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The effect of filtering on the intelligibility and quality of speech in noise*

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INTRODUCTION

It has often been difficult to find a hearing aid whose frequency response would result in good speech intelligibility and quality under different listening conditions. Noise conditions have been shown to cause particular difficulty: the hearing aid that is satisfactory to the listener in quiet often proves to be of limited benefit in noise. Digital technology opens the possibility of individualizing the type of filtering that can be done. It also makes it possible to have more than one filter available for a listener to use under different conditions, or of adapting a filter to particular listening situations.

Traditionally, hearing aid fitting procedures have been geared towards maximizing the intelligibility of a speech signal in quiet. Very little has been done to optimize the frequency response for use in noisy situations. In the past, some hearing aids included a highpass filter as a means of reducing background noise. If highpass filtering were used at all times, speech intelligibility could be preserved, but at the expense of sound quality. User-activated switches allowed the listener to decide when background noise was bothersome; a broader frequency response could be used in quiet and a highpass frequency response in noise. More recently, the manual switch has been replaced by automatic control of the slope of the highpass filter, of the highpass filter cutoff frequency or, alternatively, by compression limiting of low-frequency energy (5).

An even more recent innovation is the development of a combination digital and analog circuit that implements a self-adaptive noise filter (2). This circuit is now available in commercial hearing aids. The microprocessor is used to determine if background noise is present, the spectrum of the noise, and its intensity. The microprocessor is then used to access filters and set attenuation levels for the filters. The spectrum of the speech signal and the temporal characteristics of the speech signal are both taken into account in order to decide if there is background noise. The signal which has been processed through the adaptive filter is then sent through the standard hearing aid filter.

A simpler approach would be to design a filter to minimize noise for an individual listener based on knowledge of the spectrum of the noise and of the hearing characteristics of the listener. This type of filtering could be automatically activated in a digital hearing aid when background noise is detected. The underlying rationale for this type of filtering, which we call REDMASK (reduced masking), is to keep noise close to threshold in order to minimize the masking effect of the noise. At positive signal-to-noise ratios, acceptable speech intelligibility should be obtained. Because the noise is close to threshold, it is barely audible and, consequently, the quality of the signal should be superior to that of conventional amplification.

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definition of quality was provided to the subject in the instructions, so that each subject could use his own definition of quality. The filters were then rank ordered from 1 to 4 based on the results of each tournament. The number "1" represents the lowest rank and the number "4" represents the highest rank.

The portion of the study assessing the effect of filtering on the perception of intelligibility and quality was done in two parts. In the first part, continuous discourse was presented through the REDMASK filter at a sensation level of 10 dB. This assured that noise within all one-third octave bands would lie below the listener's threshold, since the signal-to-noise ratio was 15 dB. The hypothesis to be tested in this portion of the study was that the REDMASK processed signal would be judged of better quality (because of the absence of noise) than the signal processed through the other filters, although the intelligibility of the signal might not be optimal. The four filters presented in this part of the study consisted of the MCL-shaped, the highpass, the reference, and the REDMASK (10 SL) filters.

In the second part of the study, the continuous discourse was presented at a higher sensation level through the REDMASK filter (30 dB above the listener's threshold). It was hypothesized that perceived intelligibility would increase with increased sensation level, but that perceived quality would decrease (the noise in this experimental condition was 15 dB above threshold and 15 dB below the speech). The four filters evaluated in this second part of the study consisted of the MCL-shaped, the highpass, the reference, and the REDMASK (30 SL) filters. All of the filters used in the study were quite different from the types of filter provided by the subjects' own hearing aids.

Speech recognition scores were obtained on the N.U. Auditory Test No. 6 presented against a background of pink noise at a 15 dB signal-to-noise ratio through the various filters. Presentation levels were the same as those used for the intelligibility and quality judgments.

RESULTS AND DISCUSSION

Part 1. Judgments of perceived intelligibility and quality.

The rank data for individual subjects, mean ranks, and standard deviations for the intelligibility and quality tournaments are shown in **Table 2**. These data were analyzed using the Friedman rank analysis of variance technique. Separate analyses were done for the intelligibility and the quality data. The rank order of the four filters was found to differ significantly ($p < .05$) for paired-comparison judgments of relative intelligibility. The MCL-shaped filter was ranked highest and the REDMASK (10 SL filter) was ranked lowest. Mean ranks were 3.0 for the MCL-shaped filter, 2.95 for the reference filter, 2.5

Table 2
Ranks assigned on the basis of paired-comparison judgments of intelligibility and quality of speech-in-noise processed through four different filters. The number "4" represents the highest rank and number "1" represents the lowest rank.

