Frequency and Temporal Resolution in Elderly Listeners with Good and Poor Word Recognition

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Phillips, S.L., Gordon-Salant, S., Fitzgibbons, P.J., Yeni-Komshian, G.H. (2000). Frequency and temporal resolution in elderly listeners with good and poor word recognition. *Journal of Speech, Language and Hearing Research 43*(1), 217-228.

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Abstract:

There is a subgroup of elderly listeners with hearing loss who can be characterized by exceptionally poor speech understanding. This study examined the hypothesis that the poor speech-understanding performance of some elderly listeners is associated with disproportionate deficits in temporal resolution and frequency resolution, especially for complex signals. Temporal resolution, as measured by gap detection, and frequency resolution, as measured by the critical ratio, were examined in older listeners with normal hearing, older listeners with hearing loss and good speech-recognition performance, and older listeners with hearing loss and poor speech-recognition performance. Listener performance was evaluated for simple and complex stimuli and for tasks of added complexity. In addition, syllable recognition was assessed in quiet and noise. The principal findings were that older listeners with hearing loss and poor word-recognition performance did not perform differently from older listeners with hearing loss and good word recognition on the temporal resolution measures nor on the spectral resolution measures for relatively simple stimuli. However, frequency resolution was compromised for listeners with poor word-recognition abilities when targets were presented in the context of complex signals. Group differences observed for syllable recognition in quiet were eliminated in the noise condition. Taken together, the findings support the hypothesis that unusual deficits in word- recognition performance among elderly listeners were associated with poor spectral resolution for complex signals.

KEY WORDS: hearing loss, speech perception, frequency resolution, temporal resolution

Article:

Hearing loss is a common consequence of the aging process and is typified by a loss of sensitivity that is greater in the higher frequencies than in the lower frequencies (Schuknecht, 1964). Sensorineural hearing loss is accompanied by difficulties with speech perception (Bess & Townsend, 1977; Dirks, Morgan, & Dubno, 1982; GordonSalant, 1986), particularly in the presence of background noise (Duquesnoy & Plomp, 1980). Often, however, word- and syllable-recognition ability are preserved, provided the speech signal is amplified to an audible level (van Tasell, Hagen, Koblas, & Penner, 1982). Although many elderly listeners with hearing loss recognize speech well at high presentation levels (Kasden, 1970), there remains a subgroup of elderly listeners with hearing loss who have inordinate difficulty understanding amplified speech in quiet (Gaeth, 1948; Schuknecht, 1964; Stach, Loiselle, & Jerger, 1991). This group has received limited benefit from amplification and must rely mainly on other coping mechanisms to receive spoken communication. A better understanding of the underlying mechanisms for the failure in speech understanding in this group of people potentially can lead to improved signal processing methods or rehabilitation strategies.

The cause of exaggerated problems with the discernment of speech in some elderly listeners is not clear. Although increased difficulty with speech perception may be related in part to a decline in peripheral auditory sensitivity, the additional difficulties that some elderly listeners experience may be due to auditory processing problems, such as poor frequency or temporal resolution. Several investigators have found a relationship between frequency resolution and speech recognition abilities in younger listeners (Dreschler & Plomp, 1985; Patterson, Nimmo-Smith, Weber, & Milroy, 1982) and in elderly listeners (Patterson et al., 1982; van Rooij, Plomp, & Orlebeke, 1989). Temporal resolution in the form of gap detection has also been related to speech- perception performance among younger listeners (Dreschler & Plomp, 1985; Irwin & McCauley, 1987; Tyler, Summerfield, Wood, & Fernandes, 1982). Although the spectral resolution abilities of listeners with poor speech understanding have not been investigated specificially, Preminger and Wiley (1985) obtained psychophysical tuning curves (PTC) from listeners with sensorineural hearing loss and a wide range of speech recognition scores. Three listeners with sensorineural hearing loss and poor word-recognition scores demonstrated poorly defined PTCs in the region of hearing loss, and their PTCs were poorer than those of listeners with a matched audiogram and good speech recognition. These results suggest that frequency resolution is compromised in listeners with difficulties understanding speech.

It is also possible that a central auditory processing problem may underlie the speech-recognition deficits of some elderly listeners. Schucknecht (1964), in describing a subgroup of elderly listeners with hearing loss and poor speech recognition, saw their pattern as characteristic of neural loss in the auditory system. Jerger, Jerger, Oliver, and Pirozzolo (1989) reported that 23% of elderly listeners (N = 130) with normal cognitive status demonstrated reduced central auditory function as determined by performance on competing words and sentences. The central auditory system is also thought to be necessary for analysis of specific signal attributes, such as frequency, intensity, and duration (Albeck, Nebenzahl, & Lewis, 1992; van Rooij & Plomp, 1990). Central mechanisms are intrinsically necessary for processing complex stimuli, such as extracting a signal from a competing background of noise (Albeck et al., 1992; Pichora-Fuller, Schneider, & Daneman, 1995; Watson & Foyle, 1985). Thus, deterioration of neurons in the central auditory nervous system potentially can limit frequency resolution for more complex signals, which may contribute to reduced speech-recognition performance. One goal of this study was to examine frequency resolution for complex stimuli by listeners with poor word recognition, to evaluate the possible effects of deterioration in central auditory mechanisms.

