Speech reception thresholds in noise with and without spectral and temporal dips for hearing-impaired and normally hearing people

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People with cochlear hearing loss often have considerable difficulty in understanding speech in the presence of background sounds. In this paper the relative importance of spectral and temporal dips in the background sounds is quantified by varying the degree to which they contain such dips. Speech reception thresholds in a 65-dB SPL noise were measured for four groups of subjects: (a) young with normal hearing; (b) elderly with near-normal hearing; (c) young with moderate to severe cochlear hearing loss; and (d) elderly with moderate to severe cochlear hearing loss. The results indicate that both spectral and temporal dips are important. In a background that contained both spectral and temporal dips, groups (c) and (d) performed much more poorly than group (a). The signal-to-background ratio required for 50% intelligibility was about 19 dB higher for group (d) than for group (a). Young hearing-impaired subjects showed a slightly smaller deficit, but still a substantial one. Linear amplification combined with appropriate frequency-response shaping (NAL amplification), as would be provided by a well-fitted ''conventional'' hearing aid, only partially compensated for these deficits. For example, group (d) still required a speech-to-background ratio that was 15 dB higher than for group (a). Calculations of the articulation index indicated that NAL amplification did not restore audibility of the whole of the speech spectrum when the speech-to-background ratio was low. For unamplified stimuli, the SRTs in background sounds were highly correlated with absolute thresholds, but not with age. For stimuli with NAL amplification, the correlations of SRTs with absolute thresholds were lower, but SRTs in backgrounds with spectral and/or temporal dips were significantly correlated with age. It is proposed that noise with spectral and temporal dips may be especially useful in evaluating possible benefits of multi-channel compression. © *1998 Acoustical Society of America.* [S0001-4966(97)04812-1]

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INTRODUCTION

People with cochlear hearing impairment often complain that their greatest problem is understanding speech when background noise is present. This problem is often quantified in the laboratory by estimating the speech-to-noise ratio required to achieve a given level of intelligibility, such as 50%. We will refer to this ratio as the Speech Reception Threshold (SRT), and will express it in decibels (dB).

For people with moderate to severe cochlear losses, the SRT typically is higher than for normally hearing people. In other words, the hearing impaired need a higher signal-to-noise ratio to achieve the same level of performance. However, the difference in SRT for normal and hearing-impaired people varies greatly depending on the nature of the background sound. When the background sound is a steady noise with the same long-term average spectrum as the speech (called speech-shaped noise), the difference is typically in the range 2–5 dB (Glasberg and Moore, 1989; Plomp, 1994). This represents a substantial deficit, since intelligibility in this situation worsens by 11% to 19% for each 1-dB decrease in speech-to-noise ratio (Plomp and Mimpen, 1979; Laurence *et al.*, 1983; Moore *et al.*, 1992; Nilsson *et al.*, 1994). When the background is a single competing talker (Carhart and Tillman, 1970; Duquesnoy, 1983; Hygge *et al.*, 1992; Moore *et al.*, 1995), a time-reversed talker (Duquesnoy, 1983), or an amplitude-modulated noise (Duquesnoy, 1983; Takahashi and Bacon, 1992; Eisenberg *et al.*, 1995), the difference in SRT between normal and hearing-impaired people can be much larger, ranging from about 7 dB up to about 15 dB. This represents a very large deficit indeed. At signal-to-background ratios where normally hearing people would achieve almost 100% intelligibility, hearing-impaired people may be understanding almost nothing. Thus, the problems faced by hearing-impaired people, in comparison to normally hearing people, are much greater when the background sound is a single talker than when it is a steady speech-shaped noise.

Normally hearing people achieve markedly lower SRTs in a background of a single talker than in a background of speech-shaped noise, whereas hearing-impaired people do not (Duquesnoy, 1983; Festen, 1987a, b; Festen and Plomp, 1990; Hygge *et al.*, 1992; Moore *et al.*, 1995). The relatively poor performance of hearing-impaired people when listening in a background of a single talker appears to arise from a failure to take advantage of ''dips'' in the competing voice. These dips may be of two types: temporal and spectral. The temporal dips arise because there are moments when the overall level of the competing speech is low, for example during brief pauses in the speech or during production of low-energy sounds such as m, n, k, or p. During these temporal dips the signal-to-background ratio is high, and this allows brief ''glimpses'' to be obtained of the target speech. The spectral dips arise because the spectrum of the target speech is usually different from that of the background speech measured over any short interval. Although parts of the target spectrum may be completely masked by the background, other parts may be hardly masked at all; the signal-to-background ratio may often exceed 20 dB. Thus, parts of the spectrum of the target speech may be ''glimpsed'' and used to infer the structure of the complete speech sound.

The reasons why hearing-impaired people fail to take advantage of the dips in the background noise are not clearly understood. Specifically, it is not clear whether the problem arises mainly from a failure to take advantage of temporal dips or from a failure to take advantage of spectral dips. People with cochlear hearing loss generally show impaired temporal resolution for stimuli with slowly fluctuating envelopes which would lead to a reduced ability to take advantage of temporal dips (Festen, 1987a, b; Glasberg *et al.*, 1987; Moore and Glasberg, 1988b; Festen and Plomp, 1990; Glasberg and Moore, 1992; Festen, 1993; Moore, 1995). They also show reduced frequency selectivity, which would lead to a reduced ability to take advantage of spectral dips (Glasberg and Moore, 1986; Tyler, 1986; Moore, 1995).

The main goal of this paper is to clarify and quantify the relative importance of spectral and temporal processing for the ability to understand speech in background sounds with temporal and spectral dips, such as a single competing talker. This was done by measuring SRTs in several background sounds, which varied in the extent to which they contained temporal dips, spectral dips, or a combination of the two. Both normally hearing and hearing-impaired subjects were used. In experiment 1, the stimuli were presented without any frequency response shaping. In experiment 2, the hearing-impaired subjects were tested with a frequency-gain characteristic corresponding to the National Acoustics Laboratories' recommendation (Byrne and Dillon, 1986).

I. EXPERIMENT 1

A. Method

1. Subjects

Four groups of subjects were tested:

(a) Ten young subjects (mean age 25.1 years, s.d. 3.3 years) with normal hearing. The absolute thresholds of all subjects were better than 20 dB HL at all of the standard audiometric frequencies (125, 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz) and average thresholds were close to 0 dB HL.

