Temporal Fine-Structure Cues to Speech and Pure Tone Modulation in Observers with Sensorineural Hearing Loss

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Objective: The purpose of this study was to examine the effect of sensorineural hearing loss on the ability to make use of fine temporal information and to evaluate the relation between this ability and the ability to recognize speech.

Design: Fourteen observers with normal hearing and 12 observers with sensorineural hearing loss were tested on open-set word recognition and on psychophysical tasks thought to reflect use of fine-structure cues: the detection of 2 Hz frequency modulation (FM) and the discrimination of the rate of amplitude modulation (AM) and quasifrequency modulation (QFM).

Results: The results showed relatively poor performance for observers with sensorineural hearing loss on both the speech recognition and psychoacoustical tasks. Of particular interest was the finding of significant correlations within the hearing-loss group between speech recognition performance and the psychoacoustical tasks based on frequency modulation, which are thought to reflect the quality of the coding of temporal fine structure.

Conclusions: These results suggest that sensorineural hearing loss may be associated with a reduced ability to use fine temporal information that is coded by neural phase-locking to stimulus fine-structure and that this may contribute to poor speech recognition performance and to poor performance on psychoacoustical tasks that depend on temporal fine structure.

The present study investigated the relation between speech recognition and performance on psychoacoustical tasks that are thought to depend on the fidelity with which temporal fine structure is neurally represented in observers with sensorineural hearing loss. Several previous studies have investigated relations between speech perception and performance on psychoacoustical tasks (e.g., Dreschler & Plomp, 1985; Festen & Plomp, 1983; Glasberg &

Moore, 1989; Horst, 1987; Tyler, Summerfield, Wood & Fernandes, 1982). These studies have measured performance on a variety of auditory tasks, most notably tasks involving pure tone detection thresholds, frequency resolution, and temporal gap detection. In general, the correlation between such variables and speech performance has been found to be relatively modest, particularly when statistically controlling for variability in audiometric thresholds (see Moore, 1995 for a review).

In the present study, the focus on psychoacoustical tasks related to temporal fine structure was motivated by the hypothesis that neural phase-locking (Kiang, Watanabe, Thomas & Clark, 1965) may provide useful cues for speech recognition (Miller, Schilling, Franck & Young, 1997; Young & Sachs, 1979). For example, studies in the cat suggest that auditory nerve phase-locking may provide important information about vowel formant frequencies, particularly for speech presented at moderate to high stimulus levels (Young & Sachs, 1979). Although several studies have demonstrated good retention of speech comprehension in observers with normal hearing after stimulus manipulations that disrupt temporal fine structure (e.g., Saberi & Perrott, 1999; Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995), it is plausible that fine-structure cues could play a role in speech comprehension under conditions in which some of the other redundant cues are absent (e.g., Stickney, Nie & Zeng, 2002), such as might be the case in sensorineural hearing loss.

Research on auditory neuropathy, more recently referred to as "auditory dys-synchrony," has suggested that the pronounced speech processing deficits relative to pure tone threshold characterizing this disorder may be due to pronounced deficits in temporal processing (e.g., Zeng, Oba, Garde, Sininger & Starr, 1999). Whereas the speech processing deficits associated with auditory dys-synchrony may be due to a reduced ability to code the coarser temporal information associated with the envelope in addition to the cycle-by-cycle information coded by phase-locking to temporal fine structure, this condition nevertheless highlights the importance of temporal coding for the understanding of speech.

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Because of the possible importance of phase-locking in speech recognition, it is of interest to examine the possibility that poor speech recognition in observers with sensorineural hearing loss may be due to a reduced ability to process sound through neural phase-locking. In this regard, it is appropriate first to consider whether existing data suggest that phase-locking may be reduced as a result of sensorineural hearing loss. The physiological data are mixed on this question. Whereas an animal study by Woolf, Ryan, and Bone (1981) indicated degraded phase-locking in individual auditory nerve fibers, studies by Harrison and Evans (1979) and Miller et al. (1997) did not provide consistent evidence for a reduction in the precision of phase-locking.

