

# Low- and High-Pass Filtered Northwestern University Auditory Test No. 6 for Monaural and Binaural Evaluation

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## Abstract

Two protocols developed for the *Tonal and Speech Materials for Auditory Perceptual Assessment* audio compact disc are low- and high-pass filtered versions of the Northwestern University Auditory Test No. 6 (female speaker). Two experiments were performed on subjects with normal hearing to determine the needed filter characteristics of the words. In Experiment I, word-recognition performance was determined at 70 dB SPL for four low-pass cut-offs (800 to 1700 Hz) and for four high-pass cut-offs (1700 to 3000 Hz). Based on the data from Experiment I, the low-pass (1500-Hz cut-off) and high-pass (2100-Hz cut-off) conditions were selected for inclusion on the compact disc. In Experiment II, psychometric functions were obtained in quiet for the two filter conditions with lists 3 and 4 included on the compact disc. Because the high-pass filtered words were recorded on channel 1 and concurrently the corresponding low-pass filtered words were recorded on channel 2, a binaural fusion paradigm is also available on the compact disc. For the compact disc trials, which involved 120 subjects with normal hearing, psychometric functions were generated for monaural low-pass, monaural high-pass, and binaural spectral fusion (low- and high-pass) conditions, with each of the subjects providing data at one of six levels for each of three conditions.

**Key Words** Binaural spectral fusion, high-pass filtered, low-pass filtered

This paper describes two monaural filtered speech paradigms in which the Northwestern University Auditory Test No. 6 (NU No. 6), female speaker, were degraded by low- and high-pass filtering. When presented concurrently, the two monaural speech tasks constitute a binaural spectral fusion listening paradigm. These filtered speech materials are included on the *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0* compact disc.

Filtered speech materials were introduced as a diagnostic technique for temporal lobe prob-

lems by Bocca et al (1954), who observed that with monaural low-pass filtered materials, word-recognition performance by patients with temporal lobe lesions was poorer in the ear contralateral to the lesion than in the ear ipsilateral to the lesion. A second use of filtered speech materials involves the binaural spectral fusion paradigm described by Matzker (1959), in which a low-pass band of a speech signal is presented to one ear and a high-pass band of the speech signal is presented to the other ear. Matzker and other investigators (Linden, 1964; Smith and Resnick, 1972) reported that the binaural spectral fusion task was sensitive to lesions in the brain stem. More recently, low-pass filtered materials presented monaurally and binaural spectral fusion materials have been incorporated into the Willeford (1977) test battery.

The degradation of the speech signal that is produced by filtering is affected by the cut-off frequency of the filter and by the rejection rate of the filter. The following are three generali-

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ties that may be applied: (1) for low-pass filtered materials, the lower the cut-off frequency, the poorer the word-recognition performance; (2) for high-pass filtered materials, the higher the cut-off frequency, the poorer the word-recognition performance; and (3) for both low-pass and high-pass filtering techniques, the steeper the rejection rate of the filter, the poorer the word-recognition performance.

Two experiments were performed to define the effect that low- and high-pass filtering had on word-recognition performance of the NU No. 6. The purpose of Experiment I was to document the effects that four low-pass and four high-pass cut-off frequencies had on the monaural word-recognition performance of young adults at a comfortable listening level. The four cut-off frequencies selected for each condition represented the range of listening from difficult to easy. The target cut-off frequency was one that produced 70 to 80 percent correct word-recognition performance at a comfortable listening level. The purpose of Experiment II was to define the psychometric functions for the low- and high-pass frequency cut-offs that provided the target performance. The compact disc trials provided the psychometric functions for the filtered materials recorded on the compact disc. Three conditions were studied in the compact disc trials (monaural low-pass filtered, monaural high-pass filtered, and binaural spectral fusion, i.e., simultaneous low-pass filtered to one ear and high-pass filtered to the other ear).