(b) Eleven elderly subjects (mean age 74.1 years, s.d. 3.2 years) with near-normal hearing for frequencies up to 4 kHz. The mean absolute thresholds for this group were 9.5, 9.1, 11.4, and 21.0 dB HL for the frequencies 500, 1000, 2000, and 4000 Hz, respectively. Two of these subjects had hearing losses greater than 30 dB at 4 kHz. Excluding these two subjects, the mean absolute threshold at 4 kHz was 17.4 dB HL. The data for this group were analyzed both including and excluding these two subjects. Most of the 11 subjects had mild losses (10–45 dB) at frequencies above 4000 Hz.

(c) Six young hearing-impaired subjects (mean age 29.2 years, s.d. 9.4 years). Five had moderate to severe cochlear hearing loss and one (S4) had only a mild loss. The data for this group were analyzed both including and excluding the subject with a mild loss.

(d) Ten elderly subjects (mean age 76.5 years, s.d. 4.2 years) with moderate to severe cochlear hearing loss.

The elderly subjects were all alert, able to follow instructions, and able to concentrate. The audiograms of the subjects in groups (c) and (d) are shown in Fig. 1.

2. Stimuli

The speech materials used were the sentence lists recorded at the House Ear Institute in Los Angeles (the Hearing in Noise Test—HINT) (Nilsson *et al.*, 1994). The following background sounds were used:

(1) A steady speech-shaped noise with the same long-term average spectrum as the target speech (referred to as HINT noise). This provided a reference condition against which SRTs in other types of noise can be compared. The spectrum of this noise is shown by the dashed line in Fig. 2.

(2) A single competing female talker. This sound was taken from a compact disc (CD) of test sounds recorded by ReSound Corporation. The passage lasts approximately 1 min. For our tests, the sample was recycled, to give a continuous sample about 7 min in length. This background has both spectral and temporal dips, as described earlier. The speech was digitally filtered so that its long-term average spectrum matched that of the HINT noise. The result is shown as the solid line in Fig. 2.

(3) A noise with the same spectrum as the HINT noise, but with the overall temporal fluctuations of the single talker. This was achieved by extracting the envelope of the speech of the single female talker, and imposing that envelope on the HINT noise. The envelope was extracted by calculating the root-mean-square amplitude of the speech in a 10-ms-long sliding temporal window. We refer to this noise as ''noise modulated by speech.''

(4) Steady HINT noise filtered so as to have spectral dips in several frequency regions. The filtering was based on the equivalent-rectangular-bandwidth (ERB) scale derived from the auditory filter bandwidths for normally hearing subjects (Glasberg and Moore, 1990). Each ERB represents one auditory filter bandwidth. The relationship between number of ERBs and frequency is

$$\text{ERB number} = 21.4 \log_{10}(4.37F + 1), \qquad (1)$$

where F is frequency in kHz.

The noise was filtered in a number of ways:

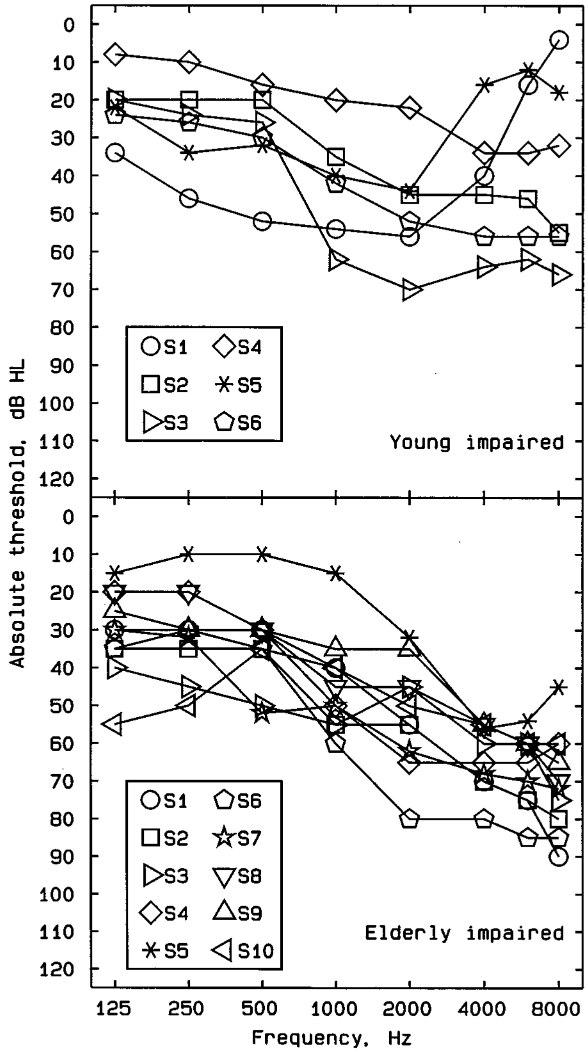

FIG. 1. Audiograms for each subject in the young hearing-impaired group (top) and the elderly hearing-impaired group (bottom).

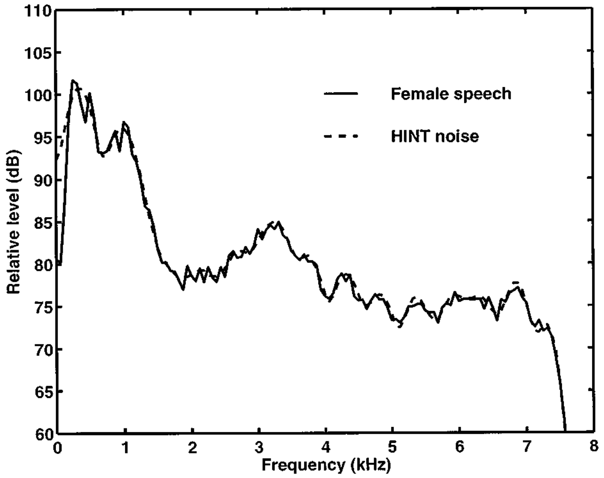

FIG. 2. The dashed line shows the long-term average spectrum of the HINT noise. The solid line shows the long-term average spectrum of the female talker after filtering to match the spectrum to that of the HINT noise.

