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Do adaptive frequency response (AFR) hearing aids reduce 'upward spread' of masking?

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Abstract—Speech recognition scores in noise are improved for some subjects who wear hearing aids that reduce low-frequency noise with an adjustable high-pass filter circuit. To evaluate whether these improvements were related to a reduction in upward spread of masking, pure-tone masking patterns for a low-frequency band-pass noise were measured in normal and hearing-impaired subjects. The filter skirt of the noise masker was very steep, with attenuation above the 1000 Hz cutoff greater than 120 dB per octave. Masking patterns for the same noise were also obtained in the presence of a high-pass filter that simulated the effects of an adaptive frequency response (AFR) hearing aid. Differences in the masking patterns were considered a measure of upward spread of masking. On average, subjects with high-frequency hearing loss demonstrated greater amounts of upward spread of masking than did normal-hearing listeners. Further, monosyllabic speech recognition in noise testing indicated improvements in performance of the hearing-impaired subjects related to the decrease of upward spread of masking in the high-pass filtering conditions.

Key words: *adaptive frequency response, hearing aids, high-pass filters, pure-tone masking patterns, speech recognition in noise, upward spread of masking.*

INTRODUCTION

The results of several recent experiments indicate that under some conditions, improved speech recognition in noise is possible with commercially available hearing aids that reduce low-frequency energy via an adjustable high-pass filter circuit (1,2). Recently, a study by Fabry and Van Tasell (3) reported that because speech-to-noise ratios are not improved by these "adaptive frequency response" (AFR) hearing aids, any improvement in speech recognition in noisy backgrounds is related either to auditory factors (such as upward spread of masking) or to nonauditory factors, including distortion or internal noise added by the hearing aid.

There is considerable support for the contribution of either auditory or nonauditory factors to improved speech intelligibility under certain background noise conditions. Preves and Newton suggested that conventional, peak-clipping hearing aids produce greater distortion than AFR hearing aids due to a lack of hearing aid "headroom" (4). They contend that AFR hearing aids prevent the hearing aid from reaching output saturation for lower input signals that saturate conventional devices. Thus, one explanation for results showing improved speech recognition in noise by subjects wearing AFR hearing aids is that the hearing aid used for comparison (in most instances peak-clipping, "linear" hearing aids) added significant amounts of distortion. This argument assumes, however, that distortion will degrade speech intelligibility. Although hearing aid distortion has been linked to poor speech quality (5), it is unclear whether it affects speech intelligibility adversely.

Psychophysical data suggest that auditory effects, such as upward spread of masking, may

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contribute to poor speech intelligibility by hearing-impaired subjects. Trees and Turner (6) and Gagne (7) reported that hearing-impaired subjects with precipitous high-frequency hearing loss showed "excessive" upward spread of masking relative to normal-hearing subjects for narrow-band noise masking experiments. Upward spread of masking effects are most pronounced for low-frequency, band-limited noises (8); presumably, high-pass filtering via AFR filter circuitry would be maximally effective under those conditions.

In the present study, the effects of *nonauditory* factors were minimized via a laboratory model of an AFR hearing aid that added very little distortion or noise. By isolating the auditory factors, the intention of the present study was to determine whether upward spread of masking was reduced by the processing used in AFR hearing aids, and if so, whether that reduction is accompanied by a change in speech recognition.

The following experimental questions were considered:

1. Is upward spread of masking excessive in subjects with precipitous high-frequency hearing loss?
2. Does the filtering imposed by commercially available adaptive frequency response hearing aids improve speech recognition by reducing upward spread of masking?

METHODS

Subjects

Eight male hearing-impaired subjects between the ages of 20 to 45 years of age participated in this experiment. All subjects had precipitous high-frequency hearing loss in the frequency region between 1000 and 2000 Hz, with no air-bone gaps greater than 5 dB measured at any audiometric frequency (250–8000 Hz). Audiologic and immittance findings excluded middle-ear and retrocochlear pathology.

Four subjects (two females and two males) with normal hearing also participated in this study; they ranged in age from 28 to 50 years old and had thresholds of 20 dB HL or more for all audiometric frequencies between 250 and 8000 Hz.