Subject	Intelligibility judgments				Quality judgments			
	MCL	HP	REF	REDMASK (10 SL)	MCL	HP	REF	REDMASK (10 SL)
1	4	2.5	2.5	1	3.5	2	3.5	1
2	4	2	3	1	4	1	3	2
3	4	2	3	1	2	1	3	4
4	3	2	4	1	1	2	4	3
5	4	2	3	1	3	2	4	1
6	4	1	3	2	3	1	2	4
7	1	3.5	2	3.5	1	2.5	2.5	4
8	3	2	4	1	3	1	4	2
9	1	4	2	3	1	3	2	4
10	2	4	3	1	1	3	4	2
Mean	3	2.5	2.95	1.55	2.3	1.9	3.2	2.7
S.D.	1.2	1.0	.69	.96	1.2	.82	.82	1.3

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Table 3
One-third octave band pressure levels (dB SPL) for speech, noise, and thresholds for two subjects through the test filters.

	Center frequency Hz of one-third octave band	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
SUBJECT #1															
	Threshold	89	87	88	89	87	85	88	93	92	90	83	74	77	70
	MCL	104	103	102	101	100	104	108	113	114	114	113	114	112	110
Speech	Highpass	79	80	85	91	97	103	108	113	115	114	113	114	112	110
Signal	Reference	90	90	91	92	92	93	92	93	94	91	90	91	88	87
	REDMASK 10SL	82	81	81	79	81	82	85	90	88	87	79	69	71	64
	MCL	90	88	88	86	85	88	92	96	98	98	99	101	99	98
Noise	Highpass	66	66	71	76	81	87	92	96	98	99	98	101	99	98
Signal	Reference	77	76	76	77	76	76	76	77	77	76	75	77	76	75
	REDMASK 10SL	69	67	66	65	65	66	69	74	72	71	64	55	58	51
	Center frequency Hz of one-third octave band	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
SUBJECT #2															
	Threshold	78	79	80	78	71	67	65	65	67	65	64	66	64	67
	MCL	111	110	113	112	109	110	111	113	115	114	114	116	113	113
Speech	Highpass	84	84	88	95	100	106	111	113	115	114	114	116	114	113
Signal	Reference	92	95	100	103	102	100	97	97	99	95	91	94	89	93
	REDMASK 10SL	98	96	94	91	86	82	79	83	84	82	81	82	79	80
	MCL	96	95	96	95	91	91	92	94	96	96	97	100	98	99
Noise	Highpass	67	67	72	78	82	88	92	95	97	97	97	101	99	100
Signal	Reference	77	79	84	87	85	83	79	79	81	78	75	78	75	80
	REDMASK 10SL	82	80	77	74	69	65	63	66	66	65	65	67	66	68

for the highpass filter and 1.55 for the REDMASK (10 SL) filter. The Wilcoxon matched pairs test revealed that the mean rank of the REDMASK (10 SL) filter was significantly lower than that of the other three filters.

The rank order of the filters for judgments of quality differed from that for perceived intelligibility. The reference filter and REDMASK filter (10 SL) received the highest mean ranks (3.2 and 2.7, respectively), while the MCL-shaped filter and the highpass filter received lower mean ranks (2.3 and 1.9, respectively). The Friedman analysis of variance failed to reveal significant differences among the four filters.

The results of the judgments of perceived intelligibility are in agreement with the results of previous studies. The filters which placed the speech signal sufficiently above the listener's threshold (the MCL-shaped filter, the highpass filter, and the reference filter) resulted in a more intelligible speech-in-noise signal than a filter which kept the noise inaudible but also limited the audibility of the speech.