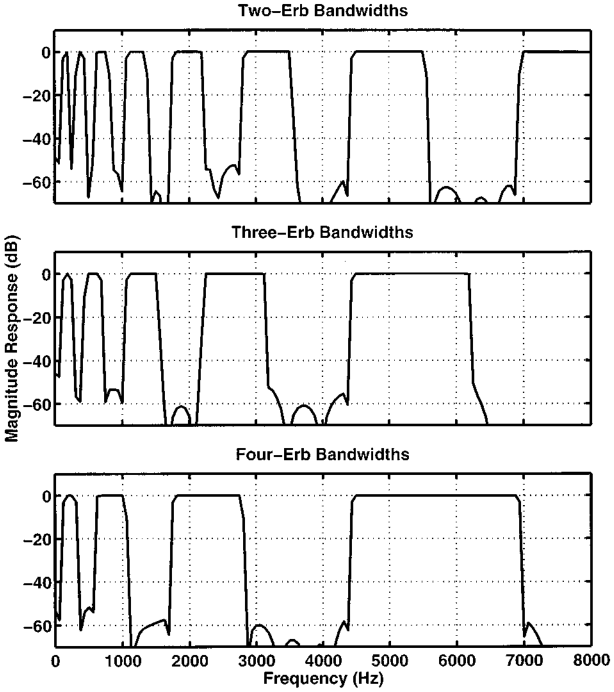

FIG. 3. Characteristics of the digital filters used to produce the noises with multiple spectral notches.

(a) with an alternating pattern of two ERBs present and two ERBs removed,
(b) with an alternating pattern of three ERBs present and three ERBs removed, and
(c) with an alternating pattern of four ERBs present and four ERBs removed.

The characteristics of the digital filters used are illustrated in Fig. 3. The filters were designed using the function fir2 in MATLAB (Krauss *et al.*, 1994) with an *n* of 800. Prior to filtering, the last 400 samples of the source file were appended to its beginning, and the first 400 samples were appended to its end. After filtering, the first 800 samples were discarded, eliminating both filtering onset transients and delays. We anticipated that normally hearing subjects should be able to take advantage of the relatively narrow spectral dips in the noise with 2-ERB spectral gaps. However, hearing-impaired subjects generally have reduced frequency selectivity and so we thought that they might not be able to take advantage of the spectral dips until they became relatively wide (spectral gaps of three and four ERBs).

(5) A noise with both spectral and temporal dips obtained by applying the temporal envelope of a single talker to a speech shaped noise [as in (3)] and then filtering that noise [as in (4)].

The overall level of backgrounds (1)–(3) was always the same for a given subject (usually 65 dB SPL). For backgrounds (4) and (5), the spectrum level of the noise in the passbands of the digital filters was left the same as for the original HINT noise. Thus, the overall level of the noise was slightly reduced by the filtering (by about 3 dB). This was done so that we could examine benefits of removing part of the background spectrum without the confounding effect of increases in level of the remaining part of the spectrum.

TABLE I. Mean SRTs in quiet and in various masking conditions for the four groups of listeners. The SRTs in quiet are expressed as level in dB SPL. The SRTs for the masking conditions are expressed as speech-to-background ratios in dB. A smaller number indicates better performance. Numbers in parentheses are standard deviations across subjects. For the older subjects with near-normal hearing, the upper numbers refer to results for the whole group and the lower numbers refer to results excluding two subjects whose absolute thresholds at 4 kHz exceeded 30 dB HL. For the young hearing-impaired subjects, the upper numbers refer to results for the whole group and the lower numbers refer to results excluding one subject with a mild loss.

	Young normal hearing $N=10$	Older normal hearing $N=11$ $(N=9)$	Young hearing impaired $N=6$ $(N=5)$	Older hearing impaired $N=10$
Speech in quiet	19.7 (2.2)	29.9 (3.8) 29.8 (3.5)	51.8 (10.3) 55.0 (8.0)	57.5 (5.9)
Steady noise masker	−3.8 (2.0)	−2.0 (1.9) −2.2 (2.1)	−1.4 (3.0) −0.6 (2.5)	2.5 (2.2)
Single voice masker	−11.9 (2.8)	−7.7 (2.9) −8.2 (2.9)	−6.1 (3.7) −4.7 (0.9)	0.8 (2.8)
Noise modulated by speech	−10.0 (2.5)	−6.3 (2.2) −6.9 (1.9)	−4.1 (3.3) −2.8 (1.2)	1.5 (1.9)
Noise with two-ERB gaps	−12.5 (1.9)	−8.9 (2.1) −9.4 (2.1)	−6.1 (3.2) −5.1 (2.1)	−0.4 (1.5)
Noise with three-ERB gaps	−16.1 (1.9)	−10.9 (3.1) −11.6 (3.0)	−6.6 (2.8) −5.7 (1.9)	−1.1 (1.4)
Noise with four-ERB gaps	−18.7 (1.7)	−12.6 (2.1) −13.0 (2.1)	−7.1 (2.7) −6.2 (1.8)	−2.1 (1.7)
Modulated noise with two-ERB gaps	−16.5 (1.8)	−12.3 (4.2) −13.5 (3.6)	−7.1 (2.7) −6.0 (0.7)	−1.8 (2.4)
Modulated noise with three-ERB gaps	−17.9 (2.9)	−13.7 (3.2) −14.5 (2.7)	−6.4 (4.6) −5.0 (3.2)	−2.0 (1.8)
Modulated noise with four-ERB gaps	−22.6 (2.6)	−15.7 (2.9) −16.5 (2.5)	−8.5 (3.7) −7.2 (2.3)	−3.1 (2.5)

tBackground sounds (2)–(5) were produced by digital processing using a Silicon Graphics Indy computer. All processing was done using a 16-kHz sampling rate and floating point arithmetic. When processing was complete, samples were converted to 16-bit integers and up-sampled to a 44.1-kHz rate. They were transferred digitally to recordable compact disc (CDR) for use in the experiment. The speech was played back from digital audio tape (DAT). The target speech and background sounds were independently amplified and their levels were controlled by independent manual attenuators. The outputs of the attenuators were mixed using an active mixer. The stimuli were presented to the better hearing ear, or to the left ear if the audiograms were very similar for the two ears, using Sennheiser HD 424 earphones, which have a ''diffuse field'' response.