Existing psychophysical data are generally consistent with an interpretation that sensorineural hearing loss may be associated with degraded phase-locking, or, perhaps, a reduced ability to interpret phase-locking information. One example comes from a complex pitch perception study by Arehart and Burns (1999). The primary hypothesis of that study was that reduced pitch perception in observers with sensorineural hearing loss is due to poor frequency selectivity. This hypothesis was tested by contrasting pitch perception for two-component complex tones in which the tones were either both presented to the same ear or were presented dichotically (one component to each ear). Arehart and Burns reasoned that if poor frequency selectivity were an important factor contributing to poor pitch perception performance in the observers with hearing loss, performance would improve in the dichotic condition where the tones fell into separate auditory channels. The results indicated similar performance in the monotic and dichotic conditions, a finding that is incompatible with a frequency selectivity interpretation. It was argued that the poor complex pitch perception in observers with sensorineural hearing loss might instead be due to a degraded ability to make use of fine temporal cues.

Psychoacoustical studies on the detection of low rate frequency modulation (FM) are also pertinent to this question. Moore and Sek (1995; 1996) have argued that FM detection for a low rate of FM (e.g., 2 to 5 Hz) depends on the ability of the auditory system to phase-lock to the temporal fine structure of the carrier frequency. This argument is based in part on similarities between FM and amplitude modulation (AM) detection at high carrier frequencies, where phase-locking is absent, but differences at low carrier frequencies, where phase-locking is present. Previous studies have shown that some observers with sensorineural hearing loss exhibit poor performance on this type of task (Lacher-Fougere & Demany, 1998; Moore & Skrodzka, 2002;

Zurek & Formby, 1981), and these results have been interpreted in terms of reduced phase-locking in sensorineural-impaired ears.

For the purposes of the present study, two psychophysical tasks thought to be based on temporal fine-structure cues were identified. One task was the low rate FM detect task, at carrier frequencies of 500 and 1000 Hz. The second task used here was modulation rate discrimination for 100 Hz modulation at a carrier frequency of 1500 Hz, with both amplitude and quasifrequency modulated (QFM) stimuli. Because modulation rate was always reduced from the 100 Hz standard, the sidebands should not be spectrally resolvable from the carrier at this frequency (Houtsma & Smurzynski, 1990), so that discrimination is likely to be based on temporal rather than spectral cues. For AM stimuli, temporal information at the 1500 -Hz carrier frequency might be based on phase-locking to the fine structure or to the envelope of the stimulus (Hall, Buss & Grose, 2003). Because QFM is associated with a shallow temporal envelope, it was thought that performance on this condition would be more likely to depend on the temporal fine structure rather than the temporal envelope (Hall et al., 2003). Contrasted with the AM stimulus, the QFM stimulus was therefore expected to provide a more sensitive indication of the coding of temporal fine structure. For both of these psychophysical tasks, observers with normal hearing were tested in quiet and in the presence of a background masking noise. The purpose of this background masker was to elevate thresholds, such that the signal level (defined in dB SL) was comparable to that of observers with hearing loss (see Moore, 1995).

In the present study, speech recognition was assessed for both unfiltered speech and for speech low pass–filtered at 1800 Hz. There were two reasons for this filtering. One was to make the task more difficult, such that ceiling effects could be avoided. The other was to limit the speech energy to the frequency range where phase-locking is most robust (Kiang et al., 1965; Rose, Brugge, Anderson & Hind, 1967), and therefore most likely to be of consequence for the perception of speech.

METHODS

Observers

Observers with normal hearing serving as experimental control subjects were 14 adults, 1 man and 13 women, ranging in age from 19 to 48 yr (mean = 27.5 yr). None of these observers had a history of ear problems, and all had pure tone thresholds of 15 dB HL or less at octave frequencies 250 Hz to 8 kHz. Observers with sensorineural hearing loss had mild

to moderate hearing impairments and were recruited from the Speech and Hearing Clinic at The University of North Carolina Hospitals. This group comprised 12 adults, 9 men and 3 women, ranging in age from 23 to 55 yr (mean = 45 yr). Obs HL3 had a confirmed case of Meniere disease, and pathogenesis for the remaining observers was unknown, though clinical assessment suggested a cochlear site of lesion. Table 1 shows audiometric data on the observers with hearing loss, along with the plotting symbol used to report data below. All 12 of the observers with hearing loss and all but one of the observers with normal hearing participated in the FM detection experiment. Eight of the 12 observers with hearing loss and all but one of the observers with normal hearing completed the modulation rate discrimination tasks. One data set was eliminated because the observer was inadvertently run at an inappropriate (high) sound level, and other missing data were due to observer availability. All observers were paid for their participation.