Temporal processing mechanisms may be located more centrally than the cochlea (Plomp, 1964; Shannon, 1993); therefore, deficits in auditory temporal processing may reflect dysfunction in central auditory processing. This notion has been supported by the finding that gap-detection abilities are compromised in listeners with lesions of the central auditory nervous system, especially the cortex (Shannon, 1993). In several studies, gap-detection abilities have been found to be affected by lesions as high as the cortex (Efron, Yund, Nichols, & Crandall, 1985; Robin, Tranel, & Damasio, 1990; Tanaka, Yamadori, & Mori, 1987). The effects of deterioration in central auditory mechanisms also may be revealed more readily on temporal-resolution measures that present stimuli of greater complexity. Thus, a second objective of this study was to examine temporal resolution for simple and complex stimuli by listeners with poor word recognition. Although temporal and spectral resolution for simple and complex stimuli have been examined previously for listeners with hearing loss (Green & Forrest, 1989; van Rooij, Plomp, & Orlebeke, 1989, 1990), they have not been examined previously among elderly listeners with poor word-recognition scores.

Some aspects of the speech-perception problem in question may also be cognitive in origin. Cognitive skills such as auditory attention, semantic processing, and dynamic working memory appear to be necessary to receive and understand a spoken message (CHABA, 1988; Pichora-Fuller et al., 1995). Age-related declines in cognitive skills have been reported (Fisk & Rogers, 1991; Jerger et al., 1989; McDowd & Filion, 1992). In addition, the effects of aging and hearing loss can compound cognitive difficulties. Neils, Newman, Hill, and Weiler (1991) found that when increased demands are made on the attention of elderly listeners with hearing loss, memory performance suffers. Possibly the reduced audibility of the speech signal in elderly listeners with hearing loss serves to increase the demands of the listening situation when distracting signals are also present.

In this investigation, the performance of elderly listeners with hearing loss and poor word-recognition performance was compared with that of elderly listeners with hearing loss and good word-recognition performance on a range of speech and nonspeech measures. Performance of elderly listeners with normal hearing was also evaluated to identify the extent of the effects of hearing loss on the performance measures. The auditory processing measures were derived with simple and complex stimuli and with simple and complex tasks; the speech-recognition measures were the Nonsense Syllable Test (NST; Resnick, Dubno, Hoffnung, & Levitt, 1975) in quiet and noise. The primary objectives of this study were as follows: (a) to determine whether elderly listeners with poor word-recognition performance differ from elderly listeners with good word-recognition performance on frequency resolution measures and temporal resolution measures; (b) to determine whether these two groups exhibit performance which differs from that of a comparison group with normal hearing; and (c) to identify the extent to which these psychoacoustic abilities contribute to syllable recognition.

METHOD

Participants

Twelve volunteers between the ages of 60 and 80 years were recruited for each of three elderly groups. The first group included listeners with pure tone thresholds within the normal range (≤20 dB HL, re: ANSI, 1996) from 500 to 4000 Hz and excellent word-recognition scores (WRS = 90%–100%) for the CID W-22 word lists in quiet (elderly normal, or EN, mean = 70 years, range = 60–78 years). The second group consisted of listeners with mild-to-moderate hearing loss and excellent WRS in quiet (elderly hearing-impaired with good word recognition, or EHIG, mean = 72 years, range = 64–79 years). The third group included listeners with mild-tomoderate hearing loss and poor WRS in quiet (<70%) (elderly hearing-impaired poor, or EHIP, mean = 73 years, range = 60–80 years). The hearing losses of participants in the second and third groups were of cochlear origin, as determined from normal tympanograms and acoustic reflexes elicited within the 90th percentile range for individuals with cochlear lesions (Silman & Gelfand, 1981). The audiometric thresholds of listeners in the EHIG and EHIP groups were matched within 10 dB on an individual basis at each frequency (see Table l). When a close match could not be made (in two cases), the listeners were selected such that those with the good WRS had poorer thresholds than those with the poor WRS. All of the listeners with hearing loss reported case histories suggesting a gradual, progressive hearing loss over a period of years. Three of the 12 listeners in the EHIG group and 4 of 12 listeners in the EHIP group showed some asymmetry in pure tone thresholds. None of these ear differences was greater than the amount of interaural attenuation for the Etymotic 3-A insert earphones used for all stimulus presentations, indicating

Table 1. Pure tone thresholds of elderly hearing-impaired subjects with good and poor word-recognition abilities.

