between younger and older listeners for 500 and 2000 Hz separately. As seen in Table 2 and shown in Figure 5, the median number of phase-locked responses

Table 2. Matched-Pair Wilcoxen Results for the AM ASSRs for Younger and Older Listeners across Modulation Rate, Carrier Frequency, and Age of Listener

		Z	p
Main Effects	Pairwise Comparisons		
Rate	20–40	-2.81	.005*
	20–90	-1.89	.059
	40–90	-2.46	.014*
Frequency		-1.19	.234
Age		-1.74	.082
Interactions			
Age x Rate	20	-.36	.716
	40	-.31	.759
	90	-2.05	.040*
Age x Frequency	500	-2.322	.020*
	2000	-.308	.758

Note: p = p-value, Z = test statistic for Wilcoxen, * = significant difference.

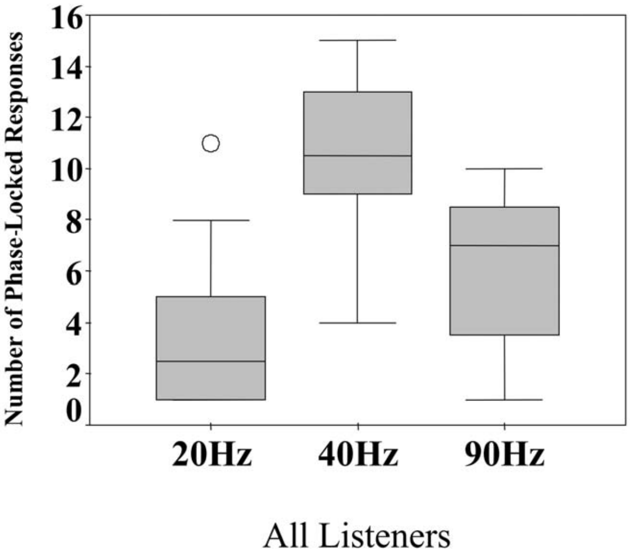

Figure 3. The distribution of the number of phase-locked responses is shown across modulation rate for each listener pair. The bars represent the range of raw scores, the line represents the median, and the box represents the middle 50% of the distribution of responses. The open circle at the modulation rate of 20 Hz denotes an outlier. The maximum number of responses is 16 per condition.

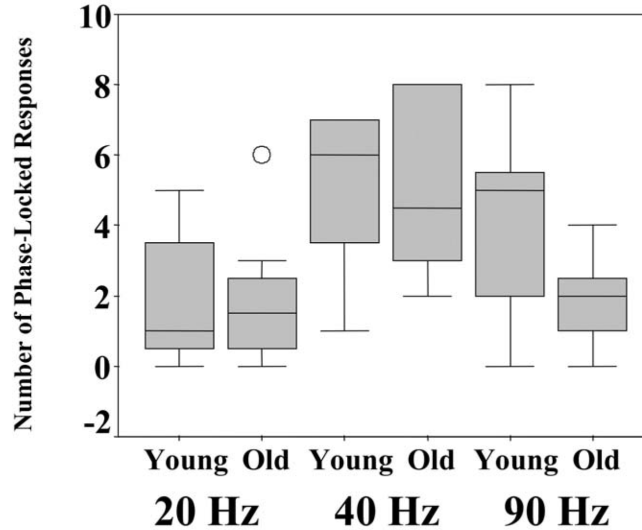

Figure 4. The distribution of the number of phase-locked responses is shown across modulation rate for each listener pair separated by listener group. Bars represent the range of raw scores, the line represents the median, and the box represents the middle 50% of the distribution of responses. The circle for older listeners at a modulation rate of 20 Hz represents an extreme score. The maximum number of responses is eight per condition.