For the young normally hearing subjects and the elderly subjects with near-normal hearing, backgrounds (1)–(3) were presented at an overall level of 65 dB SPL, which is close to the level of normal conversational speech [as described above, backgrounds (4) and (5) had slightly lower overall levels]. For the hearing-impaired subjects the level of presentation depended on the SRT in quiet. If the SRT in quiet was 55 dB SPL or less, then the presentation level was 65 dB SPL. If the SRT in quiet was greater than 55 dB SPL, the presentation level was the SRT in quiet plus 10 dB.

3. Procedure

An adaptive procedure was used to estimate the SRT in each background noise. The SRTs for speech in quiet were also measured. The adaptive procedure was as recommended for use with the HINT materials (Nilsson *et al.*, 1994). Each SRT reported is based on the use of two complete lists. Prior to testing, practice was given with the steady noise background, the background with four-ERB spectral dips, and the background with four-ERB spectral dips and temporal dips, using lists 26–28. Testing started with measurement of SRTs in quiet. Then the conditions with background noise were tested, using a different randomized order for each subject. Subjects were seated in a single-walled sound-attenuating booth situated within the testing room. Subjects communicated with the tester via a microphone located in the sound-attenuating chamber.

B. Results

The results obtained are summarized in Table I. The SRTs in quiet are expressed as level in dB SPL. The SRTs in background sounds are expressed as signal-to-background ratios in dB. Lower numbers indicate better performance. For group (b) (elderly subjects with near normal hearing), the upper figure in each row shows results for the whole group, and the lower figure shows results excluding the two subjects whose absolute thresholds at 4 kHz exceeded 30 dB HL. For group (c) (young hearing-impaired subjects), the upper figure in each row shows results for the whole group, and the lower figure shows results excluding the subject with a mild loss.

Consider first the results for the young normally hearing subjects. The mean SRT in quiet is similar to what has been observed in previous studies (Moore and Glasberg, 1993; Nilsson *et al.*, 1994). The highest (poorest) mean SRT with background noise occurs for the steady noise masker (HINT noise). The mean SRT decreases by about 8 dB for the background of a single talker, which is consistent with earlier work, as reviewed in the introduction. The mean SRT for the noise modulated by speech is 6.2 dB lower than for the steady noise but 1.9 dB higher than for the single talker. This indicates that the temporal dips in the single talker are of major importance, but that spectral dips also play some role. The difference in SRT between the single talker and the modulated noise is unlikely to be due to the fact that the background speech was meaningful; Duquesnoy (1983) showed that SRTs were similar for a background of speech and time-reversed speech. Introducing spectral dips in the steady noise leads to improved performance, and the improvement increases as the width of the spectral dips increases. This confirms that normally hearing subjects are able to take advantage of spectral dips in background sounds. Finally, introducing spectral dips into the noise modulated by speech results in yet further decreases in the SRTs. For the modulated noise with four-ERB gaps, the mean SRT is about 19 dB lower than for the steady HINT noise. This illustrates the very large advantage of listening in spectral and temporal dips that can be obtained by normally hearing subjects.

Consider next the results for the elderly subjects with near-normal hearing. Generally, the pattern of results is similar to that obtained for the young normally hearing subjects. However, the elderly subjects appear to take slightly less advantage of spectral and temporal dips. This may partly reflect the fact that their absolute thresholds were *slightly* higher than for the young subjects, especially at high frequencies. The reduced absolute sensitivity is reflected in the SRT in quiet, which is, on average, about 10 dB higher for the elderly subjects than for the young subjects. Mean SRTs for the speech in background sounds are slightly but consistently lower when the results for the two subjects with a slight hearing loss at high frequencies are excluded. Thus, even this mild hearing loss was sufficient to produce some elevation of the SRTs. Although ''dip listening'' is somewhat reduced in the elderly subjects, its effects are still substantial. For the modulated noise with four-ERB gaps, the mean SRTs are about 14 dB lower than for the steady HINT noise.

We consider the results for the two groups of hearing-impaired subjects together, as the pattern of results was similar. Overall, the elderly subjects performed somewhat more poorly than the young subjects, which may reflect the fact that the elderly subjects had slightly greater hearing losses, on average. This is consistent with the average SRTs in quiet, which were 51.8 dB for the young subjects and 57.5 dB for the elderly subjects. The young subject with the mild hearing loss performed consistently better than the remaining young hearing-impaired subjects. Hence, the mean SRTs for the young hearing-impaired group were consistently higher (and the s.d.s were smaller) when the data for the subject with the mild loss were excluded, although the SRTs remained below those for the elderly group. The SRTs were somewhat lower for the background of a single talker than for the steady HINT noise, but the difference was less than for the normally hearing subjects, indicating a reduced ability to take advantage of spectral and/or temporal dips. The SRTs in the noise modulated by speech were only 1–3 dB lower than for the steady noise, indicating a limited ability to take advantage of temporal dips. Thresholds in the steady noise with two-ERB gaps were only 3–5 dB lower than in the steady HINT noise with no spectral gaps, which is close to what would be expected from the slightly lower overall level of the noise with spectral gaps. Thus, for this noise, there was very little advantage of the spectral gaps. The SRTs decreased by only 1–2 dB when the width of the spectral gaps was increased from two to four ERBs, indicating a very limited ability to take advantage of spectral dips. The SRTs for the noises with both spectral and temporal dips were much higher than normal. For example, for the modulated noise with four-ERB gaps, the SRTs for the young hearing-impaired subjects were 14–16 dB higher than for the young normally hearing subjects (depending on whether the subject with the mild loss was included), while the SRTs for the elderly hearing-impaired subjects were 12–13 dB higher than for the elderly subjects with near-normal hearing.

To assess the statistical significance of the effects described above, an analysis of variance (ANOVA) was conducted with group as a between-subjects factor and type of background as a within-subjects factor. The main effect of group was highly significant [$F(3,33)=79.9$, $p<0.001$]. The main effect of type of background was also significant [$F(8,264)=149.6$, $p<0.001$]. Finally, the interaction of group and type of background was highly significant [$F(24,264)=11.9$, $p<0.001$]. This confirms that the decrease in SRT produced by the spectral and temporal dips varied across groups; the decrease was greatest for the young normally hearing group and smallest for the elderly hearing-impaired group.