The quality judgments revealed a tendency for subjects to prefer the quality of the reference and the REDMASK (10 SL) filter. For four subjects the REDMASK (10 SL) filter was ranked highest and for four subjects the reference filter was ranked highest. The four filters produced signals which differed with regard to overall level as well as spectral content. A major difference between the MCL-shaped and highpass filters as opposed to the reference and REDMASK (10 SL) filters is the amount of high-frequency energy present. The reference filter and the REDMASK (10 SL) filter contain considerably less high-frequency energy than the MCL-shaped and highpass filters. The preference of these subjects for signals with less high-frequency emphasis is consistent with the find-

ings of Thompson and Lassman (7) and Lutman and Clark (4), whose subjects preferred a flat frequency rather than a rising frequency response. An example of the contrast between the different filters is shown in **Table 3**. One-third octave band pressure levels for the speech signal and for the pink noise are tabulated for the four different filters for two of the subjects. The subject's thresholds for one-third octave bands of noise also are included. As is evident from the table, there are large differences (up to 30 dB) between the band pressure levels for the various filters.

Part 2. Judgments of perceived intelligibility and quality.

The issue of the level of presentation and its effect on the intelligibility and quality of REDMASK processed speech was addressed in the second portion of the study. The MCL-shaped, highpass, and reference filters were identical to those used in the first part of the study. In this portion of the study, the REDMASK filtered signal was presented at 30 dB SL, rather than 10 dB SL.

The rank data for individual subjects, the mean ranks, and standard deviations for this second portion of the study are shown in **Table 4**. The reference and REDMASK (30 SL) filters received the highest ranks (3.2 and 3.1, respectively) and the MCL-shaped and the highpass filters received lower ranks (2.1 and 1.7, respectively) when intelligibility was used as a criterion. A Friedman analysis of variance revealed that the differences among filters was significant ($p < .05$). A post hoc Wilcoxon matched pairs test revealed that the mean rank of the highpass filter was significantly lower than that of the other three filters.

The results of the quality tournament revealed that the reference filter was perceived to result in the highest quality (rank = 3.3), followed by the MCL-shaped filter (rank = 2.5), the REDMASK (30 SL) filter (rank = 2.2), and the highpass filter (rank = 2.0). The Friedman analysis of variance failed to reveal significant differences among the ranks of these filters.

The results of the second part of the study demonstrate that increasing the sensation level of the REDMASK processed signal from 10 dB to 30 dB did result in the predicted increase in perceived intelligibility. The increase in level also resulted in the predicted decrease in quality. A comparison of the rankings by individual subjects of the quality of the REDMASK processed signal in the first quality tournament (REDMASK 10 SL) with their corresponding rankings in the second quality tournament (REDMASK 30 SL) revealed a systematic decrease in the quality ranking with an increase in sensation level. While four subjects ranked the REDMASK processed signal as having the highest quality at 10 dB SL, only one subject ranked REDMASK processed speech as having the highest quality at 30 dB SL. These results demonstrate that increasing the sensation level of the REDMASK processed signals

Table 4
Ranks assigned on the basis of paired-comparison judgments of intelligibility and quality of speech-in-noise processed through four different filters. The number "4" represents the highest rank and number "1" represents the lowest rank.

Subject	Intelligibility judgments				Quality judgments			
	MCL	HP	REF	REDMASK (10 SL)	MCL	HP	REF	REDMASK (30 SL)
1	2	1	4	3	3.5	1	3.5	2
2	2	1	3	4	3	2	4	1
3	2	1	4	3	2	1	4	3
4	2	1	3.5	3.5	2	1	4	3
5	2	1	4	3	3.5	2	3.5	1
6	4	1	3	2	3	1	4	2
7	1	3	2	4	1	3	4	2
8	2.5	1	2.5	4	3	1	2	4
9	1	4	2	3	1	4	2	3
10	2	3	4	1	3	4	2	1
Mean	2.1	1.7	3.2	3.1	2.5	3	3.3	2.2
S.D.	.83	1.2	.82	.96	.92	1.3	.92	1.0