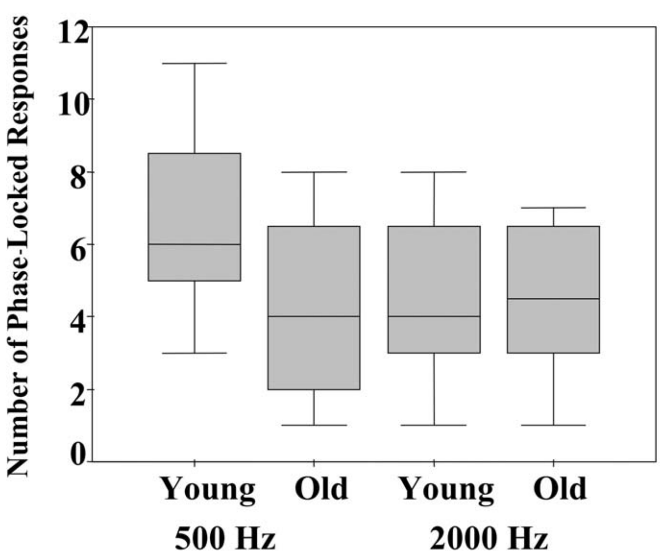

Figure 5. The distribution of the number of phase-locked responses (ordinate) is shown across carrier frequency (abscissa) for each listener pair separated by listener group. Bars represent the range of raw scores, the line represents the median, and the box represents the middle 50% of the distribution of responses. The maximum number of responses is 12 per condition.

for younger listeners was significantly higher than the median number of phase-locked responses for older listeners for 500 Hz. There was no significant difference between the median numbers of responses by age for 2000 Hz. Figure 6 shows the number of phase locked responses for pairs of listeners for the 500 Hz (top graph) and for the 2000 Hz (bottom graph) carrier frequency. For the 500 Hz carrier frequency, the older member of the pair had fewer phase-locked responses than the younger member of the pair with only one exception. The lower graph in Figure 6 shows no consistent pattern in phase-locking capability for the 2000 Hz carrier frequency between members of the pairs.

ASSRs and Word Recognition

Performance on the R-SPIN-LP was variable across the older listeners, making it possible to identify a range of word-recognition ability. For younger listeners, the mean percent correct for the HP sentences (M = 99.0, SD = 1.3) was higher than the mean percent correct for the LP sentences (M = 83.8, SD = 5.1). A similar pattern of performance for older listeners was found in that the mean percent correct for the HP

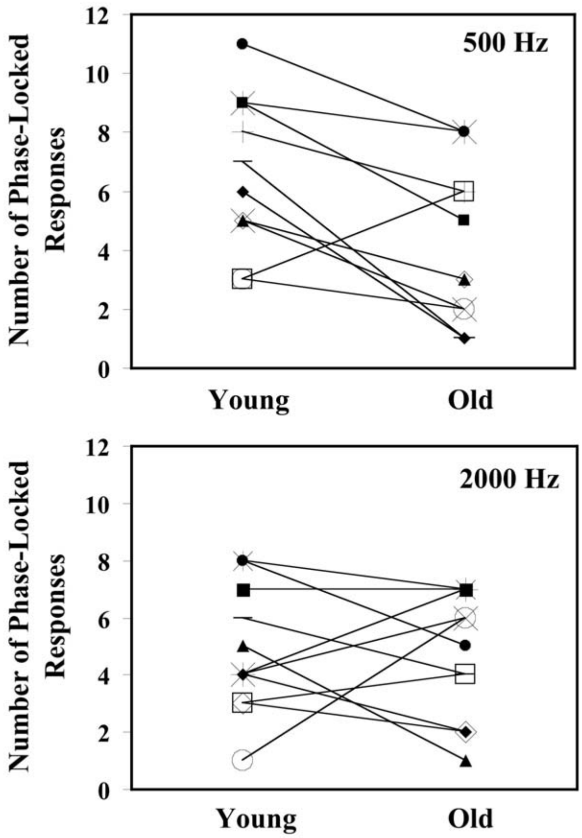

Figure 6. The corresponding number of phase-locked responses is shown for each listener pair from each listener group. The top graph represents the responses to the 500 Hz carrier frequency, and the bottom graph represents responses to the 2000 Hz carrier frequency. The maximum number of responses is 12 per condition.

sentences (M = 97.3, SD = 2.8) was better than the mean percent correct for the LP sentences (M = 65.7, SD = 15.0).