## METHOD

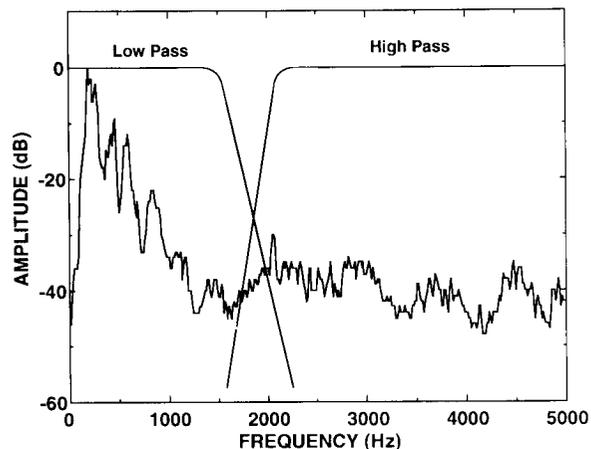
### Material Preparation

The four lists of the NU No. 6 spoken by a female were digitized from an analog recording (Revox, Model B77) using a 16-bit analog-to-digital converter (Antex, Model SX-10) at 20,000 samples/sec and an antialiasing filter set to 8800 Hz (96 dB/octave rejection). Following the digitization, the files were edited to minimize the file length. (These are the digital masters from which the NU No. 6 materials included on the *Speech Recognition and Identification Materials, Disc 1.1* compact disc were made [Wilson et al, 1990, 1991].) Each file was interleaved with itself to provide two isolated channels of materials.

The recorded randomizations of the filtered word lists were obtained by passing the two outputs of the digital-to-analog converter

through filters (Wavetek, Model 753A) that had rejection characteristics of 115 dB/octave. The first filter low passed one channel and the second filter high passed the other channel. The filtered signals were then recorded on the two channels of a digital audio tape (DAT) (Sony, Model PCM-2500A). In this manner, low-pass and high-pass versions of the same materials were recorded simultaneously. The materials were calibrated to a 1000-Hz tone that reflected the peaks of the unfiltered words on a VU meter. On the final recordings, then, the words in some of the low-pass conditions, especially the wider filter conditions, continued to peak at 0 VU, whereas all of the words in the high-pass conditions peaked at levels substantially below 0 VU (e.g., -25 VU and below). This relationship in calibrating the low- and high-pass materials is illustrated in Figure 1, in which the averaged normalized spectra of these NU No. 6 materials are shown (from Fig. 1, Wilson et al, 1991), along with idealized low-pass filter (1500-Hz cut-off with 115 dB/octave rejection) and high-pass filter (2100-Hz cut-off with 115 dB/octave rejection) functions. Within the low-pass filter, the low-frequency energy in the speech spectrum continues to peak at 0 dB. In contrast, within the high-pass filter, the high-frequency energy in the speech spectrum peaks at -30 dB.

For data collection during Experiments I and II, the materials recorded on DAT were reproduced (Sony, Model PCM-2500A) and fed through an audiometer (Grason-Stadler, Model 10) to a TDH-50P earphone encased in a P/N 510C017-1 cushion. The subjects in Experiments



**Figure 1** Average normalized spectra of the NU No. 6 materials spoken by a female speaker are shown with idealized low-pass (1500-Hz cut-off) and high-pass (2100-Hz cut-off) filter functions (115 dB/octave rejection). (Modified from Wilson et al, 1991.)

I and II wrote their responses while seated in a double-walled sound booth (IAC, Model 1203A).

### Experiment I

Four randomizations of each of the four lists of NU No. 6 were recorded on DAT for each of four low-pass conditions (800-, 1200-, 1500-, and 1700-Hz cut-offs) and four high-pass conditions (1700-, 2100-, 2500-, and 3000-Hz cut-offs). Eight young adults (mean age 20.5 years) with normal hearing ( $\leq 20$  dB HL, ANSI, 1989) listened to two lists for each of the eight filtered conditions at 70 dB SPL.

### Experiment II

Two randomizations of each of the four NU No. 6 lists were recorded on DAT for a low-pass cut-off of 1500 Hz and for a high-pass cut-off of 2100 Hz. Fifteen young adults with normal hearing ( $\leq 20$  dB HL, ANSI, 1989) participated in two 1-hour sessions, during each of which a psychometric function for one of the filtered conditions was obtained. The functions were obtained at eight levels in 8-dB increments from 2 dB above the speech-recognition threshold (for most subjects, the eight levels were in the 22 to 82 dB SPL range).