Apparatus

The output of a noise generator was shaped by a Fern digital filter to provide a band-pass low-frequency noise with cutoff frequencies of 200 Hz and 1000 Hz. The filter slope on the low-pass filter exceeded 120 dB/octave (**Figure 1**). This noise was attenuated and mixed with the channel 1 output of a Grason-Stadler GSI-10 diagnostic audiometer, which was equipped for either Bekesy tracking or delivery of tape-recorded stimuli. Subsequently, the output of the mixer (noise plus tones or recorded speech) was high-pass filtered by a Krone-Hite filter at either 200 Hz or 1500 Hz, amplified, and delivered to a TDH-49 earphone located in a sound-isolated suite.

PROCEDURES

Masking Patterns

Continuous Bekesy tracking was used with sinusoidal stimuli swept from 200 to 6000 Hz at a rate of 0.5 octaves/min; stimulus intensity was varied by 5 dB/sec increments. Each sweep took approximately 9 min. Each subject completed a threshold sweep at the beginning and end of the test session, and the average of the two measures at selected frequencies defined quiet threshold.

After subjects finished the first quiet threshold run, they completed several masked threshold traces in the presence of the low-frequency noise (**Figure 1**). For each subject, masking patterns were measured under earphones in the presence of this shaped

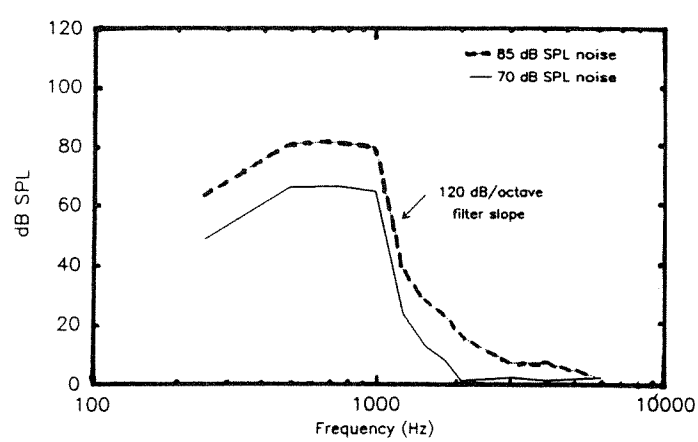

Figure 1.
Spectral measurements of band-pass noise for 70 dB SPL (solid line) and 85 dB SPL (dashed line) conditions.

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noise at overall presentation levels of 70 dB SPL and 85 dB SPL (spectrum levels of 40 and 55 dB SPL), with the Krohn-Hite high-pass filter set to either 200 Hz or 1500 Hz.

Data collected with the filter set to 200 Hz comprised the unprocessed, or AFR-off, condition. In addition, the low-pass noise was high-pass filtered at 1500 Hz to simulate the processing imposed by the average of three commercially available AFR hearing aids (**Figure 2**). In this, the AFR-on condition, the noise was filtered as shown in **Figure 3**. Each subject completed a total of eight masking patterns, comprising two masking patterns (test-retest) for both noise levels (70 and 85 dB SPL) under both test conditions (AFR-off and AFR-on). The experimental conditions were counterbalanced across subjects to avoid order effects.

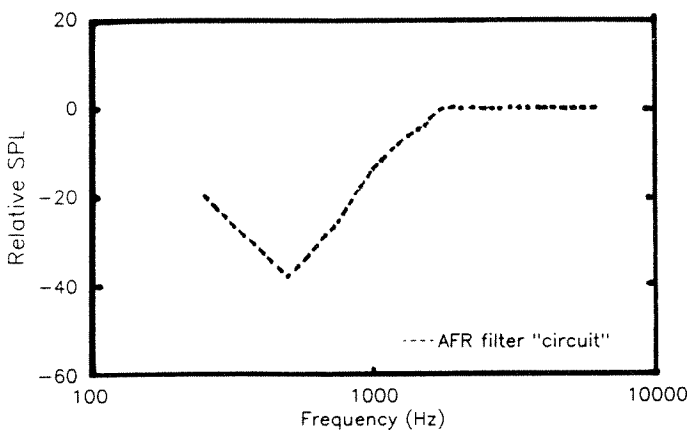

Figure 2.
Frequency response characteristics of the simulated adaptive frequency response (AFR) circuit used in the present study.