A two-way repeated measures ANOVA on the arcsine transformed scores revealed a significant main effect of word predictability, but not age. Performance on the HP sentences was significantly better than performance on the LP sentences, but the younger and older listeners performed similarly overall. The interaction, however, between age and word predictability was significant. A post hoc paired samples t-test was conducted to determine how performance on the word-recognition task changed across age of listener. Table 3 shows the results of the post hoc paired samples t-test for the interaction of predictability and age. For predictability, performance on the HP sentences was significantly better than performance on the LP sentences for both young and old groups. There was no significant difference in performance by age on the HP task, but younger listeners performed significantly better than the old listeners on the LP task.

Figure 7 shows the individual word-recognition results for the R-SPIN-LP (abscissa) for the number of phase-locked responses at 500 Hz (ordinate). Table 4 lists the results from the Kendall's tau-b statistical analysis, which revealed significant correlations between phase-locking capability for the low-frequency stimulus and performance on the R-SPIN-LP. The number of phase-locked responses at 500 Hz, however, accounted for only about 6% of the variability in word-recognition performance. Table 4 also shows that the number of phase-locked responses at 2000 Hz was not correlated with word-recognition performance. Overall, the AM ASSR and word-recognition analysis revealed significant, but weak, correlations showing that as word-recognition scores decreased, the number of phase-locked responses also decreased for the 500 Hz carrier.

The potential relation between phase-locking ability and hearing sensitivity was investigated by a correlational analysis of the data from the 28 listeners described above. Phase-locking capability at 2000 Hz was not correlated with hearing sensitivity

Table 3. Differences between Younger and Older Listeners for Word-Recognition Performance on the R-SPIN Test after Arcsine Transformation Was Conducted on the Raw Recognition Data

	Mean Difference	Standard Error	df	t	p
Young HP – Old HP	-.429	2.08	10	-.21	.840
Young LP – Old LP	7.99	1.94	10	4.12	.002*
Young HP – Young LP	19.58	1.30	10	15.12	<.001*
Old HP – Old LP	28.01	1.35	10	20.70	<.001*

Note: HP = high-predictability words, LP = low-predictability words, df = degrees of freedom, t = test statistic for t-test, p = p-value, * = significant difference.