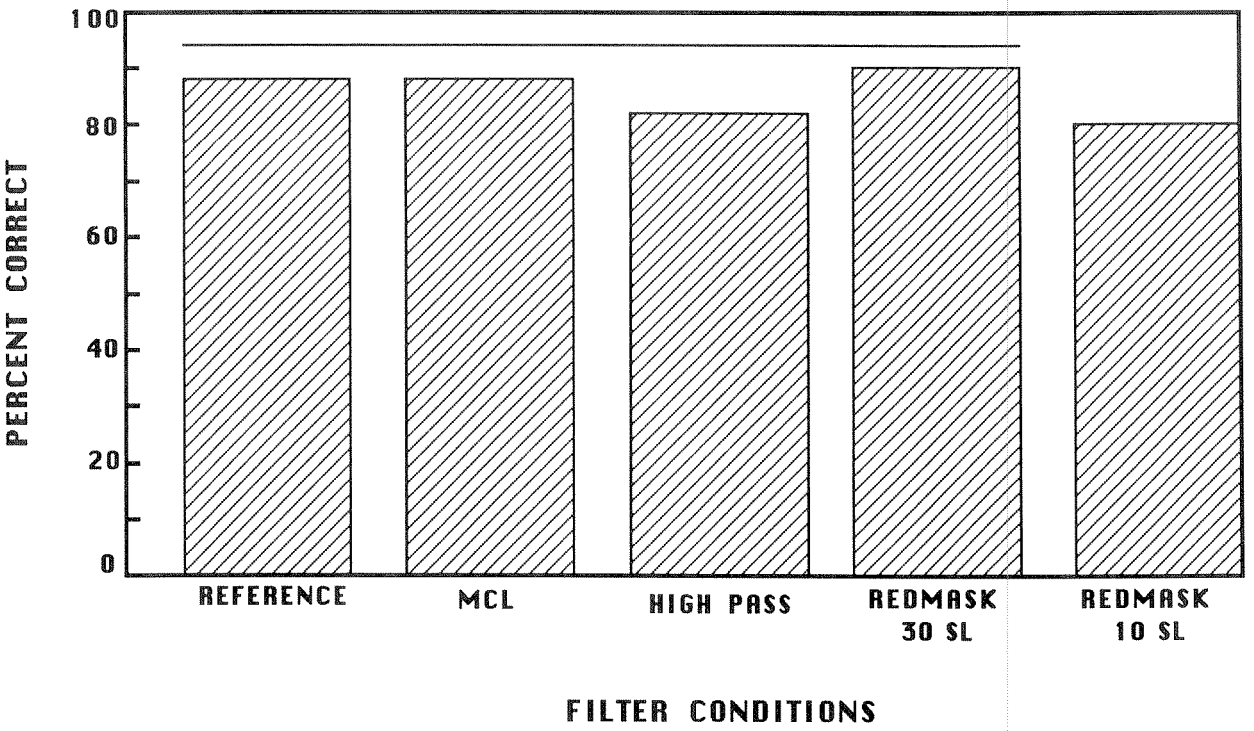

Figure 1.
Mean scores: percent correct on N.U. Auditory Test Number 6 through the five filter conditions. The horizontal line over the scores indicates means that do not differ significantly.

increased the relative intelligibility of the speech, but at the cost of a reduction in judged quality because of the increased audibility of the noise.

Results of Speech Recognition Tests

Speech recognition scores for the N.U. Auditory Test #6 (presented at 15 dB S/N) through each of the filters were converted from proportions to arcsine units to stabilize the error variance. The arcsine scores were then submitted to an analysis of variance. The factor of filtering was found to be significant ($F = 8.58$; $df = 4,36$; $p < .001$). Mean scores are shown in **Figure 1**. The mean scores obtained through the REDMASK (30 SL) filter, the MCL-shaped filter, and the reference filter are almost identical (89, 88 and 88 percent, respectively). The mean score obtained through the highpass filter was 83 percent and through the REDMASK (10 SL) filter was 69 percent

The results of the Tukey HSD method of post hoc testing are shown in **Figure 1**. A horizontal line over two or more means indicates that those means do not differ significantly. As is evident from the figure, the mean score for the REDMASK (10 SL) filter is significantly poorer than the mean scores of the MCL-shaped, the reference, or the REDMASK (30 SL) conditions. This finding is not unexpected and would be predicted by articulation index theory.

For the MCL-shaped, reference, and REDMASK (30 SL) filter, the amount of speech signal available is determined by the signal-to-noise ratio, rather than the listener's threshold. In the REDMASK (10 SL) condition, the listener's threshold determines the amount of available information, since the signal level was selected in a way that insured that the noise would be 5 dB below threshold. Since the signal-to-noise ratio used was 15 dB, approximately 5 dB less speech information was available in each band in the REDMASK (10 SL) condition.