Speech Recognition Testing

Monosyllabic word recognition was measured for each subject under both AFR-on and AFR-off conditions using 200 words from Northwestern University's NU-6 recorded tests Forms C and D. Speech presentation levels were 72 dB SPL and 88 dB SPL; speech and noise were mixed and filtered together at either 150 Hz or 1500 Hz for AFR-off and AFR-on conditions, respectively. This condition was designed to simulate the performance of a single-microphone AFR hearing aid, with speech and noise mixed at the input microphone.

RESULTS

Masking Pattern Data

Normal-hearing Subjects. Averaged results from the four subjects with normal hearing are shown for AFR-off and AFR-on conditions in **Figure 4** and **Figure 5**, respectively. Data points illustrate selected frequencies for analysis from the Bekesy tracings; intersubject variability was less than 5 dB across all test frequencies. For the 70 dB SPL masker in the AFR-off condition (**Figure 4**, solid line) there is some "upward spread" of

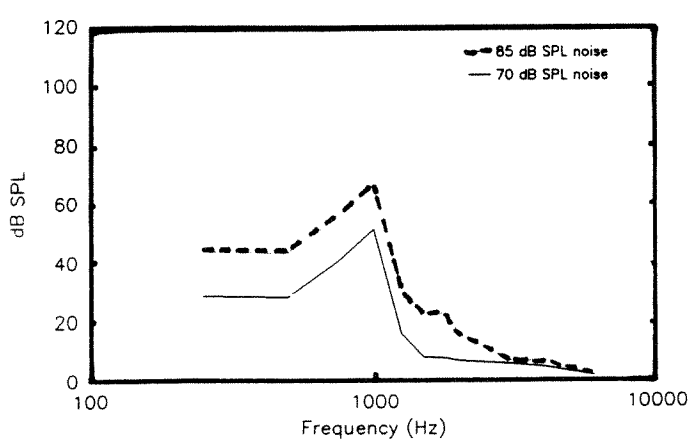

Figure 3.
Spectral characteristics of noise filtered by AFR circuit from **Figure 2** for the 70 dB SPL (solid line) and 85 dB SPL (dashed line) conditions.

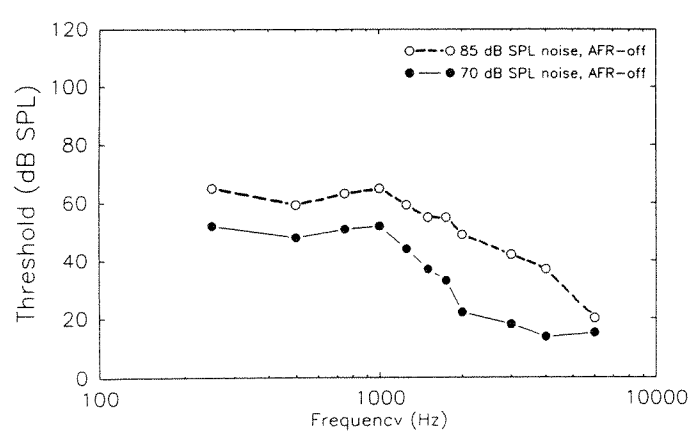

Figure 4.
Average masking pattern data from four normal-hearing subjects for the AFR-off condition for 70 dB SPL (solid line) and 85 dB SPL (dashed line) band-limited noise.

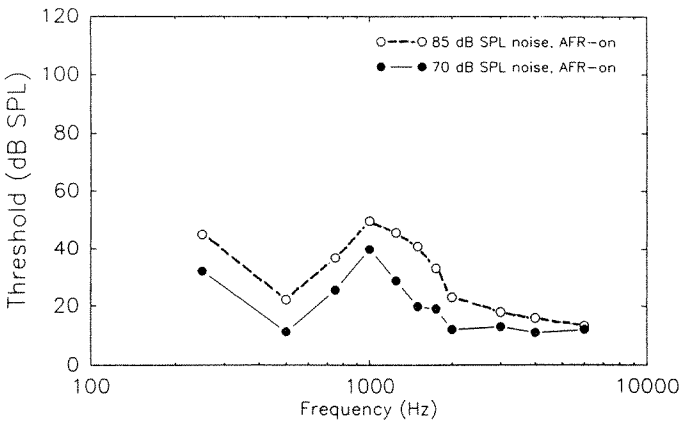

Figure 5.
Average masking pattern data for four normal-hearing subjects for the AFR-on condition for 70 dB SPL (solid line) and 85 dB SPL (dashed line) band-limited noise.