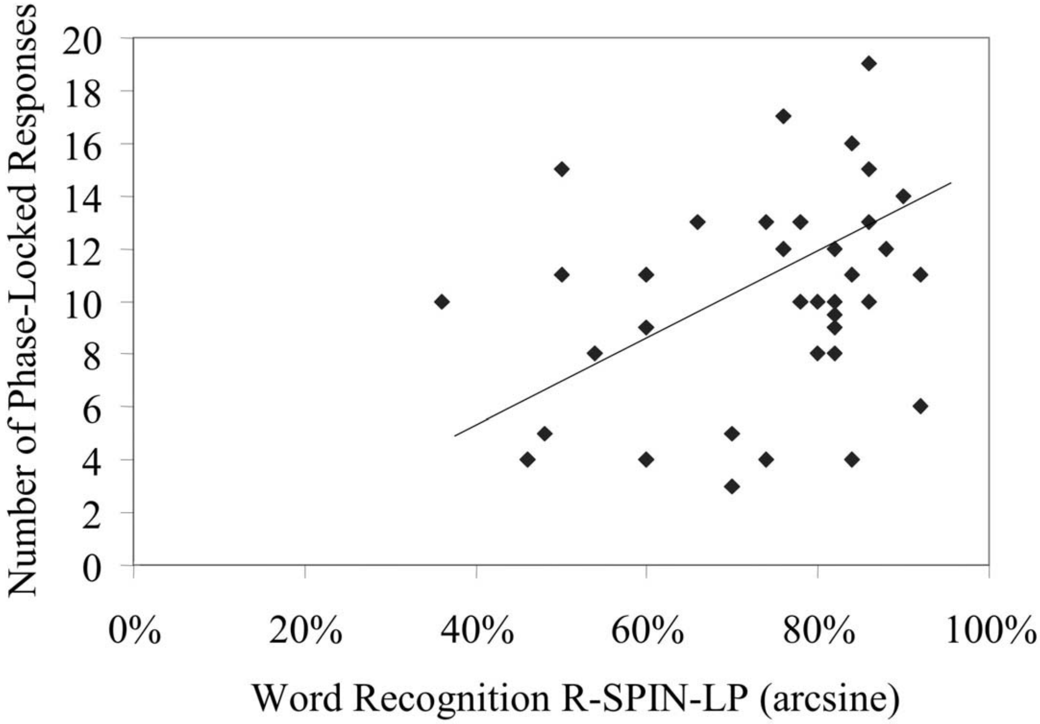

Figure 7. The number of phase-locked responses (ordinate) to the 500 Hz carrier frequency is shown as a function of word-recognition performance in percent correct (abscissa) for the R-SPIN-LP across the 28 listeners with normal hearing through 2000 Hz. The line represents the linear regression (y = bx + a).

at any test frequency (Table 4). At 500 Hz, phase-locking capability was significantly correlated with hearing sensitivity regardless of test frequency (Table 4). As hearing thresholds improved, the number of phase-locked responses increased.

Table 4. Results of the Correlational Analysis (n = 36) between the Number of Phase-Locked Responses and Performance on the R-SPIN-LP Sentences after Arcsine Transformation Was Conducted on Raw Scores

			rho	p
Phase locking $_{total}$	—	R-SPIN-LP	.114	.207
Phase locking $_{500}$	—	R-SPIN-LP	.240	.046*
Phase locking $_{2000}$	—	R-SPIN-LP	-.023	.436
Phase locking $_{2000}$	—	PTA 2k, 4k, and 8k Hz	-.051	.359
		PTA 500, 1k, and 2k Hz	.026	.428
		PTA 250, 4k, and 8k Hz	-.074	.300
		PTA 4k and 8k Hz		
Phase locking $_{500}$	—	PTA 2k, 4k, and 8k Hz	-.488	<.001
		PTA 500, 1k, and 2k Hz	-.280	.026
		PTA 250, 4k, and 8k Hz	-.481	<.001
		PTA 4k and 8k Hz	-.516	<.001

Note: PTA = pure-tone average, rho = test statistic for Kendall's tau-b test, p = p-value, * = significant difference.

DISCUSSION

AM ASSRs

Age by Modulation Rate

The results from the present study showed that the modulation rate of the AM signals directly affects the presence or absence of phase-locked responses. Overall, listeners had significantly more phase-locked responses at a rate of 40 Hz compared to both the rates of 20 and 90 Hz. That is, the slower rates of modulation, presumably generated in regions of the cortex, did not produce responses as often or as robust as higher rates of modulation, theoretically generated in thalamocortical regions (Creutzfeldt et al, 1980; Chiu and Poon, 2000; Ross et al, 2002). In addition, the responses from higher rates, presumably from the brainstem, showed that older listeners had significantly fewer phase-locked responses than younger listeners.

The greater number of responses at 40 Hz is in partial agreement with results of Rees et al (1986), who investigated steady-state responses to modulation rates of 2–400 Hz with a carrier frequency of 1000 Hz modulated only at 100%. Response magnitudes were greatest for low frequency rates (i.e., ≤40 Hz) for each of the four listeners tested (aged 19–47 years). At rates higher than 40 Hz, the response magnitude decreased linearly with an increase in rate. At modulation rates lower than 40 Hz, the response magnitudes were equivalent to or slightly higher than response magnitudes at 40 Hz. The present study showed that the lower rate of 20 Hz was similar to the higher rate of 90 Hz, not the intermediate rate of 40 Hz as found by Rees et al. The differences between these studies are likely explained by the stimulus.