### Compact Disc Trials

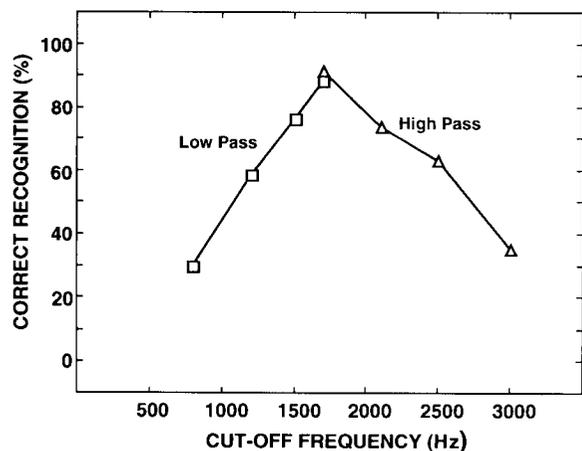
The compact disc trials involved 120 young adults with normal hearing who are described by Noffsinger et al (1994). Psychometric functions were obtained for lists 3 and 4 of the NU No. 6 for the following three filtered conditions (tracks 11 and 12): (1) monaural low-pass filtered with a 1500-Hz cut-off; (2) monaural high-pass filtered with a 2100-Hz cut-off; and (3) binaural with the low-pass condition to one ear simultaneous with the high-pass condition to the other ear. Six levels were used with the two monaural filtered conditions (15, 25, 35, 45, 55, and 65 dB HL [35 to 85 dB SPL]) and the binaural spectral-fusion condition (6, 12, 18, 24, 30, and 36 dB HL [26 to 56 dB SPL]). To avoid familiarization with the test materials, each of the 120 subjects with normal hearing listened only to one list of the materials for each of the three conditions. In this manner, data from 20 different subjects were obtained for each of the six points on the psychometric functions. Thus, with the 120 subjects, the monaural low- and high-pass conditions were evaluated at the same level with only a few (random) subjects.

To simulate clinic conditions, supplemental data were collected in which the monaural low- and high-pass conditions were presented at one level (65 dB HL) to 40 adults (mean = 27.6 years) with normal hearing. Each of these listeners, who were new to the study, were presented lists 3 and 4 of the NU No. 6 (tracks 11 and 12) under both the low- and high-pass filtered conditions. The list order and filter condition order were randomized.

## RESULTS AND DISCUSSION

### Experiment I

The mean correct recognition (in percent) obtained from the eight subjects at 70 dB SPL with the four low-pass conditions (squares) and with the four high-pass conditions (triangles) is shown in Figure 2. As the low-pass cut-off was increased from 800 Hz to 1700 Hz, there was a corresponding increase in performance from 30 percent correct to 88 percent correct. Similarly, as the high-pass cut-off was decreased from 3000 Hz to 1700 Hz, there was a corresponding increase in performance from 35 percent correct to 91 percent correct. The conditions that met the 70 to 80 percent correct target performance were the 1500-Hz cut-off for the low-pass condition (76.5% correct) and the 2100-Hz cut-off for the high-pass (73.5% correct). The crossover frequency of the current speech materials was 1725 Hz as calculated from the intersection of



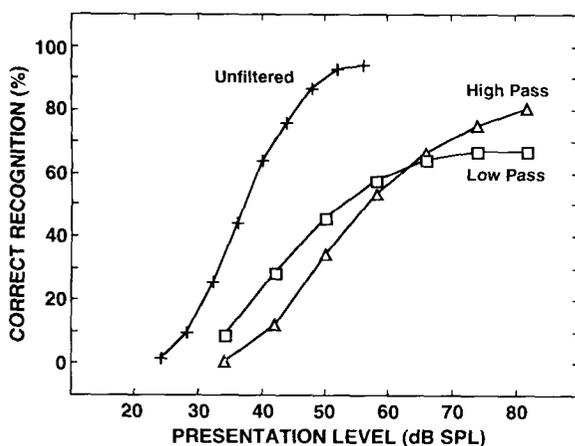
**Figure 2** Mean correct recognition (in percent) for the NU No. 6 materials ( $n = 8$ ) obtained at 70 dB SPL with the respective low-pass filter frequency (squares) and high-pass filter frequency (triangles) cut-offs in Experiment I.

the linear regressions used to fit the functions.<sup>1</sup> The 1725-Hz crossover frequency is slightly higher than the 1454-Hz and 1563-Hz crossover frequencies reported recently for the NU No. 6 materials spoken by a male speaker (Schum et al, 1991; Studebaker et al, 1993) and slightly below the 1900-Hz frequency cut-off above and below which French and Steinberg (1947) suggested equal contributions to intelligibility. Experiment II was conducted to establish psychometric functions for the NU No. 6 materials under these two filtered conditions.