CONCLUSIONS

The two filters that performed fairly well across both intelligibility and quality criteria were the reference filter and the MCL-shaped filter. The preference for the reference filter was somewhat surprising, although the fact that speech was presented in background noise may account for its good performance. The noise limited the amount of speech information available through all of the filters. As

was demonstrated in the speech recognition portion of the study, all of the filters that amplified the signal sufficiently to place the noise above threshold resulted in similar speech recognition scores. The quality of the noise, i.e., its annoyance, would change with different types of filtering. Although the differences in the filter ranks were not statistically significant, there was a trend for preference of a filter that would not emphasize high frequencies (the reference filter) or for a filter that would minimize noise (the REDMASK 10 SL filter).

The highpass filter did not seem to enhance intelligibility or quality of speech presented in a background of pink noise. Although speech recognition performance through this filter did not differ significantly from the other filters, the hearing-impaired listeners consistently ranked the highpass filter lower than the MCL-shaped filter or the reference filter for both intelligibility and quality. It is possible that, for a different type of noise, the finding might have been different.

With regard to the experimental REDMASK filter, approximately half of the subjects preferred the quality of the signal when noise was made inaudible (REDMASK 10 SL). Raising the sensation level of the signal improved speech intelligibility, but resulted in increased background noise and decreased quality. The advantage of using the REDMASK filter to maintain noise at threshold and to increase quality was thus lost. It is possible that if the REDMASK processed speech had been presented at 15 dB or 20 dB SL, quality could be maintained and optimal speech intelligibility could also be obtained, since the same amount of speech energy would be available through this filter as through the MCL-shaped filter.

An alternative method of achieving a higher speech level while keeping the noise inaudible would be to follow the REDMASK filter with an amplitude-expansion amplifier. Future experiments are planned to assess the usefulness of REDMASK plus expansion for increasing both intelligibility and quality of speech-in-noise.

APPENDIX

Instructions for Paired-Comparision Judgments of Relative Intelligibility

In this part of the experiment you will listen to pairs of hearing aids and then you will tell us which of the hearing aids makes the speech more intelligible for you. BY INTELLIGIBILITY WE MEAN THE ABILITY TO UNDERSTAND WHAT IS SAID. You will hear a man reading a passage. You will also hear a background noise. Try to ignore the noise. Listen to the speech through each hearing aid and then decide which makes the speech more intelligible for you.

Look at the terminal in front of you. You see a row of buttons; one is labeled "A" and the other is labeled "B." You will hear the speech through aid "A" first, you will then press the button labeled "B" in order to hear the speech through hearing aid "B." Listen through each hearing aid only long enough to gain a clear impression of the intelligibility of the speech, then switch to the other hearing aid. Listen to each hearing aid several times before reaching a final decision. Once you have decided which hearing aid makes the speech more intelligible, press the button marked "A" or "B" in the row labelled "SELECT." This will tell us which hearing aid you think makes the speech more understandable.

You must make a choice in each case.

After you make a choice, the examiner will choose two different hearing aids for comparison. When you hear the next recording, again begin listening through the two hearing aids, compare them, and make a new choice.

REMEMBER: YOU ARE TO CHOOSE THE HEARING AID WHICH MAKES THE SPEECH MORE INTELLIGIBILE. SWITCH BETWEEN HEARING AIDS UNTIL YOU CAN MAKE A CHOICE. YOU MUST MAKE A CHOICE IN EACH CASE.

Instructions for Paired-Comparison Judgments of Relative Quality

In this part of the experiment you will listen to pairs of hearing aids and then you will tell us which of the hearing aids is of higher quality. You will hear a man reading a passage. You will also hear background noise. Listen to the speech through each hearing aid and then decide which is preferable based on the quality of the sound.

Look at the terminal in front of you. You see a row of buttons marked "LISTEN" which contains two buttons; one is labeled "A" and the other is labeled "B." Listen through each hearing aid only long enough to gain a clear impression of the quality of the speech, then switch to the other hearing aid. Listen to each hearing aid several times before reaching a final decision. Once you have decided which hearing aid has a preferable quality, press the button marked "A" or "B" in the row labeled "SELECT." This will tell us which hearing aid you think has the better quality.

You must make a choice in each case.

After you make a choice, the examiner will choose two different hearing aids for comparison. When you hear the next recording, again begin listening through the two hearing aids, compare them, and make a new choice.

REMEMBER: YOU ARE TO CHOOSE THE HEARING AID WHICH IS OF BETTER QUALITY. SWITCH BETWEEN HEARING AIDS UNTIL YOU CAN MAKE A CHOICE. YOU MUST MAKE A CHOICE IN EACH CASE.

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