Modulation rate also was investigated by Levi et al (1993) to determine the effect of modulation rate on AM ASSRs in young normally hearing listeners. The response amplitudes were analyzed using magnitude-squared coherence to determine the strength of the response compared to the underlying neural noise. The stimuli consisted of 500 and 2000 Hz tones 100% amplitude modulated at rates from 10–80 Hz. The largest mean coherence values (i.e., the best responses) were observed for the modulation rate of 40 Hz for both the 500 Hz and 2000 Hz carrier frequencies. Data from both the younger and older listeners in the present study are supported by the data from Levi et al showing the best responses at 40 Hz.

One recent study measured modulation depth and carrier frequency of AM ASSRs in younger and older listeners. Boettcher et al (2001) recorded AM ASSRs in three groups of listeners: young (aged 22–29 years, n = 10), young-old (60–65 years, n = 7), and old-old (66–72 years, n = 6) with hearing thresholds from all listeners ≤25 dB HL. The stimuli were 520 and 4000 Hz sinusoids AM at 40 Hz at modulation depths of 0–100%. The wave morphology and amplitude of the responses from the younger listeners was similar to the wave morphology and the amplitude from the older listeners. All listeners had higher response amplitudes for the 520 Hz carrier frequency compared to the 4000 Hz carrier frequency. The 40 Hz data from the younger listeners in the present study were in agreement with the data from the younger listeners in the Boettcher study. In contrast to the data from Boettcher, the data from the older listeners in the present study showed the same number of phase-locked responses for both the 500 and 2000 Hz carrier frequencies.

The significant difference in the number of phase-locked responses between younger and older listeners at higher rates of modulation requires consideration. The interaction of age by modulation rate is accounted for by the higher number of phase-locked responses from younger listeners at 90 Hz. Given that the generator site for the 90 Hz response is presumed to be the brainstem (Picton et al, 2003), these results suggest that altered brainstem function occurs with aging.

Auditory brainstem responses from both human and animal data provide evidence that processing from the auditory nerve and upper brainstem regions can be reduced in older members of a species (Walton et al, 1997; Walton et al, 1998; Frisina, 2001; for a review, see Boettcher, 2002). The precise location of the response to the 90 Hz modulation rate was not determinable from the data, but clearly previous investigations support effects of aging in the brainstem (Schmiedt et al, 1996), and synchrony of neural firing is an important factor for phase locking (Javel, 1980).

Age by Carrier Frequency

Several studies have investigated the effect of carrier frequency on AM ASSRs, but few have studied the interaction of frequency with aging. One key finding in the present study was that younger listeners showed a larger number of responses to AM signals at 500 Hz than did older listeners. The temporal coding driven by low-frequency signals, therefore, was reduced by aging, whereas temporal coding driven by higher frequencies was not. Low-frequency signals are coded by the temporal information, that is, phase locking, up to about 4000 Hz (Moore, 1993), underscoring the importance of the frequency difference found between older and younger listeners.

The results from the present study were in agreement with several sets of previously published data. Levi et al (1993) reported that AM ASSRs from young normally hearing listeners were significantly stronger at 500 Hz than at 2000 Hz. A similar study, again in young normally hearing adults (aged 22–41 years), measured AM ASSRs in a series of experiments investigating carrier frequency, modulation rate, and modulation depth (Picton et al, 1987). The experiment used sinusoids of 500, 1000, 2000, and 4000 Hz modulated at rates from about 30 to about 50 Hz and at a depth of 100%. The 500 Hz carrier frequency always elicited larger amplitudes than the higher carrier frequencies across the various modulation rates. These data clearly showed that the best stimulus frequency for ASSRs was the lowest frequency tested. The data from the younger listeners in the present study are consistent with these findings, but the data from the older listeners are clearly different.

The effect of carrier frequency on AM ASSRs has not been investigated thoroughly in older listeners. The Boettcher et al (2001) study, described previously, provides data for different carrier frequencies in younger and older listeners. Both groups of listeners showed larger response amplitudes for the carrier frequency of 520 Hz compared to the carrier frequency of 4000 Hz. The similarities between the younger and older listeners persisted for each depth of modulation. The data from the present study disagree with the data from Boettcher in two ways. First, the older listeners in the present study had fewer phase-locked responses at 500 Hz compared to the younger listeners, whereas no age-related changes in AM ASSRs were found in the Boettcher study. Second, the number of phase-locked responses for the older listeners was similar for the 500 and 2000 Hz tones in the present study, whereas the older listeners in the Boettcher study had larger responses for the 520 Hz tone compared to the 4000 Hz tone.