### Experiment II

The psychometric functions obtained from the 15 listeners for the low-pass filtered condition (squares) and the high-pass filtered condition (triangles) are shown in Figure 3, along with the normal psychometric function for the NU No. 6 materials (unfiltered—pluses) (from Wilson et al, 1990). With respect to the normal unfiltered function, the functions for the filtered conditions are displaced to the higher sound pressure levels (15 to 18 dB at 50% correct) and have slopes that are more gradual.

<sup>1</sup>The following linear regression equations represent the mean data for the low-pass and high-pass conditions in Experiment I:  
 low pass:  $y = -20.56 + 0.064565x$  ( $R^2 = 0.99$ ); and  
 high pass:  $y = 162.69 - 0.041671x$  ( $R^2 = 0.98$ ).



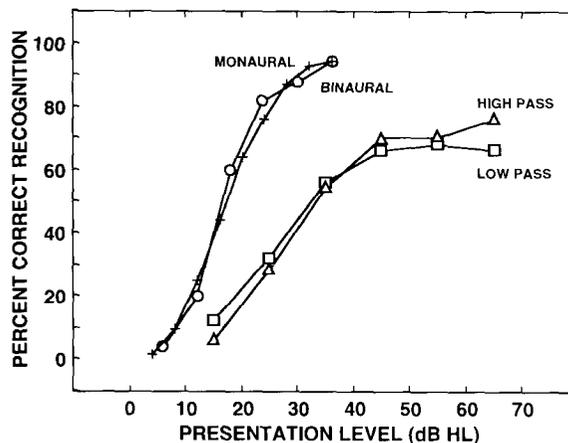
**Figure 3** Psychometric functions obtained in Experiment II ( $n = 15$ ) for the low-pass filtered (1500-Hz cut-off) condition (squares) and the high-pass filtered (2100-Hz cut-off) condition (triangles). The normal, unfiltered psychometric function for the NU No. 6 materials female speaker (+) is depicted for reference on the left side of the figure (from Wilson et al, 1990).

Between the 20 percent and 60 percent correct points the slopes of the functions<sup>2</sup> are 1.7 percent/dB (low pass) and 2.2 percent/dB (high pass); the slope of the normal NU No. 6 function (unfiltered) between the 20 percent and 60 percent correct points is about 4.5 percent/dB (Wilson et al, 1990).

### Compact Disc Trials

The mean data from the compact disc trials for the two monaural conditions and the binaural condition are presented in Figure 4 and in Table 1. In the figure, the percent correct recognition for the low-pass cut-off condition (squares), for the high-pass cut-off condition (triangles), and for the binaural (low pass to one ear and high pass to the other ear) condition (circles) are illustrated along with the normal psychometric function for the NU No. 6 materials (pluses) (Wilson et al, 1990). Each datum point on each of the three functions is the mean performance of 20 subjects. As expected, the

<sup>2</sup>The mean data for the low-pass and high-pass conditions were fit with third-degree polynomials from which the displacements of the functions and the slopes of the functions were calculated. The following equations represent the functions in Experiment II ( $R^2 = 0.99$ ):  
 low pass:  
 $y = -135.61 + 5.6400x - 0.042950x^2 + 0.0052083x^3$ ; and  
 high pass:  
 $y = 20.363 - 3.8853x + 0.012462x^2 - 0.0008350x^3$ .



**Figure 4** Percent correct recognition obtained from the compact disc trials (20 subjects/datum point) for the low-pass filtered (1500-Hz cut-off) condition (squares), the high-pass filtered (2100-Hz cut-off) condition (triangles), and the binaural (low pass to one ear and high pass to the other ear) condition (circles). The normal, monaural psychometric function for the NU No. 6 materials female speaker (+) is depicted for reference on the left side of the figure (from Wilson et al, 1990).