Stimuli

Speech Recognition • The AudiTech recordings of NU-6 words (lists 1 through 3) were used for speech testing. For each speech recognition score reported, the score is based on a single 50-item word list. Stimuli were either played directly from the CD or were low pass–filtered at 1800 Hz (Kemo, VBF 8).

Frequency Modulation Detection • Stimuli were computed in the time domain according to the following equation:

$$x(t) = \sin(2\pi f_c t + \beta \sin 2\pi f_m t)$$

$$\beta = \Delta f / f_m$$

where f_c is the carrier frequency, either 500 or 1000 Hz, f_m is the modulation rate, in this case 2 Hz, and Δf is the modulation depth. All stimuli were 400 msec in duration including $\cos^2$ ramps, which were

20 msec in duration between the 10% and 90% points.

Modulation Rate Discrimination • Stimuli were generated in the time domain. A 1500 Hz carrier tone was generated and summed with two additional tones (sidebands), spaced at equal frequency steps above and below 1500 Hz. In the AM condition, those sidebands were half the amplitude of the carrier, and all components were in cosine starting phase. In the QFM condition, the sidebands were half the amplitude of the carrier, and the starting phase of the lowest frequency tone lagged that of the other tones by π radians. All stimuli were 400 msec in duration, including $\cos^2$ ramps, which were 20 msec in duration between the 10% and 90% points.

Procedures

Speech Recognition • Speech testing was carried out using standard clinical procedures. The order of stimulus sets was random across observers, some hearing the original (full-spectrum) and some hearing the filtered lists first. Before each speech list, the speech detection threshold was established by using one of the extra NU-6 lists, and that threshold was used as a reference for determining the 35 dB SL level at which speech recognition was determined.

Procedures Common to Psychoacoustical Measures • In the psychoacoustical procedures, each threshold estimate was made based on a 3-down, 1-up track, estimating the 79% correct point on the psychometric function (Levitt, 1971). In this procedure, the signal cue was reduced after 3 correct responses, and the cue was increased after a single incorrect response. These adjustments were made in factorial steps of 1.2. Tracks continued until 8 reversals had been obtained, and threshold estimates for these tests were the geometric mean of the last 6 track reversals. The data reported here are the geometric mean of 3 or 4 threshold estimates for

TABLE 1. Thresholds and plotting symbols for observers with hearing loss

	obs	ear	Frequency (Hz)					
			250	500	1000	2000	4000	8000
✗	HL1	L	35	35	40	35	45	60
⋈	HL2	R	55	55	55	30	45	50
✕	HL3	R	55	55	55	50	45	45
◣	HL4	R	20	35	50	55	100	75
▲	HL5	R	70	75	75	65	55	75
◢	HL6	R	55	45	25	25	45	55
▼	HL7	L	55	55	40	50	50	55
■	HL8	R	35	40	45	50	50	65
◆	HL9	L	25	40	50	50	55	60
●	HL10	L	30	35	45	65	50	35
✚	HL11	L	45	50	55	55	50	60
#	HL12	L	15	30	45	50	50	45

frequency modulation detection and 6 estimates for modulation rate discrimination. The observers with normal hearing were run in quiet and in the presence of a 40 dB spectrum level gaussian background masker. This masker raised detection threshold and, consequently, stimulus presentation levels defined relative to threshold; the resultant levels were more comparable to those used for observers with hearing loss, who had median thresholds of 40 to 50 dB HL at the stimulus frequencies tested here. To minimize the effects of practice on these data, each subject spent a full 1 hr session on each condition.

Frequency Modulation Detection • In the frequency modulation paradigm, the observer's task was to select the interval containing a frequency modulated tone, with pure tone stimuli in the non-signal intervals. The modulation depth (Δf) was some value greater than 0 and represents the range over which the FM tone varied in frequency. In this task, all observers were run at 25 dB SL, with level set relative to the pure tone detection threshold at 500 or 1000 Hz.

Modulation Rate Discrimination • For modulation rate discrimination, the rate of modulation was 100 Hz in the standard interval, and in the target interval the modulation was $100 - \Delta f$ Hz. In this task, Δf was the decrement in modulation rate from the 100 Hz standard, so Δf took on values between 0 and 100. The value of Δf was never allowed to fall below 0 Hz or above 100 Hz. Stimuli were presented at 25 dB SL relative to the pure tone detection threshold at 1500 Hz.