Differences in methodology exist between the present study and the Boettcher study and may contribute to the different results. The responses in the Boettcher study were measured by amplitude, and the responses from the present study were measured by the presence or absence of a phase-locked response. The two methods are related but are not the same. The method used in the present study may have detected only the more robust phase-locked responses, not AM ASSRs of low amplitude.

The decline in low-frequency temporal coding with age noted in a psychoacoustic study by He et al (1998) supports the poorer 500 Hz AM ASSR data in the older listeners in the present study. He et al (1998) reported that difference limens for frequency between older and younger listeners decreased as stimulus frequency increased from 1000 to 4000 Hz. The authors related the poorer low-frequency difference limens to temporal processing deficits in the older listeners. The data from the present study support an age-related decrease in temporal coding for low-frequency signals.

AM ASSRs and Word Recognition

In general, the results from the present study showed that word-recognition performance for both younger and older listeners followed a predictable pattern of better performance on the HP sentences compared to the LP sentences and better performance from the younger listeners compared to the older listeners (Schum and Matthews, 1992; Gordon-Salant and Fitzgibbons, 1997). Specific to the one objective of this study, poor word-recognition performance was related to temporal coding as identified with AM ASSRs.

The 40 Hz activity in response to steady-state signals has shown a promising connection to speech understanding in older listeners. Ali and Jerger (1992) recorded responses to a 40 Hz AM steady-state signal and to a 40 Hz ERP (event related potential) in two groups of older listeners with mild degrees of hearing loss above 1000 Hz. The 40 Hz ERP for listeners with speech understanding performance proportionate to their hearing thresholds showed stronger phase coherence at 40 Hz compared to the listeners with poor speech understanding. More dramatically, the 40 Hz steady-state responses were reduced in magnitude for the listeners with poor speech understanding performance. The data from the present study is supported by data from Ali and Jerger (1992) in that the listeners with poorest word-recognition scores were also the listeners with the fewest number of phase-locked responses. The present study extended the findings of Ali and Jerger to compare the responses of young and old listeners and to define some of the details of the differences in phase-locking ability by age. Both studies provide complementary evidence that temporal coding, as measured by phase locking, bears some relation to speech-understanding ability.

Poor auditory processing related to temporal coding has been shown in other listeners with suspected temporal coding problems by AM ASSRs. McAnally and Stein (1997) used AM signals to assess the temporal coding ability in listeners with developmental dyslexia, which was defined as a reduced reading ability not predicted by age or IQ. The hypothesis for both the reading problems and the reduced magnitude in phase locking in listeners with dyslexia was a change in temporal coding for low-frequency signals. Significantly reduced response amplitudes were found at each rate of modulation for listeners with dyslexia compared to listeners from a control group. These data support the present data from the older listeners, who also have suspected auditory temporal coding problems and reduced low-frequency AM ASSRs.

In a later study (Menell et al, 1999), AM ASSRs and behavioral temporal modulation transfer functions (TMTFs) were recorded from listeners with dyslexia. TMTFs are used to assess the ability of the auditory system to resolve temporal fluctuations in a signal by a listener's ability to notice the difference between a modulated and an unmodulated tone (Viemeister, 1979). AM ASSRs were elicited by 100% modulated white noise with the same modulation rates used for the TMTFs. The TMTFs showed that the listeners with dyslexia needed greater depths of modulation to identify the modulated signal compared to listeners from the control group. The AM ASSRs showed that the listeners with dyslexia had lower amplitudes than the listeners from the control group at all modulation rates except the fastest (i.e., 160 Hz). Both behavioral and electrophysiologic data showed that differences in temporal coding exist between listeners with reading difficulties and listeners with normal reading ability.