**Table 1 Mean and Standard Deviation Percent Correct Recognition at Each of Six Presentation Levels during Compact Disc Trials**

	Presentation Level (dB HL)						
	15	25	35	45	55	65	(65)
Low-Pass Filtered							
Mean	11.8	32.0	56.4	65.2	67.0	66.6	(66.5)
SD	11.1	9.8	10.8	10.5	8.9	11.3	(8.5)
High-Pass Filtered							
Mean	5.9	27.8	53.0	69.2	69.6	75.2	(77.7)
SD	9.0	18.6	16.5	9.0	9.9	13.2	(6.9)
	Presentation Level (dB HL)						
	6	12	18	24	30	36	
Binaural Low- and High-Pass Filtered							
Mean	3.2	21.6	58.4	79.0	88.4	95.2	
SD	5.6	18.7	15.0	15.8	11.0	4.3	

Each datum point was obtained from 20 listeners with normal hearing. The data in parentheses (far right column) are from the 40 listeners in the supplemental study.

binaural condition produced a function that is essentially identical to the function for the unaltered NU No. 6 materials presented monaurally in quiet. The slopes of the two functions are the same, 4.3 percent/dB (binaural) and 4.5 percent/dB (monaural) with < 1 dB separating the functions.

With respect to the functions for the monaural (normal) or for the binaural conditions, the functions for the high- and low-pass filtered conditions are different in three ways. First, the functions for the two filtered conditions, which are very similar to one another, are displaced to the higher presentation levels by 8 dB at 20 percent correct recognition to 21 dB at 80 percent correct.<sup>3</sup> Second, the slopes of the functions for the filtered conditions are about one half the slope values for the reference conditions, 2.1 percent/dB for the high-pass condition, and 1.8 percent/dB for the low-pass condition. These slopes are the same as the slopes for the corresponding functions established in Experiment II. Third, the functions for the filtered condi-

tions reach maximum correct recognition (about 70% correct recognition) at about 50 dB HL, which is in close agreement with the findings in Experiments I and II.

The supplemental data from the 40 subjects with normal hearing demonstrated that mean recognition performance on lists 3 and 4 were 67.9 percent and 65.1 percent, respectively, for the low-pass condition, and 76.5 percent and 78.9 percent, respectively, for the high-pass condition. Because the differences between the mean data for the two lists were not significant ( $F [1, 39] = 0.019, p > .05$ ), the data for the two lists were combined and are presented in Table 1 (far right column in parentheses). At 65 dB HL, the mean recognition data from the supplemental experiment are the same as the mean recognition data from the compact disc trials. Performance on the high-pass condition was 11.2 percent better than performance on the low-pass condition, with 35 of the 40 subjects having 2 percent to 30 percent (range) better performance on the high-pass condition than on the low-pass condition.

The goal of this series of experiments was to develop a set of low-pass and high-pass filtered speech materials that for listeners with normal hearing: (1) produced equivalent word-recognition performance as a function of presentation level; (2) produced maximum performance of 70 percent correct recognition; and (3) produced normal word-recognition performance at low presentation levels when the two filtered conditions were presented in a binaural paradigm.

<sup>3</sup>The mean data for the three experimental conditions were fit with third-degree polynomials from which the displacements of the functions and the slopes of the functions were calculated. The following equations were generated to represent the functions ( $R^2 = 0.99$ ):

low pass:

$$y = -37.16 + 3.6243x - 0.027647x^2 - 0.0000574x^3;$$

high pass:

$$y = -43.54 + 3.5505x - 0.020380x^2 - 0.0000991x^3;$$

and binaural:

$$y = -17.40 + 2.3317x + 0.159920x^2 - 0.0038580x^3.$$

The data in Figure 4 indicate that these goals for the most part were achieved.

The data from the compact disc trials define on young adults with normal hearing the effects that low-pass filtering, high-pass filtering, and binaural spectral fusion (low-pass filtered speech to one ear and high-pass filtered speech to the other ear) had on the word-recognition performance of the NU No. 6 materials (female speaker). Additional data are needed to define the effects of these speech degradations on patients who are older, patients who have peripheral hearing loss, and patients who have a variety of neurologic impairments.

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