To examine possible interrelationships between audiometric thresholds, age, and the SRTs, correlations between these variables were determined for each group separately and for the combined results of groups (b)–(d), i.e., for all subjects with some degree of hearing loss. The audiometric thresholds were quantified by taking various averages, either weighting low and high frequencies equally, or giving more emphasis to high frequencies. The averages used were: 0.5, 1, and 2 kHz; 1, 2, and 4 kHz; and 2 and 4 kHz. The only case in which age was correlated with the SRTs in quiet or in noise was for the elderly group with near-normal hearing, where correlations ranged from 0.27 to 0.67. These correlations decreased, and were nonsignificant for all backgrounds except one (the steady noise with four-ERB gaps) when the mean absolute threshold at 2 and 4 kHz was partialled out. For groups (b)–(d) taken together, age was not significantly correlated with the SRTs in quiet or in any of the background noises; the maximum correlation was 0.25. It appears then, that age *per se* is only weakly related to SRTs in the various background noises. This is consistent with the finding of van Rooij and Plomp (1992) that almost all of the systematic variance in SRTs in noise for elderly subjects can be accounted for by the audiogram alone. They concluded that age differences in speech perception are probably mainly due to differences in auditory rather than cognitive factors.

In what follows, we will concentrate on the correlations for groups (b)–(d) taken together ($n=27$). Table II shows the correlation of the SRTs with the audiometric measures. All of the correlations were significant at $p<0.01$. The SRTs

TABLE II. Correlation of the SRTs with various averages of the audiometric thresholds for the combined results of groups (b)–(d).

	Average 0.5, 1, and 2 kHz	1, 2, and 4 kHz	2 and 4 kHz
Speech in quiet	0.95	0.94	0.93
Steady noise masker	0.52	0.58	0.61
Single voice masker	0.67	0.67	0.69
Noise modulated by speech	0.70	0.75	0.77
Noise with two-ERB gaps	0.71	0.76	0.79
Noise with three-ERB gaps	0.71	0.78	0.82
Noise with four-ERB gaps	0.79	0.84	0.87
Modulated noise with two-ERB gaps	0.73	0.74	0.75
Modulated noise with three-ERB gaps	0.76	0.82	0.84
Modulated noise with four-ERB gaps	0.79	0.83	0.85

in quiet were highly correlated with all of the audiometric measures, consistent with the idea that the audibility of the speech was the primary factor limiting performance. The SRTs in the steady HINT noise were only modestly correlated with the audiometric measures. This is consistent with the idea that audibility was less important for SRTs in steady noise, since performance was determined mainly by the higher-level portions of the speech which were generally well above absolute threshold. The correlations of the SRTs in quiet and in steady noise with the absolute thresholds are similar to those that have been reported in other studies (Dreschler and Plomp, 1980; Dreschler and Plomp, 1985; Glasberg and Moore, 1989).

For the noises where listening in temporal or spectral dips was assumed to be important, the SRTs were rather highly correlated with the absolute thresholds, and especially with the absolute thresholds at high frequencies (average of 2 and 4 kHz). This could be taken as indicating that the audibility of information in the spectral and temporal dips was of major importance. However, it could also have occurred partly because other factors, such as frequency selectivity, are correlated with the absolute threshold (Pick *et al.*, 1977; Glasberg and Moore, 1986; Moore, 1995). The role of audibility will be examined in more detail later.

To summarize: hearing-impaired subjects gained much less advantage than normally hearing subjects from spectral and temporal dips in background sounds. The noise containing both spectral and temporal dips revealed very considerable differences between normally hearing and hearing-impaired subjects. Thus, this noise provides a potentially very sensitive way of evaluating the effects of signal processing such as frequency-selective amplification and compression.

II. EXPERIMENT 2

A. Method

In this experiment, we examined the extent to which the reduced dip-listening abilities of the hearing-impaired subjects could be restored by improving audibility via linear amplification. In experiment 1, the portions of the target speech in spectral and temporal dips may have had levels so low that the hearing-impaired subjects were not able to make use of them. To compensate for the loss of audibility in the hearing-impaired subjects, the stimuli were subjected to the frequency-gain characteristic prescribed by the NAL (revised) procedure (Byrne and Dillon, 1986). For brevity, we will refer to this as NAL amplification. Subjects were subdivided into five groups on the basis of the pattern and severity of their hearing loss, and the NAL characteristic for each group was calculated on the basis of the average audiometric thresholds for each subgroup. The gain recommended by the NAL procedure ranged from −1–12 dB at 500 Hz and from 14–29 dB at 4 kHz. The required frequency-selective amplification was implemented by digital filtering in real time using a Tucker-Davis AP2 array processor. Speech and background noise stimuli were filtered separately and recorded on DAT. The background noises were presented with a nominal ‘‘input’’ level (before NAL amplification) of 65 dB SPL.

TABLE III. As Table I except that NAL amplification was applied to all stimuli and results are presented only for the young hearing-impaired and older hearing-impaired groups.

	Young hearing impaired $N=6$ $(N=5)$	Older hearing impaired $N=10$
Speech in quiet	39.1 (7.4) 40.1 (8.0)	42.6 (6.5)
Steady noise masker	−1.2 (1.4) −0.6 (0.6)	1.0 (2.7)
Single voice masker	−8.4 (3.7) −7.9 (3.8)	−1.9 (2.5)
Noise modulated by speech	−5.4 (2.1) −4.9 (1.9)	−1.4 (1.7)
Noise with two-ERB gaps	−6.1 (3.5) −4.8 (1.7)	−3.7 (2.1)
Noise with three-ERB gaps	−7.7 (2.4) −4.8 (2.1)	−3.9 (1.9)
Noise with four-ERB gaps	−10.0 (3.1) −7.1 (2.8)	−4.9 (2.0)
Modulated noise with two-ERB gaps	−9.2 (3.6) −8.4 (3.3)	−5.6 (2.8)
Modulated noise with three-ERB gaps	−10.6 (3.5) −9.7 (3.1)	−5.8 (2.9)
Modulated noise with four-ERB gaps	−11.4 (4.9) −10.1 (4.1)	−7.2 (2.4)

Other aspects of the stimuli and procedure were the same as for experiment 1. Only subject groups (c) young hearing-impaired and (d) elderly hearing-impaired were tested. The subjects in each group were the same as for experiment 1.