masking above 1000 Hz, compared with the noise spectra (**Figure 1**). For example, the difference between the average masked threshold and the noise spectrum at 1500 Hz was 28 dB. The disparity between masked thresholds and spectral measurements is even greater (33 dB) for the 85 dB SPL noise condition. These findings are similar to previous data for expected upward spread of masking reported by the ANSI (1969) Standard for Calculation of the Articulation Index (9), which were based on work by Carter and Kryter (10).

Hearing-impaired Subjects. Masking pattern data obtained from normal subjects formed the basis of the "reference" masked conditions. Using the methods employed by Gagne (7) and Trees and Turner (6), the quiet thresholds of hearing-impaired subjects were used to compare their masking patterns to those obtained from subjects with normal hearing. For a given condition, averaged masking patterns from normal-hearing subjects were compared with the masking patterns obtained from each hearing-impaired subject and his thresholds in quiet. For a given subject, "excess" spread of masking is indicated by the difference between the observed masking pattern and the normal masked condition *or* quiet threshold, whichever is higher.

Figures 6–9 show data from hearing-impaired subject H-1. The hatched areas in each figure indicate the region(s) of excess masking. For the 85 dB SPL noise level, it is clear that the region of excess upward spread of masking is reduced under the AFR-on condition (**Figure 7**) compared with the AFR-off condition (**Figure 6**). For the 70 dB SPL noise (**Figure 8** and **Figure 9**), data from this subject showed very little departure from the expected reference condition. That is, even for the AFR-off condition, there was only slightly more upward spread of masking than would be expected on the basis of his quiet thresholds. Under the AFR-on

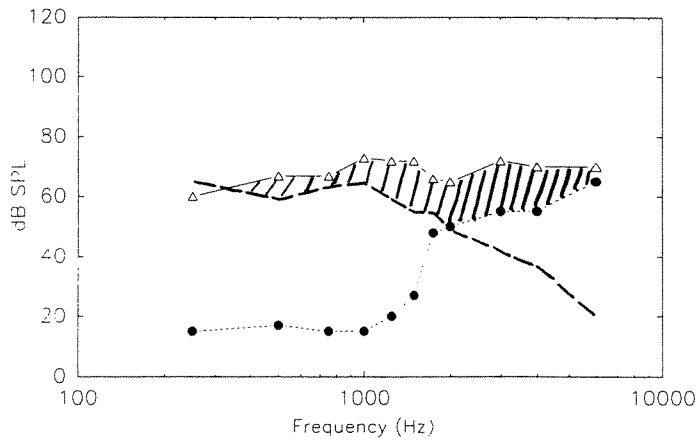

Figure 6.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-1 for the 85 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

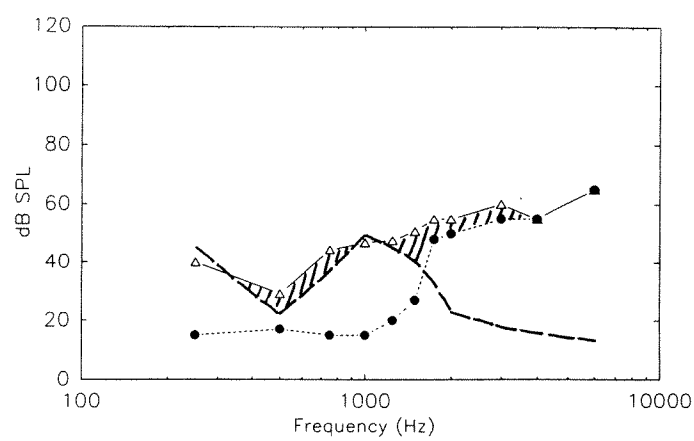

Figure 7.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-1 for the 85 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