RESULTS

Speech Recognition

Speech recognition data are shown in Figure 1. Data for individual observers with hearing loss are indicated with the symbols shown in Table 1, and the open circles show the mean scores for observers with normal hearing, with error bars indicating the 95% confidence interval around that mean. An arcsine transform was performed on the speech percent correct data before all analyses (Thornton & Raffin, 1978); tick marks along the ordinate in Figure 1 reflect this scale. All observers with normal hearing scored 98% to 100% on the full-spectrum speech stimuli and 82% to 98% on the filtered speech stimuli. Observers with hearing loss scored an average of 79% correct on the full-spectrum speech stimuli (4% to 98%) and 49% on the filtered stimuli (0% to 86%). A repeated-measures, split-plot analysis of variance (ANOVA) (Kirk, 1968) with a between-subjects factor of group and a within-subjects factor of stimulus filtering showed a main effect of group ($F_{1,24} = 13.39$, $p < 0.001$) and of stimulus
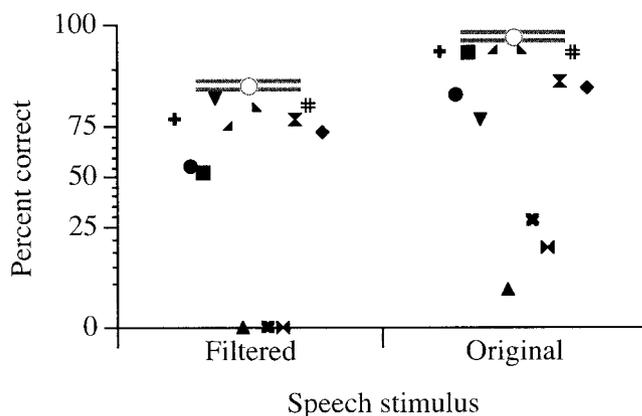

Fig. 1. Speech recognition scores for the original (full-spectrum) and the filtered stimulus are plotted in percent correct. Tick marks along the abscissa are spaced in equal arcsine units. Data for observers with hearing loss are plotted with unique symbols (as indicated in Table 1). Average data for observers with normal hearing are plotted with open circles, and error bars indicate the 95% confidence interval, defined as ± 2 standard error of the mean.

filtering ($F_{1,24} = 93.89$, $p < 0.00001$) and no interaction ($F_{1,24} = 1.37$, $p = 0.25$). That is, observers with normal hearing performed better than those with hearing loss, and filtering the speech stimulus reduced scores, but this effect was not different across the two populations.

Frequency Modulation Detection

Figure 2 shows FM detection threshold estimates for individual observers with hearing loss (with symbols in Table 1) and for the observers with normal hearing tested in noise (filled circle) and in quiet (open circle); error bars indicate the 95% confidence limits around those means. All statistics were performed on the natural log of the threshold values. A repeated-measures ANOVA with factors of frequency and background noise was performed on the data from observers with normal hearing; this indicated a significant effect of frequency ($F_{1,12} = 54.27$, $p < 0.0001$), no effect of background noise ($F_{1,12} = 0.26$, $p = 0.62$), and no interaction ($F_{1,12} = 3.10$, $p = 0.10$). A repeated-measures, split-plot ANOVA was also performed to examine differences between the observers with normal hearing and those with hearing loss, using a between-subjects factor of group and a within-subjects factor of frequency. For the observers with normal hearing tested in quiet, this analysis showed a significant effect of group ($F_{1,23} = 28.11$, $p < 0.0001$) and of frequency ($F_{1,23} = 19.75$, $p < 0.001$), but the interaction between group and frequency failed to reach significance ($F_{1,23} = 0.03$, $p = 0.87$). That is, observers with normal hearing performed better than
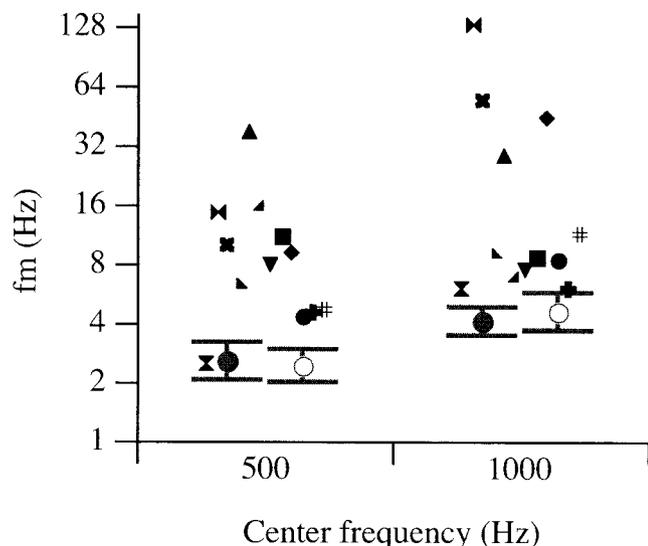
Fig. 2. Thresholds on the FM detection test at 500 and 1000 Hz are plotted. Data for observers with hearing loss are plotted with unique symbols (as indicated in Table 1). Average data for observers with normal hearing are plotted with circles, filled circles for testing in noise background, and open circles for testing in quiet. Error bars indicate the 95% confidence interval, defined as ± 2 standard error of the mean.
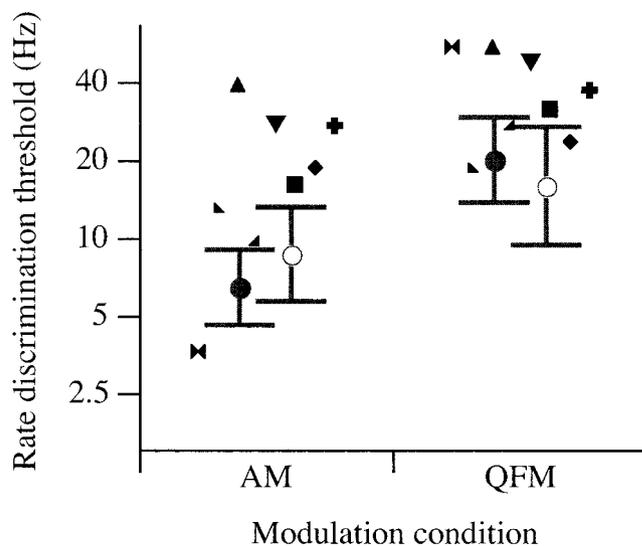