	Pure tone thresholds (in dB HL)			
Subject ID	500 Hz	1000 Hz	2000 Hz	4000 Hz
EHIG-1	10	25	55	60
EHIP-12	10	30	50	70
EHIG-2	45	55	50	65
EHIP-4	55	55	60	75
EHIG-3	40	45	55	65
EHIP-10	35	45	45	65
EHIG-4	40	50	55	60
EHIP-1	35	50	60	60
EHIG-5	55	45	45	55
EHIP-7	45	45	55	65
EHIG-6	35	40	45	70
EHIP-5	25	50	55	65
EHIG-7	30	35	35	45
EHIP-2	30	40	45	50
EHIG-8	50	50	45	75
EHIP-9	25	45	45	45
EHIG-9	30	35	60	80
EHIP-6	15	49	55	70
EHIG-10	20	25	45	70
EHIP-8	10	25	45	55
EHIG-11	45	40	45	55
EHIP-3	50	50	50	50
EHIG-12	30	45	65	70
EHIP-11	20	35	60	60

Note. EHIG = elderly listeners with hearing impairment and good word-recognition scores. EHIP = elderly listeners with hearing impairment and poor word-recognition scores.

that crossover hearing from the nontest ear would not influence performance. All participants were high school graduates, who were in overall good health. Each participant demonstrated normal mental status as determined by the Portable Mental Status Questionnaire (Pfeiffer, 1975).

Preliminary testing included a complete audiological evaluation, consisting of pure tone threshold assessment, acoustic-immittance testing, and word-recognition testing in quiet at 95 dB SPL—a level chosen as the single level measurement most likely to represent maximum word-recognition score (Kamm, Morgan, & Dirks, 1983). The word-recognition test was the CID W-22 test (Auditec) because this test includes a proportion of words with consonant clusters that may be a clearer predictor of everyday speech-perception abilities than consonant-vowel-consonant (CVC) monosyllables used exclusively in other tests (CHABA, 1988). The elderly listeners with hearing loss were assigned to good and poor speech-perception groups according to results on word-recognition testing in quiet (W-22).

Speech Recognition Measures

Stimuli

Nonsense-syllable-recognition performance was assessed using the NST. This test has well-documented acoustic characteristics and test-retest reliability (Dubno, Dirks, & Langhofer, 1982; Resnick et al., 1975). Commercial tape recordings of the NST were used in the experiments (Cosmos Distributing, Inc.). The tape recordings included all seven subtests of the NST on one track and the cafeteria noise on the second track. The consonants within the seven subsets were chosen to represent the most common perceptual confusions among listeners with normal hearing and with hearing loss (Resnick et al., 1975).

Procedure

The NST was played back on a Marantz cassette tape player to a Madsen OB-822 audiometer and delivered to the listener monaurally through an Etymotic 3-A insert earphone. For the elderly listeners with normal hearing, the ear chosen for testing was the right ear or the ear with better pure tone thresholds. For listeners with hearing loss, the test ear was chosen such that the audiometric thresholds of the test ears of each pair of listeners from the EHIG and EHIP groups were matched as closely as possible. The speech level for the NST was set at 95 dB SPL to maximize audibility for each listener with hearing loss without exceeding the loudness discomfort level (Dirks, Kamm, Dubno, & Velde, 1981; Dubno & Dirks, 1982). The NST was presented in quiet and in noise at a signal-to-noise ratio (SNR) of +5 dB. Listeners identified the syllable presented from a closed set of choices, written in enlarged orthographic form, by circling their choice. The listeners were instructed to guess if they were uncertain of the syllable perceived. The test was presented in its entirety on the day of the initial audiological evaluation. Testing was conducted in a double-walled, sound-treated chamber for this and all subsequent experiments. For half of the subjects in each group, the quiet condition was presented before the noise condition. For the other half, the noise condition was presented first.

Frequency Resolution Measures

The frequency resolution abilities of listeners in each group were measured using the critical ratio, defined as the threshold for a 2000-Hz tone in a notched-noise background (Patterson et al., 1982). The notched-noise background consisted of a fixed level of bandlimited noise that featured an attenuation band, or spectral notch, centered at 2000 Hz. The critical ratio was measured in three conditions: a baseline condition, a condition with increased signal complexity, and a condition with increased task complexity.

Stimuli

For the baseline condition, the stimulus was a 2000- Hz sinusoid of 250 ms total duration that included 50 ms cosine-squared rise/fall envelopes. A 2000-Hz signal was chosen because of the high correlation (r = .80) between frequency resolution at this frequency and speech reception thresholds for sentences in noise (Horst, 1987). This tonal probe stimulus was mixed with a noise masker that featured a steep attenuation band (spectral notch) centered at the 2000-Hz probe frequency. The noise masker had an overall bandwidth of 2400 Hz and was constructed of two discrete bands (800 Hz–1400 Hz and 2600 Hz–3200 Hz), leaving a 1200-Hz attenuation band centered at the 2000-Hz probe frequency. This notch width of .6 times the 2000-Hz center frequency was selected to elicit optimal probe tone thresholds (Hall & Grose, 1991). The spectrum level of the masker was 50 dB/Hz outside the notch region, with a 250-ms duration (50-ms rise/fall times), that was simultaneous onset to offset with that of the probe tone.