B. Results

The results are given in Table III. Consider first the SRTs in quiet. The NAL amplification reduced the mean SRT by 13–15 dB for the young subjects (depending on whether the subject with the milder loss was included) and by 14.9 dB for the elderly subjects. The mean SRT for both groups remained above that for the young subjects with normal hearing (Table I), which is not surprising since the frequency-gain characteristics prescribed by the NAL procedure provided only partial compensation for the hearing loss (see the Discussion section). Nevertheless, the ‘‘aided’’

SRTs are well below the level of normal conversational speech, which is about 65 dB SPL (Pearsons *et al.*, 1976).

Consider now the SRTs in the presence of background sounds. The NAL amplification had very little effect for the steady HINT noise, reducing the mean SRT (relative to that measured in experiment 1) by 0 to -0.2 dB for the young group and by 1.5 dB for the elderly group. This seems reasonable, since in this noise the low-level portions of the speech would be masked even when linear amplification was applied; only the higher level portions of the speech would have contributed to intelligibility and these were mostly above absolute threshold even without amplification (as in experiment 1).

The NAL amplification improved the mean SRT in modulated noise by about 1–3 dB for both groups, indicating that it partially restored the ability to make use of temporal dips. However, performance with this noise remained well below that for the young normally hearing group (Table I). The NAL amplification produced an improvement in the mean SRT of about 2–3 dB for the single talker background. The fact that the improvement was similar for these two backgrounds suggests that the NAL amplification did not markedly improve the ability to listen in the spectral dips of the single talker.

For the steady noises with spectral gaps, NAL amplification led to modest decreases in mean SRT ranging up to 3 dB. For the modulated noises with spectral gaps, the improvement was somewhat larger, ranging from 2–5 dB. However, the SRTs remained well above the values for the young normally hearing subjects. For example, the mean SRT in the modulated noise with four-ERB spectral gaps was 11.2 dB higher for the young hearing-impaired group with NAL amplification than for the young normally hearing group (12.5 dB higher excluding the subject with the mild loss). For the same noise, the mean SRT for the elderly hearing-impaired group was 15.4 dB higher than for the young normally hearing group and 8.5 dB higher than for the elderly group with near-normal hearing.

To assess the statistical significance of the effects described above, an analysis of variance (ANOVA) was conducted with group as a between-subjects factor and type of background as a within-subjects factor. The main effect of group was significant $[F(1,14)=12.95,\ p=0.003]$, the elderly impaired group having higher SRTS than the young impaired group. The main effect of type of background was also significant $[F(8,112)=39.5,\ p<0.001]$. Finally, the interaction of group and type of background was just significant $[F(8,112)=2.25,\ p=0.03]$. This reflects the finding that the decrease in SRT produced by the spectral and temporal dips was greater for the young group than for the elderly group.

As in experiment 1, correlations were determined between the audiometric thresholds, ages, and the SRTs. Within each group, age did not correlate significantly with the SRTs in background sounds. However, for both groups combined, some significant correlations with age did occur. Age was not significantly correlated with the SRT in quiet ($r=0.27$) or in steady HINT noise ($r=0.39$). However, age was moderately correlated with the SRTs in backgrounds with spectral and/or temporal dips. Furthermore, several of these correlations remained significant when the effects of absolute threshold were partialled out. Considering the case where the mean absolute threshold at 0.5, 1, and 2 kHz was partialled out, significant partial correlations were obtained between age and the SRT in a single talker background ($r=0.83$, $p<0.001$), in noise modulated by speech ($r=0.74$, $p<0.001$), in unmodulated noise with three- and four-ERB gaps ($r=0.65$, $p<0.01$ and $r=0.78$, $p<0.001$), and in modulated noise with two-, three- and four-ERB gaps ($r=0.54$, $p<0.05$; $r=0.70$ $p<0.01$; and $r=0.53$, $p<0.05$, respectively). It appears that when reduced audibility is partially compensated for by NAL amplification, age may play a significant role when the background contains spectral and/or temporal dips.

TABLE IV. Correlation of the SRTs with various averages of the audiometric thresholds for the combined results of groups (c) and (d) using stimuli with NAL amplification.

	Average 0.5, 1, and 2 kHz	1, 2, and 4 kHz	2 and 4 kHz
Speech in quiet	0.62	0.43	0.39
Steady noise masker	0.33	0.26	0.23
Single voice masker	0.50	0.35	0.32
Noise modulated by speech	0.43	0.33	0.33
Noise with two-ERB gaps	0.59	0.40	0.32
Noise with three-ERB gaps	0.44	0.34	0.35
Noise with four-ERB gaps	0.39	0.23	0.21
Modulated noise with two-ERB gaps	0.58	0.37	0.34
Modulated noise with three-ERB gaps	0.61	0.47	0.48
Modulated noise with four-ERB gaps	0.53	0.32	0.30

The correlations of the SRTs with the audiometric thresholds are shown in Table IV for the combined results of both groups. The correlations were markedly lower than for stimuli without NAL amplification (Table II), consistent with the idea that NAL amplification partially compensates for loss of audibility. When the contribution of audibility is reduced, other suprathreshold factors, such as reduced frequency selectivity, and individual differences in cognitive factors, may play a greater role.

In summary, NAL amplification only partially compensated for the relatively poor performance of the hearing-impaired subjects when listening to speech in noises with spectral and temporal dips. The SRTs in noises with temporal modulation and spectral dips were improved by 2–5 dB by the NAL amplification, but remained 7–15 dB higher than for young normally hearing subjects. The SRTs for speech in background noise with spectral and/or temporal dips were correlated with age, suggesting a possible role for cognitive factors that decline with age.

III. ASSESSING THE ROLE OF AUDIBILITY

It remains unclear whether the failure of NAL amplification to restore performance to normal reflects deficits in suprathreshold processing, perhaps related to reduced frequency selectivity and/or temporal resolution, or whether the failure occurred because NAL amplification was not sufficient to restore audibility to normal. Even with NAL amplification, part of the speech spectrum may have been below absolute threshold. To clarify this issue we calculated the articulation index (AI) for stimuli at the measured SRTs, taking into account the absolute thresholds of the subjects, the speech spectrum, and the amount of NAL amplification (if any). Our main concern was to determine the proportion of the speech spectrum that was above the *absolute* threshold. Hence, the calculations did not take into account the presence of the background noises. If all of the speech spectrum is above the absolute threshold, then deficits in performance in the presence of background noise must be due to masking effects of that noise.