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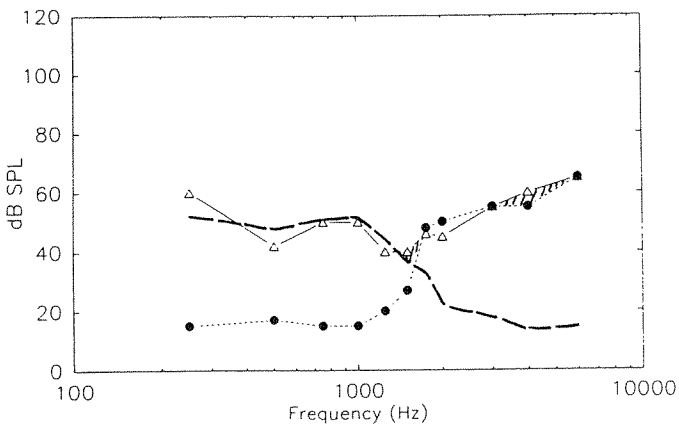

Figure 8.
Dashed line indicates normal masking pattern for 70 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from Subject H-1 for the 70 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

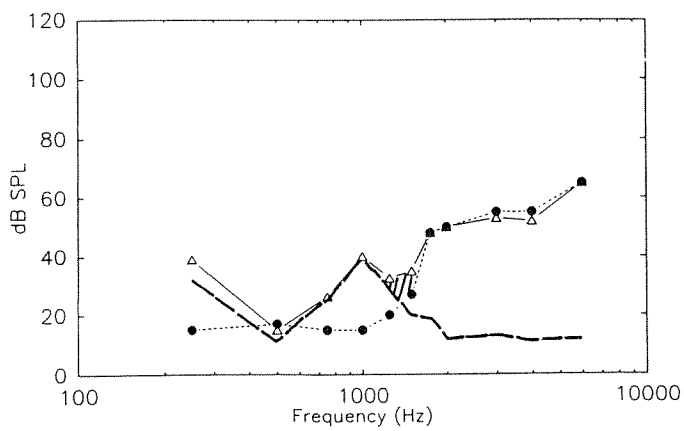

Figure 9.
Dashed line indicates normal masking patten for 70 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked threshold (open triangles) from Subject H-1 for the 70 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

condition, the hatched areas indicating upward spread of masking have been reduced marginally. At least for this subject, the high-pass filtering imposed by the AFR-on conditions reduced upward spread of masking for the high-level background noise, but it was unnecessary for the 70 dB SPL noise condition. This rather large change in the amount of upward spread of masking between AFR-on and AFR-off conditions for the 85 dB SPL noise was found for five of eight hearing-impaired subjects (HI-1, HI-2, HI-5, HI-6, HI-8).

Data from the three remaining subjects were similar to those obtained from subject HI-4 (**Figure 10** and **Figure 11**). Masking patterns from that subject indicate that excessive upward spread of masking was present for *both* AFR-off (**Figure 10**)

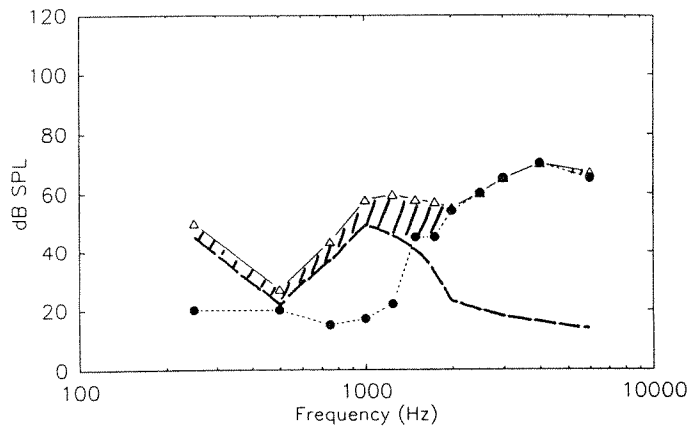

Figure 10.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-4 for the 85 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