The results from the present aging study complement the results from the two developmental dyslexia studies in that both groups of listeners with suspected temporal processing problems showed a reduction in the number or magnitude of responses elicited by AM ASSRs. The reduced responses to time-altered signals in both groups (i.e., older listeners and listeners with dyslexia) may be a factor common to reduced speech processing ability in the auditory system.

Effect of Threshold Differences between Younger and Older Listeners

Hearing sensitivity differences between younger and older listeners continue to confound studies of human aging. Behavioral pure-tone thresholds for older listeners in the current study were slightly, but significantly, higher than thresholds for younger listeners at 250 and 4000 Hz. The effect of these threshold differences on the AM ASSRs and their correlation with word-recognition performance is unknown.

Data from behavioral TMTFs suggest that high-frequency hearing loss has minimal effects on AM thresholds at lower frequencies. Bacon and Viemeister (1985) found level dependent changes in the TMTF from listeners with hearing loss as compared to listeners with normal hearing. They suggested that the loss of neural contributions from the high-frequency end of the cochlea may have influenced the responses to low-frequency stimuli. In the present study, a similar effect could have occurred for the older listeners, resulting in reduced innervation for AM ASSRs. Loss of innervation, however, should have had a greater effect on the 2000 Hz AM ASSRs compared to the 500 Hz AM ASSRs. The current data, however, showed reduced responses at 500 Hz rather than at 2000 Hz for the older listeners, suggesting that high-frequency hearing loss does not explain the differences in response between younger and older listeners.

Electrophysiologic measures of amplitude-modulated thresholds in chinchillas with varying degrees of high-frequency hearing loss (Henderson et al, 1984) showed opposite results. Following exposure to an 8000 Hz band of noise, amplitude modulation thresholds were unchanged for the lowest and highest modulation frequencies (≤64 Hz and ≥1024 Hz) but increased for intermediate modulation frequencies (i.e., 128 Hz). Subsequent noise exposures (8000 + 4000 and 8000 + 4000 + 2000 Hz) resulted in no further increase in modulation threshold. Subsequent experiments showed that the increase in modulation thresholds at 8000 Hz relative to pre-exposure was a result of high-frequency hearing loss. These data suggest that some modulation frequencies are influenced by high-frequency hearing sensitivity. The high-frequency hearing loss in the older listeners from the present study, therefore, cannot be ignored as a possible confound to the numbers of phase-locked responses in older listeners.

The role of hearing sensitivity in auditory processing is both complex and important in the study of temporal coding. The data from the present study, in combination with data from previously published work, suggests that threshold differences between listeners at the stimulus frequency play a minor role in suprathreshold temporal processing. The possibility, however, that high-frequency hearing loss contributed to differences in temporal coding for frequencies adjacent to or removed from the stimulus frequency could not be ruled out by the present study. Further studies are needed to resolve this issue.

SUMMARY

The present study has provided evidence of poor timing analysis in older listeners at the physiologic level in response to time-altered (i.e., AM) signals. Age-related changes to temporal coding were demonstrated at lower brainstem levels and for low-frequency signals. Data from the present study revealed that listeners with fewer phase-locked responses also had poorer word-recognition performance for R-SPIN-LP sentences. The exploration, and use, of electrophysiologic responses to measure auditory timing analysis in humans has the potential to facilitate the diagnosis and rehabilitation of speech understanding problems in older listeners.

In conclusion, the abundance of behavioral data regarding one form of reduced temporal coding in older listeners has now been confirmed with ASSRs. The results from the present study showed electrophysiologic evidence of age-related changes in the coding of time-altered signals. Younger listeners, not older listeners, showed a significant advantage in phase locking for low frequencies compared to high frequencies. The effect of aging on temporal processing, as measured by phase locking, was found for low-frequency stimuli where phase locking in the auditory system should be optimal. These results suggest that low-frequency coding may be affected deleteriously by aging. The data from the present study offer a new tool of investigation into temporal processing in the aged auditory system.

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