A laboratory computer digitally constructed the stimuli and noise for this and all subsequent psychoacoustic experiments, using commercial software (Tucker- Davis Xperimenter). The digital signals and the noise were created with an array processor (TDT AP2) using an inverse Fast Fourier Transform routine. All frequencies and bandwidths of the stimuli and noises were confirmed on a spectrum analyzer (Nicolet, Model 446AR). The digitally generated and mixed stimuli were converted from digital to analog form by a 16-bit D/A converter with a 40-kHz sampling rate and low-pass filtered at 7000 Hz (Frequency Devices 901.F).

For a second condition, overall signal complexity was increased by presenting the notched-masker noise burst within a temporal sequence of four additional noise bursts that served as a distracting background context. The component noise bursts in sequence were temporally contiguous, each with a 250-ms duration that included 50-ms rise-fall envelopes. Additionally, the context noise bands featured constant spectrum levels within bandwidths of 2400 Hz, each with a different center frequency that was varied randomly between 1000 and 2000 Hz across trials within a listening block. For this condition, the spectrally notched noise band with tonal probe always occupied the third, or middle, sequence position in each listening trial.

A third condition was designed to increase the level of task difficulty. This condition used the same noise- band stimulus sequences as described above. Task difficulty was increased by allowing the notched noise band with tonal probe to occur in the second, third, or fourth sequence location on any given listening trial. The sequence location of this target noise burst was varied randomly over trials within a listening block.

Procedure

For each condition, tonal probe thresholds were measured using an adaptive two-interval forced-choice (2IFC) discrimination paradigm. The two intervals of a listening trial were spaced 500 ms apart, with one interval presenting the standard notched noise band without tonal probe and the other comparison interval containing the mixed combination of notched noise and tonal probe. The interval containing the probe tone occurred with equal probability in the first or second interval, and listeners selected this comparison interval using a keyboard response. For the baseline condition, the standard and comparison stimuli were the notched noise alone and the notched noise with probe tone, respectively. For the second condition of increased stimulus complexity using noise burst sequences, the notched- noise component was always fixed in the middle sequence location, without the tonal probe for the standard sequence, and mixed with the probe in the comparison sequence. Within the standard and comparison sequences, center frequencies of the context noise bursts without spectral notches varied randomly across intervals of a trial and trials of a listening block. The third condition of increased task difficulty was the same as the second condition, except the notched-noise sequence component, alone or mixed with probe, varied randomly across listening trials among second, third, or fourth sequence locations. For conditions presenting noise-burst sequences, listeners were informed about the possible sequence locations(s) of the target component. Intervals of a listening trial were marked by visual display on a computer monitor that also provided correct- response feedback with each trial.

For each condition, probe-tone thresholds were measured using an adaptive rule for intensity change, which dictated that probe level was decreased following two consecutive correct-response trials and increased in level subsequent to each incorrect response. The procedure was used to track a threshold probe level corresponding to 70.7% correct discrimination (Levitt, 1971). All variations in probe level were performed digitally in a trial-by-trial stimulus construction. For each condition, each block of listening trials commenced using a suprathreshold probe level of 85 dB SPL and an initial step-size for level change of 8 dB that was reduced to 2 dB following three reversals in level change. A threshold estimate for each block of trials was calculated as an average of the even-numbered reversal-point level values associated with the 2-dB step-size. Several experimental runs were conducted for each condition, along with a running average of the most recent three threshold estimates. Once the running averages stabilized within a range of 10%, a final threshold estimate was taken as the most recent three-value average. This average value was then used to calculate a critical ratio as the difference between probe level and the 50-dB spectrum level of the noise masker outside the spectral notch.

Temporal Resolution Measures

Temporal resolution abilities of the listener groups were assessed by measuring the threshold for the detection of a silent interval, or gap, that was presented between two tone bursts. The baseline condition consisted of a simple detection measure for a gap embedded between two tone bursts, each of which varied randomly in frequency from 1000 Hz to 2000 Hz. In a second condition, signal complexity was increased in order to examine the effect of increased processing demands upon the gap-detection ability of each listener by including a sequence of five tone bursts of varying frequency, with the gap located consistently between the second and third tone burst. In the third condition, task difficulty was increased by randomizing the location of the gap within the sequence of five tone bursts, in order to examine the effects of increased task demands on the gap- resolution ability of each listener.

Stimuli

Gap thresholds were measured using the same 2AFC procedure as described for the critical ratio measures. For the baseline condition, the stimuli consisted of two sequential tone bursts, each of which varied randomly in frequency within a range of 1000–2000 Hz over trials within a listening block. Duration of each tone burst also was varied randomly within a block of listening trials between 200 and 300 ms to avoid the inclusion of overall duration as a target cue. Tonal component durations included 2-ms rise/fall times. The stimuli were presented at a suprathreshold level of 85 dB SPL. In the standard interval, the two tones were presented sequentially, with no interstimulus interval. In the comparison interval, the second tone burst of a pair had a varied delay time that effectively created a zero-amplitude interval that defined the temporal gap.

For a second condition, overall stimulus complexity was increased by presenting five sequential, contiguous pure tones, each of which varied randomly in frequency (1000–2000 Hz) over a block of trials. All tones in a sequence were varied individually in duration between 200 ms and 300 ms, including the 2-ms rise-fall envelope, over a block of trials. The third tone in the comparison tonal sequence incorporated the delay time to create a gap for the comparison listening interval. The standard stimuli incorporated no delay time and therefore no gap in the sequence of tones.