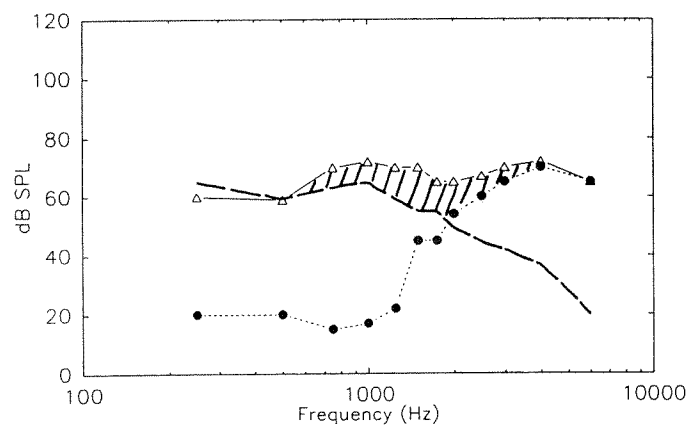

Figure 11.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-4 for the 85 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

and AFR-on (**Figure 11**) conditions. Even when low frequencies were reduced by the high-pass filter, masked thresholds were greater than predicted from the normal masking patterns and HI-4's quiet thresholds for both the 70 and 85 dB SPL noise conditions.

Speech Recognition Testing

Table 1 shows the difference in speech recognition scores between AFR-on and AFR-off conditions for normal and hearing-impaired subjects. Positive numbers indicate that speech recognition was higher for the AFR-on condition than for AFR-off; this was the case for all subjects except HI-3 (for the 70 dB noise level).

Additionally, masking pattern data were correlated with changes in speech recognition scores. Assuming that improved performance on NU-6 word lists reflected real-world changes in speech intelligibility (admittedly, a rather large intuitive jump), a predictive measure of benefit would be of use clinically to determine the efficacy of AFR hearing aids for a specific individual.

Figure 12 shows a scatterplot of the dB change (AFR-off minus AFR-on) at 1500 Hz versus the percent change in speech recognition (AFR-on minus AFR-off) for all hearing-impaired subjects and conditions. The correlation between these data was modest, at 0.61, but it was substantially better than the correlation between hearing threshold sensitivity and changes in speech recognition performance of 0.21.

Articulation Index (11) values were calculated from the relationship between the long-term spectral peaks of speech stimuli and each subject's masked-

Table 1.
Improvement in Speech Recognition

	Percentage	
	70 dB SPL	85 dB SPL
Normals	8	30
HI-1	12	36
HI-2	29	45
HI-3	−5	8
HI-4	15	7
HI-5	30	27
HI-6	4	19
HI-7	5	17
HI-8	19	26

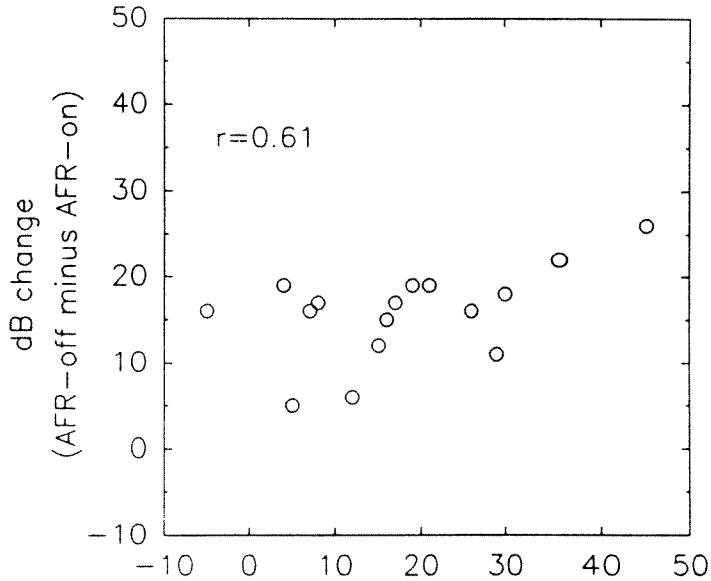

Figure 12.
Data compare the change in masked threshold at 1500 for AFR-on and AFR-off conditions to the percent change in speech recognition scores under the same conditions. Data on the ordinate are the AFR-on masked thresholds minus AFR-off thresholds for the same subject; data on the abscissa are the difference in speech recognition for AFR-on minus AFR-off conditions.

or quiet-threshold for AFR-on and AFR-off conditions. The long-term speech spectrum was measured, using a signal analyzer, for the monosyllabic word lists presented at 70 and 85 dB SPL. Articulation Index (AI) values were computed from the speech-to-masked-threshold or speech-to-threshold ratio, whichever was less, in each of 15 one-third-octave bands between 200 Hz and 6000 Hz. Pavlovic's bandweights for "average speech" comprised the band importance function (12). The data are shown in **Figure 13**, along with Black's (13) transfer function relating calculated AI to monosyllabic word recognition. Although the *absolute* speech recognition scores were not predicted for all subjects, one finding consistent with previous studies (3) is that within-subject changes in AI were related monotonically to speech intelligibility.