To calculate the AI, the speech was analyzed in $\frac{1}{3}$-octave bands and the root-mean-square (rms) level in each band was expressed in dB HL, i.e., relative to the normal absolute threshold for that band. The absolute thresholds of each subject at the $\frac{1}{3}$-octave center frequencies, and the amounts of NAL amplification, were estimated by interpolation from the audiometric frequencies. It was then possible to calculate the rms level of the speech relative to the absolute threshold in each $\frac{1}{3}$-octave band. It was assumed that the dynamic range of the speech in each band extended from 12 dB above to 18 dB below the rms level. The proportion of the 30-dB dynamic range that was above the absolute threshold in each band was multiplied by the importance value for that band, and the products were summed to give the AI. Values for the importance function were those for ''average speech'' as specified in Pavlovic (1987). According to ANSI (1969), AI values over approximately 0.7 lead to essentially perfect performance for sentence material. This should be borne in mind when considering the AI values.

Consider first the AIs for speech at the SRTs in quiet without any amplification. The mean AIs for groups (a), (b), (c), and (d) (with standard deviations in parentheses) were 0.26, 0.23 (0.09), 0.16 (0.03), and 0.16 (0.10), respectively. The slightly lower AIs for the impaired groups may have occurred because the hearing-impaired subjects had learned to make more effective use of low-frequency information falling in the range where their hearing was relatively good. When NAL amplification was applied, the SRTs in quiet (expressed as the input level prior to NAL amplification) decreased, but the mean AIs for groups (c) and (d) for speech at the SRT in quiet increased to 0.21 (0.09) and 0.22 (0.16), respectively. Thus, to achieve the same level of intelligibility, these groups required slightly higher AIs when NAL amplification was applied than when it was not. A higher AI with NAL amplification was found for five out of six subjects in group (c) and for seven out of ten subjects in group (d). The higher AIs may have occurred because the NAL amplification partially restored the audibility of higher frequencies, but these subjects did not make very effective use of that information, possibly because of a lack of opportunity for acclimatization (Gatehouse, 1992).

Table V shows the mean AI for each group for speech at a level corresponding to the mean SRT in steady noise, and the mean SRT in modulated noise with four-ERB gaps; these represent the highest and lowest SRTs, respectively, when background sounds were present. Except for group (a), AIs were calculated individually for each subject and then averaged within groups.

TABLE V. Mean AIs for speech at levels corresponding to the SRTs in steady noise, and in modulated noise with four-ERB gaps. The calculated AIs do not take into account the effect of the background noise; they indicate the proportion of the speech spectrum that was above the absolute threshold. Numbers in parentheses are standard deviations across subjects. For the older subjects with near-normal hearing, the upper numbers refer to results for the whole group and the lower numbers refer to results excluding two subjects whose absolute thresholds at 4 kHz exceeded 30 dB HL. For the young hearing-impaired subjects, the upper numbers refer to results for the whole group and the lower numbers refer to results excluding one subject with a mild loss.

Group	Speech level at SRT in steady noise	modulated noise, 4-ERB gaps
(a) Young normal	1.0	0.92
(b) Older normal	0.92 (0.04)	0.75 (0.06)
	0.94 (0.02)	0.75 (0.07)
(c) Young impaired	0.47 (0.18)	0.31 (0.13)
	0.41 (0.12)	0.27 (0.07)
(c) With NAL amplification	0.82 (0.14)	0.60 (0.18)
	0.80 (0.14)	0.59 (0.19)
(d) Older impaired	0.43 (0.15)	0.32 (0.16)
(d) With NAL amplification	0.72 (0.15)	0.55 (0.18)

For group (a), the AIs for the two cases were 1.0 and 0.92, i.e., almost all of the speech spectrum was above absolute threshold. Thus, for this group, the SRTs in noise must have been determined by the masking effects of the noise rather than by part of the speech spectrum being below absolute threshold. For group (b), the AIs were somewhat smaller, but still at or above 0.75. In particular, the mean AI at the SRT in steady noise, excluding the two subjects with mild-high frequency loss, was 0.94. The SRT for this group was 1.6 dB higher than for the normal subjects. For speech presented at the SRT for the normal subjects (i.e., 1.6 dB lower, on average), the mean AI for this group is 0.93. It seems unlikely that the very small reduction in audibility associated with an AI of 0.93 would be sufficient to account for the difference in SRT between groups (a) and (b). For the modulated noise with four-ERB gaps, the AI was reduced to 0.75, which is still above the value required for near-perfect intelligibility of sentences. Thus performance was probably determined mainly by the masking effects of the background noise. The SRT for group (b) with this noise was 6.9 dB higher than for group (a). For speech presented at the SRT for normal subjects, the AI was reduced to 0.58. This is sufficiently low that performance probably would have been limited partly by some of the speech spectrum being below absolute threshold.

For group (c), the AIs without NAL amplification were markedly lower than 1. It seems likely that performance in this case was partly limited by some of the speech spectrum being below absolute threshold. With NAL amplification the AIs increased markedly, to 0.82 ($N=6$) or 0.80 ($N=5$) for speech at a level corresponding to the SRT in steady noise. For speech presented at the SRT for the normal subjects with steady noise (i.e., 2.6 dB lower, on average) the mean AI was 0.77 ($N=6$) or 0.74 ($N=5$), high enough to give near-perfect intelligibility. It seems likely that performance with NAL amplification was determined mainly by the masking effect of the background noise, although reduced audibility may have played some role. For speech at the SRT in modulated noise with four-ERB gaps, the AI was increased markedly when NAL amplification was applied, but it remained at or below 0.6. Thus, in this case, performance was probably partly limited by part of the speech spectrum being below absolute threshold. For speech presented at the SRT for the normal subjects with this noise (i.e., 11.2 dB lower, on average) the mean AI was 0.31 ($N=6$) or 0.27 ($N=5$). These values are small enough to indicate that reduced audibility would have played a substantial role.