A third condition was designed to increase the level of task difficulty. This condition used the same tone sequences as described above. Task difficulty was increased by allowing the delay time that created the gap to occur at the beginning of one of the second, third, or fourth tones of the series of five for the comparison listening interval. The specific location of the gap was varied randomly over trials within a listening block.

Procedure

For each condition, gap thresholds were measured using an adaptive 2IFC paradigm, as described in the critical ratio procedure. One interval presented the standard tone pair without a gap, and the comparison interval contained the tone pair with a gap. The gap occurred with equal probability in the first or second interval of a given trial, and listeners selected this comparison interval using a keyboard response. Listeners received correct/incorrect feedback following each trial. For the baseline condition, the standard stimulus without the gap and the comparison stimulus with the gap were each tone-burst pairs; tones of each pair varied randomly in frequency and duration. For the second condition of increased signal complexity, the standard and comparison tonal sequences varied in both frequency and duration components, with the gap created by a delay in the third tone of the sequence for the comparison interval. Listeners were told that the position of the target gap within the sequence of tones was located before the third tone. The third condition, involving increased task difficulty, was the same as the second condition except that the location of the gap varied randomly across listening trials among second, third, and fourth tonal locations. Listeners were told that target position could vary, and they were instructed to choose the interval that contained a gap in the tonal sequence.

For each condition, the adaptive rule for threshold measurements dictated that gap duration be decreased following two consecutive correct-response trials and increased following each incorrect response. Each block of listening trials began with an 80-ms gap and used an initial 10-ms step size for gap changes; this was reduced to 1 ms after the first three reversals. A threshold for the trial run was defined as the average of the data from the last even-numbered reversal-point values associated with the l-ms step size. Successive trial-run threshold estimates for the baseline condition were collected with running averages of the most recent three estimates taken until these averages stabilized within a range of 10%. A final gap threshold was then taken as the most recent running average. The final threshold for the complex signal and complex task conditions was the average of performance on three runs.

A complete set of frequency and temporal resolution conditions was accomplished in two 2-hour sessions. For training purposes, the basic resolution task (frequency or temporal) was presented first, with the two more complex versions of the stimuli and task presented in a counterbalanced order in four schedules. Breaks were provided every half hour. For half the listeners in each group, the frequency resolution conditions were conducted before beginning the temporal resolution conditions. For the other half of the subjects, the temporal resolution conditions were conducted first. All listening was monaural through an insert earphone (ER-3A), calibrated in a 2cm3 coupler (B&K, DB 0138).

RESULTS

N ST Scores

The mean percent-correct nonsense syllable recognition scores and standard deviations, obtained in quiet and noise, from the three groups are shown in Figure l. The percent-correct scores of the individual participants in each condition were converted to rationalized arcsine units (RAU; Studebaker, 1985). The RAUs were used as the dependent variable for a repeated measures analysis of variance (ANOVA), with listener group as a between-subjects variable and NST condition (quiet or noise) as the within-subjects variable. The resulting ANOVA showed significant main effects of subject group [$F(2, 33) = 36.79$, $p < .0001$] and NST condition [$F(l, 33) = 136.52$, $p < .0001$] and a significant interaction of group by condition [$F(2, 33) = 5.03$, $p < .01$].

Tests of simple main effects showed that the group effect was significant for both quiet and noise conditions and that there was a significant difference in performance between quiet and noise conditions for all groups ($p < .0001$). Multiple comparison tests (StudentNewman-Keuls) showed that when listening in quiet, the listeners with normal hearing performed better than the two listener groups with hearing loss. In addition, the elderly listeners with hearing loss and good word- recognition scores performed better than those with poor word-recognition scores ($p < .01$). Multiple comparison tests examining group effects in the noise condition showed that the listeners with normal hearing performed better than the two listener groups with hearing loss. However, a significant difference in performance

Figure 1. Mean NST scores and standard deviations of the three listener groups, in quiet and noise (EN = elderly normal, EHIG = elderly listeners with hearing impairment and good word-recognition scores, EHIP = elderly listeners with hearing impairment and poor word-recognition scores).