DISCUSSION

Previously, Fabry and Van Tasell (3) calculated AI values for subjects wearing actual AFR hearing

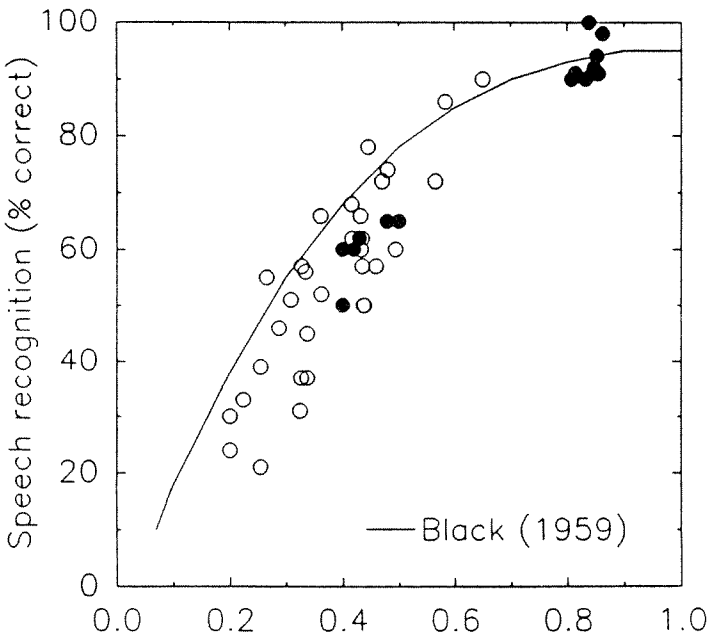

Figure 13.
Speech recognition scores for normal (filled circles) and hearing-impaired (open circles) subjects plotted as a function of AI for AFR-on and AFR-off conditions. Solid line depicts the AI transfer function developed by Black (13).

aids in background noise, and found that AI uncorrected for upward spread of masking effects typically over-predicted speech recognition scores. In the present study, the deleterious effects of hearing-aid-related factors (such as saturation and distortion), were minimized, because hearing aid performance was modeled with a laboratory system. This allowed for better isolation of auditory factors, such as upward spread of masking, to be assessed directly via the masking pattern data. As a result, the AI predictions were more accurate than in the Fabry and Van Tasell (3) study. This has several implications for using the AI as a tool for assessing performance of signal processing techniques on wearable hearing aids.

First, it may be possible to use masked threshold data to predict benefit from AFR hearing aids. Presumably, if hearing-impaired persons differ in the degree to which they suffer from upward spread of masking, then they would be expected to differ in expected benefit from devices that attenuate low-frequency energy. If 1500 Hz is used as a guide, it is speculated that "satisfied" hearing aid users will show greater reduction in masked threshold than unhappy users. Caution is advised, however, when measuring *aided* masked thresholds with actual hearing aids. Data from the present study are consistent with previous work that suggests that substantial amounts of harmonic and intermodulation distortion may be produced when actual hearing aids are evaluated under conditions of band-limited noise (14).

Second, although AI results were related monotonically to speech recognition for all subjects, this conclusion holds true only for speech and noise levels that are below the threshold of discomfort. At least one recent study has reported decreases in speech recognition for high presentation levels (15).

Finally, although AI predicted speech recognition scores reasonably well, it does not allow for user preference on factors not related to speech intelligibility. It is possible that these factors, such as speech quality or improved listening ease, may play an important role in acceptance of signal processing hearing aids.

CONCLUSIONS

1. Upward spread of masking was excessive for several of the hearing-impaired subjects used in this study.

2. For some hearing-impaired subjects, high-pass filtering resulted in improved speech recognition that was related in a somewhat predictable sense to reduced upward spread of masking. This benefit is restricted to band-pass noise conditions, and improvements in speech intelligibility are usually no greater than those achieved by subjects with normal hearing.

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