For group (d), the AIs without NAL amplification were lower still. It seems certain that performance in this case was partly limited by some of the speech spectrum being below absolute threshold. With NAL amplification the mean AI increased markedly, to 0.72 for speech at a level corresponding to the SRT in steady noise. For speech presented at the SRT for the normal subjects with steady noise, the mean AI was 0.61. It seems likely that performance with NAL amplification was determined mainly by the masking effect of the background noise, although reduced audibility may have played some role. For speech at the SRT in modulated noise with four-ERB gaps, the AI was increased to 0.55 when NAL amplification was applied. Thus, in this case, performance was probably partly limited by part of the speech spectrum being below absolute threshold. For speech presented at the SRT for the normal subjects with this noise, the mean AI was 0.21. This value is small enough to indicate that reduced audibility would have played a substantial role.

IV. DISCUSSION

Linear amplification according to the NAL prescription is generally regarded as one of the better formulas for fitting linear hearing aids. Also, our implementation of the NAL prescription, using digital filtering, was more accurate than would normally be achieved in a conventional, wearable, linear hearing aid; even though NAL targets were based on groups, the gains used for each individual were always within 3 dB of the target gains for that individual. In particular, the target gains at higher frequencies were achieved, which is often not the case in wearable aids. Our results showed that, even with NAL amplification, the performance of the hearing-impaired subjects remained worse than that of the normally hearing subjects. Furthermore, the AI calculations indicated that, for the noise giving the lowest SRTs (modulated noise with four-ERB gaps), performance was partly limited by some of the speech spectrum being below absolute threshold. In other words, the NAL amplification did not provide sufficient gain to restore audibility of the low-level parts of the target speech.

While it is possible to increase the amount of linear gain applied, this can only be done to a limited extent because of loudness recruitment, which nearly always is associated with cochlear hearing loss. The threshold for detecting sounds is higher than normal, but once the sound level is increased above the absolute threshold, the rate of growth of loudness level with increasing level is greater than normal. At a sound level of 90–100 dB SPL, the loudness in an impaired ear often ‘‘catches up’’ with that in a normal ear (Fowler, 1936; Steinberg and Gardner, 1937; Moore *et al.*, 1996). As a consequence, the range of sound levels over which sounds are both audible and comfortable (the dynamic range) is much smaller for hearing-impaired than for normally hearing people.

Most rules for prescribing the insertion gain of a linear aid are appropriate for speech inputs with a moderate level. However, in conditions where a wide dynamic range is required, for example, when listening to speech in noise with spectral and temporal dips, it may be impossible to apply sufficient linear gain to ensure that all of the speech spectrum is above absolute threshold while preventing the noise from becoming unpleasantly loud.

One way of dealing with loudness recruitment is to use hearing aids with fast-acting compression or automatic gain control (AGC). Such aids can increase the available dynamic range and can make it possible for the hearing-impaired person to deal with sounds covering a wide range of levels without needing to adjust the volume control on the aid (Villchur, 1973; Lippmann *et al.*, 1981; Moore *et al.*, 1992). In principle, they can also improve the ability to listen in dips of a competing sound by increasing the gain for signals in the dips, thus improving the intelligibility of the speech. However, laboratory studies of systems using fast-acting compression have given mixed results, with some studies showing no benefit or even a worsening in comparison to linear amplification and others showing moderate benefits (Villchur, 1973; Lippmann *et al.*, 1981; Villchur, 1982; Moore and Glasberg, 1988a; Moore *et al.*, 1992; Hickson, 1994; Moore, 1995).

The laboratory studies have generally used test materials covering a much smaller range of sound levels than would be encountered in everyday life. Also, when background sounds have been used, the most common sound has been steady speech-shaped noise. Our results suggest that this is not the most effective noise for revealing benefits of compression; noises with spectral and temporal dips might be much more sensitive; preliminary results obtained in our laboratories indicate that this is, indeed, the case.

Although our results suggest that the relatively poor performance of the hearing-impaired subjects when listening to speech in background noise with spectral and/or temporal dips was at least partly due to part of the target speech spectrum being below absolute threshold, it is likely that other supra-threshold factors also contributed to their poor performance, especially when NAL amplification was applied. In particular, it seems likely that reduced frequency selectivity contributed to the relatively poor performance when the background noise had spectral dips (Patterson *et al.*, 1982; Moore, 1995). Consider, for example, the AI values shown in Table V for the young impaired group and the modulated noise with four-ERB gaps. The mean AI value without NAL amplification was only 0.31, suggesting that a major factor limiting performance was the proportion of the target speech spectrum that was above absolute threshold. However, when

NAL amplification was applied, the AI at the SRT increased to 0.6. Since much more of the speech spectrum was above absolute threshold in this condition, but the same performance level was obtained (50% correct), it seems reasonable to infer that the masking effect of the background noise played a substantial role in limiting performance. The mean SRT for this group with NAL amplification was 11.2 dB higher than for the young normally hearing group, which is a very large difference, probably too large to be explained by the small difference in AI (0.6 for the impaired group with NAL amplification and 0.75 for the normal group without amplification). However, it is very difficult to infer from our results the relative importance of reduced audibility and reduced frequency selectivity.

For stimuli without NAL amplification, age was not correlated with the SRTs in any of the background noises, once the effect of absolute threshold was partialled out. This finding is similar to that of Takahashi and Bacon (1992). They measured speech intelligibility in both unmodulated noise and noise that was sinusoidally amplitude modulated at an 8-Hz rate with 100% modulation depth, using young normally hearing subjects, and three groups of older subjects (mean age 54.3, 64.8 and 72.2 years). They found that even mild hearing impairment had a large effect on the ability to understand speech in modulated noise. However, there was no significant effect of age once the effect of absolute threshold had been partialled out. In contrast, our results for stimuli with NAL amplification showed that SRTs in backgrounds with spectral and/or temporal dips were significantly correlated with age. Several of these correlations remained significant when the effects of the mean absolute threshold at 0.5, 1, and 2 kHz were partialled out. Thus, when reduced audibility is partially compensated for by NAL amplification, age may play a significant role when the background contains spectral and/or temporal dips. It is possible that the ability to reconstruct the speech from incomplete information (glimpses obtained in spectral or temporal valleys) plays a strong role in this situation, and that this cognitive ability declines with age.

In conclusion, people with cochlear hearing loss have a reduced ability to make use of both spectral and temporal dips in background sounds. This reduced ability may occur partly because of supra-threshold deficits such as reduced frequency selectivity. However, inaudibility of part of the speech spectrum may also play an important role. Linear amplification only partially compensates for the deficits. When linear amplification was applied, the SRTs in backgrounds with spectral and/or temporal dips were significantly correlated with age.

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