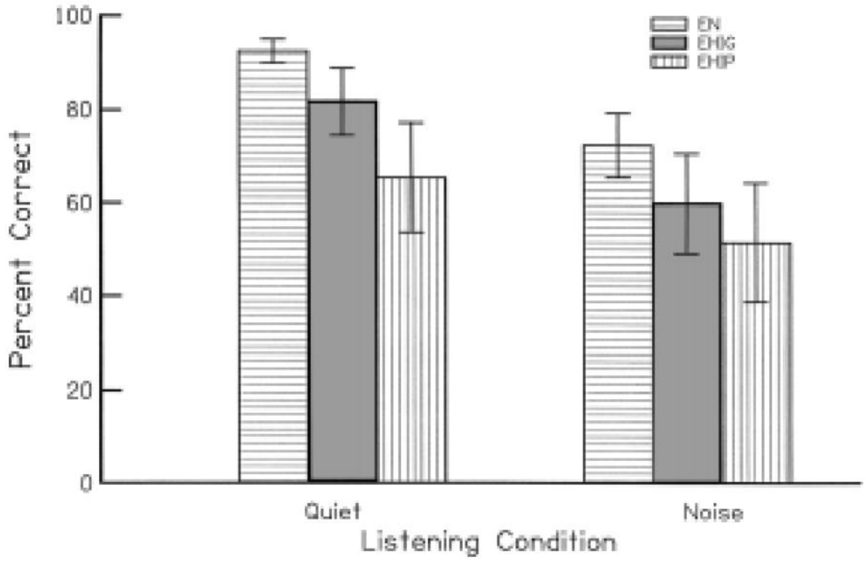
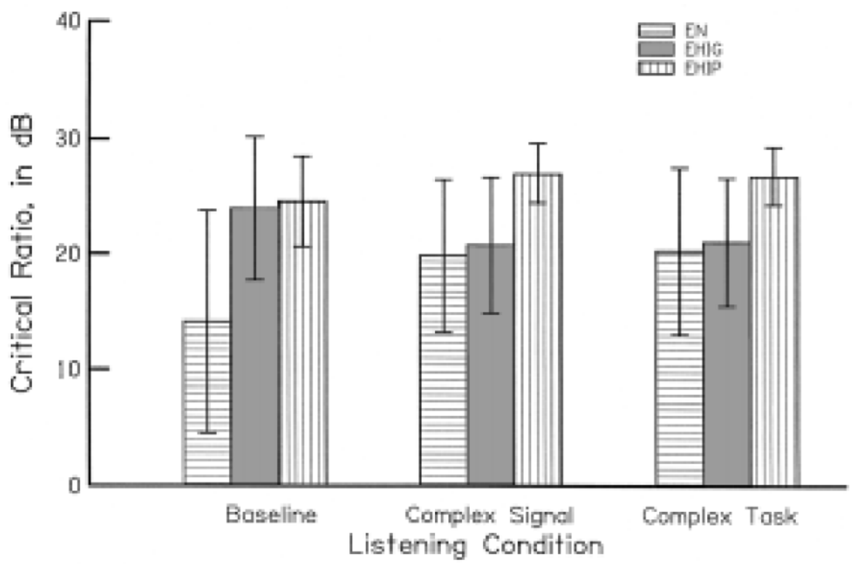


Figure 2. Mean critical ratios and standard deviations of the three listener groups in three listening conditions (EN = elderly normal, EHIG = elderly listeners with hearing impairment and good word- recognition scores, EHIP = elderly listeners with hearing impairment and poor word-recognition scores).



was not observed in the noise condition between the two listener groups with hearing loss.

Critical Ratios

The mean critical ratios and the standard deviations of all three groups in the three stimulus conditions are shown in Figure 2. A split-plot factorial design ANOVA was used with one between-subjects factor (group) and one within-subjects factor (signal condition) (Shavelson, 1988). The results showed a significant group effect [$F(2, 33) = 7.11$, $p < .003$] and a significant interaction between group and condition [$F(4, 66) = 6.29$, $p < .0002$]. The main effect of condition was not significant [$F(2, 66) = 2.99$, $p > .05$].

Tests of simple main effects showed that the listener groups performed differently in all three stimulus conditions. Multiple comparison tests (Student-Newman-Keuls) indicated that listeners with normal hearing performed better than the two groups of listeners with hearing loss on the baseline critical ratio measure. In addition, listeners with hearing loss and good WRS performed significantly better than those with poor WRS on the frequency resolution tasks involving increased signal complexity and increased task complexity ($p < .05$). There was also a significant condition effect for listeners with normal hearing only, in which performance was better for the baseline condition than for the two complex conditions.

Gap Detection

The mean gap-detection thresholds and standard deviations for all three groups in the three gap-detection conditions are shown in Figure 3. An ANOVA using the split-plot factorial design showed significant main effects of group [$F(2, 33) = 10.85$, $p < .0002$] and condition [$F(2, 66) = 3.87$, $p < .03$]. The interaction between group and condition was not significant [$F(4, 66) = .423$, $p > .05$].

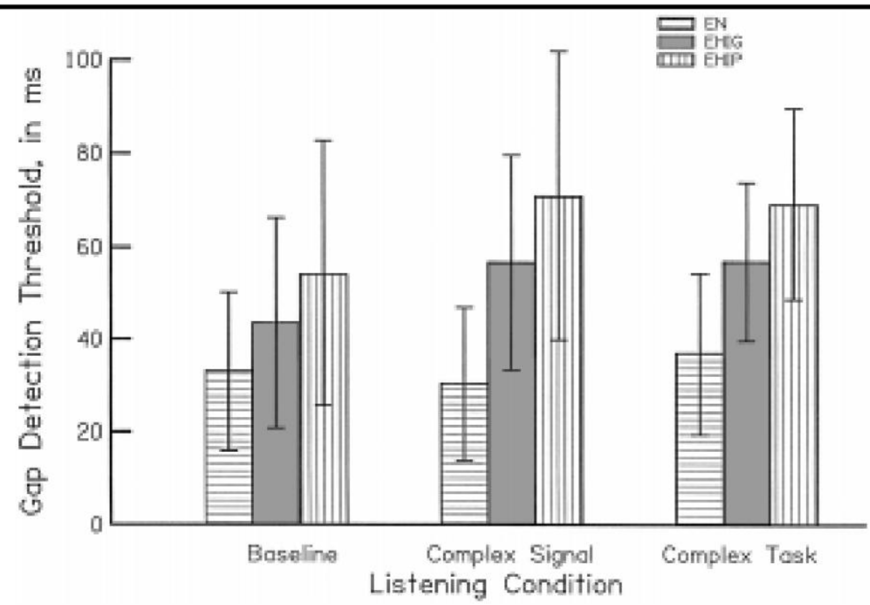
Multiple comparison tests (Stu dent-Newm an -Keuls) examing the group effect showed that listeners with normal hearing performed better than listeners with hearing loss ($p < .05$). However, there were no significant differences in gap-detection thresholds between the two groups with hearing loss. Analysis of the condition effect indicated that temporal resolution was better for the baseline condition than the two conditions involving multiple signals and randomized targets ($p < .05$).

Relationships Among Syllable Recognition, Critical Ratio, and Gap Detection

Stepwise multiple linear regression analyses were performed to determine which of the temporal and frequency resolution measures were associated with performance on syllable recognition. Two multiple regression analyses were performed: one in which the NST scores in quiet served as the criterion variable and one in which the NST scores in noise served as the criterion variable. The data of all listener groups were included in the analysis. Because of the multicollinearity of several of the possible predictor variables, the independent variables submitted to the analysis were reduced to the following three measures: (l) high frequency pure tone average (1000, 2000, and 4000 Hz, PTA), (2) one gap detection measure (complex task), and (3) one critical ratio measure (complex task). The multiple regression analysis for the NST in quiet retrieved only one significant predictor variable, the PTA, which accounted for 56% of the variation in scores ($p < .0001$). Similarly, for the NST presented in noise, there was one significant predictor; PTA accounted for 35% of the variation in scores ($p < .0001$) and was the only significant predictor variable retrieved in the analyses.

PTA was removed from the analysis to examine further the relationship between temporal and spectral measures. With PTA removed, the NST in quiet showed that the critical ratio within a complex signal and in a

Figure 3. Mean gap-detection thresholds and standard deviations (in ms) of the three listener groups in three listening conditions (EN = elderly normal, EHIG = elderly listeners with hearing impairment and good word-recognition scores, EHIP = elderly listeners with hearing impairment and poor word-recognition scores).



complex task accounted for 18% of the variation in scores ($p < .04$). For the NST in noise, the only significant predictor variable retrieved was baseline gap detection, which accounted for 19% of the variation in scores ($p < .03$).

DISCUSSION

Performance on Critical Ratio Measures

Critical ratios derived in the baseline condition showed that listeners with hearing loss have poorer frequency resolution than listeners with normal hearing, as shown previously (Glasberg & Moore, 1986; Hall & Fernandes, 1983; Horst, 1987). The range of critical ratios exhibited by the elderly listeners with hearing loss in the present study is similar to the results found for elderly listeners by Patterson, Nimmo-Smith, Weber, and Milroy (1982). However, Patterson et al. did not report the hearing sensitivity of their participants, which limits direct comparisons across studies. Listeners with hearing loss and poor WRS in the current study performed similarly to those with good WRS in the baseline measure, suggesting that listeners with poor word-recognition scores have no greater deficit in basic frequency resolution abilities beyond those demonstrated by other listeners with hearing loss.

Listeners with poor WRS showed larger critical ratios than the other listener groups when signal complexity and task complexity were increased. This suggests that elderly listeners who exhibit poor speech recognition also have difficulty with spectral resolution of complex signals and spectral resolution in complex tasks. However, there were no performance differences for this group between the complex task and the complex signal condition, suggesting that the additional demands of task difficulty do not produce excessive performance decrements, at least for the stimuli used in the present experiments.

Performance on Gap-Detection Measures

Elderly listeners with normal hearing performed better than elderly listeners with hearing loss on the gap-detection measures, but performance differences were not observed between the two listener groups with hearing loss. Many of the listeners demonstrated gap thresholds above 40 ms, including two listeners with normal hearing. This outcome is probably due to the increased difficulty of detecting a gap between tones of varying frequency (Fitzgibbons & Gordon-Salant, 1994; Formby & Forrest, 1991). Schneider, Pichora-Fuller, Kowalchuk, and Lamb (1994) found that gap detection thresholds between tone bursts that varied in frequency were four times longer than thresholds between tone bursts of the same frequency for young listeners with normal hearing. In the present experiment, bordering tones varied in both frequency and duration, creating a rather complex task in the baseline gap-detection condition. When compared with results found by Fitzgibbons and Gordon-Salant for elderly listeners with normal hearing and hearing loss for tones that shifted in frequency in a consistent manner across trials, gap-detection thresholds for the current experiment were longer for both normal-hearing listeners and those with hearing loss.

The current results suggest that elderly listeners with hearing loss have decreased temporal resolution, compared to elderly listeners with normal hearing. However, the temporal resolution measures used in the present experiments failed to distinguish the performance of older hearing-impaired listeners with good and poor word recognition. Given these findings, poor temporal resolution does not appear to be the principal source of the excessive word-recognition deficits of the experimental group. Temporal resolution performance did account for a small proportion of the variance (<20%) in NST performance in noise for all three groups combined. These results suggest that limitations in temporal resolution of elderly listeners appear to contribute to some of the older listeners' difficulties with syllable recognition in noise.

Performance on the NST

Listeners with normal hearing performed better than the listeners with hearing loss on the NST presented in quiet and noise. This performance pattern is in agreement with previous results (Gelfand, Piper, & Silman, 1986). Listeners with poor WRS performed more poorly than those with good WRS in quiet, a finding that was expected because the listeners in these two groups were selected for their speech-recognition abilities.

As expected, all groups performed more poorly in noise than in quiet. However, listeners with good and poor word-recognition abilities did not exhibit differences in nonsense-syllable recognition scores in noise. One possible explanation for this performance pattern is that listeners with poor WRS are experiencing some sort of internal, or central, neural interference or "noise." This internal noise would interfere with the ability to process speech in quiet. The addition of external noise would add only minimally to the interference provided by the internal noise. This theory has been suggested previously by Novak and Anderson (1982) to explain their findings that listeners with poor WRS were less affected by noise on an MLD measure than listeners with good WRS. Validation of this theory is difficult because the internal noise threshold of a listener cannot be observed directly with behavioral measures.

General Interpretation

The present findings indicate that elderly listeners with hearing loss and reduced word-recognition ability have more difficulty processing complex nonspeech stimuli in the spectral domain than elderly listeners with hearing loss and minimal word-recognition difficulties. Because the two groups with hearing loss did not perform differently on the baseline critical ratio measure, the findings for complex stimuli suggest that the problem may exceed deficits attributed exclusively to the auditory periphery. One possibility is that more extensive deterioration of neural units in N VIII and/or the pathways and nuclei of the central auditory nervous system occurs in listeners with poor WRS and prevents the extensive coding and recoding that is necessary for accurate resolution of complex stimuli. The implication is that difficulties with frequency resolution for other complex stimuli, such as speech, would result in a distorted signal's being sent to the auditory cortex. Moreover, the deterioration of neural units has been modeled as an increase in neural noise (Talland, 1968). As a consequence, the effects of additional external interference, in the form of background noise, predictably would increase the resulting distortion of speech only marginally. The current results for the NST support this notion because listeners with poor WRS showed no performance shifts from quiet to noise conditions, unlike listeners with good WRS.

An alternative interpretation of the present findings derives from more cognitive processing theories. Extraction of a signal from background noise may be seen as an act of selective attention. Selective attention has been hypothesized to require two processes: the selection of relevant information and the inhibition of irrelevant information (McDowd & Filion, 1992). The difficulty experienced by these listeners may be with selection of relevant information or feature extraction and processing. A lack of fidelity in the processing of the signal because of loss of neurons may place these listeners at a disadvantage for tracking and selective attention when competing stimuli are providing alternative messages.

If selective feature processing is problematic for some listeners, it would put them at a disadvantage for focused attention on a target signal in multiple-signal experiments where the target-signal location is consistent within the series. In experiments with visual targets, this is called feature learning, which allows the listener to focus attention on the target signal within a visual array in a consistent search condition (Rogers, 1992). In the present critical ratio experiments, the elderly listeners with poor WRS may have been unable to focus attention specifically on the 2000-Hz probe tone. Nevertheless, the present findings argue against a global cognitive processing deficit in elderly listeners with poor word recognition, because these listeners did not exhibit excessive difficulty in the more complex gap-detection conditions. A cognitive deficit is expected to be revealed on complex tasks, regardless of the specific attribute to be discriminated.

The principal finding of this study was that elderly listeners with hearing loss and poor word-recognition abilities have significantly poorer frequency resolution for complex signals and for signals in complex tasks than elderly listeners with either hearing loss and good word-recognition abilities or with normal hearing. In addition, listeners with hearing loss and poor word-recognition abilities do not perform more poorly on a consonant-recognition task in noise than those with good word-recognition abilities. Future research is needed to determine whether listeners with poor WRS also have difficulty with discrimination of differences in the spectral characteristics of a complex signal. This would have implications for the listener's use of formant cues to understand speech. In addition, closer examination of consonant recognition and discrimination abilities might reveal the extent to which listeners with hearing loss and poor word-recognition scores are able to make use of complex spectral cues in consonant recognition.

Acknowledgments

Preparation of this article was supported in part by Grant No. R01-AG09191 from the National Institute on Aging, National Institutes of Health. Data were collected at the University of Maryland, College Park. We would like to thank Willard Larkin for helpful comments and support.

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