Fig. 3. Thresholds on the modulation rate discrimination test for AM and QFM stimuli are plotted. Data for observers with hearing loss are plotted with unique symbols (as indicated in Table 1). Average data for observers with normal hearing are plotted with circles, filled circles for testing in noise background, and open circles for testing in quiet. Error bars indicate the 95% confidence interval, defined as ± 2 standard error of the mean.

observers with hearing loss, and thresholds were lower at 500 than 1000 Hz, but this frequency effect was not different across the two populations. The same pattern of results was obtained in an ANOVA that used the noise-masked data from observers with normal hearing.

Modulation Rate Discrimination

Data for modulation rate discrimination are displayed in Figure 3, which shows the geometric mean across estimates for individual observers with hearing loss (with symbols in Table 1). Also shown is the geometric mean across observers with normal hearing tested in noise (filled circle) and in quiet (open circle), with error bars indicating the 95% confidence limits around those means.

All statistics were performed on the natural log of the threshold values. The effect of testing observers with normal hearing in noise was assessed with a repeated-measures ANOVA, with two levels of modulation pattern (AM and QFM) and two levels of background (noise versus quiet). There was a main effect of modulation pattern ($F_{2,18} = 27.12$, $p < 0.0001$), no significant effect of background ($F_{1,9} = 0.51$, $p = 0.50$), and a significant interaction ($F_{2,18} = 3.98$, $p < 0.05$). That is, for the observers with normal hearing, the effect of modulation pattern differed based on the presence of the background masker.

A repeated-measures, split-plot ANOVA was performed with data from observers with hearing loss and those with normal hearing tested in quiet, using the between-subject factor of group and the within-subject factor of modulation pattern. This analysis indicated a significant effect of modulation pattern ($F_{1,19} = 19.00$, $p < 0.0005$), a significant effect for group ($F_{1,19} = 5.45$, $p < 0.05$), and no interaction between modulation pattern and group ($F_{1,16} = 0.21$, $p = 0.65$). A separate repeated-measures, split-plot ANOVA comparing the observers with hearing loss and observers with normal hearing tested in masking noise indicated the same pattern of results. There was a significant effect of modulation pattern ($F_{1,16} = 31.56$, $p < 0.0001$), a significant effect of group ($F_{1,16} = 12.05$, $p < 0.005$), and no interaction between modulation pattern and group ($F_{1,16} = 1.09$, $p = 0.31$). In both these analyses, observers with normal hearing performed better than those with hearing loss, and thresholds were lower for the AM than the QFM stimuli, but this modulation type effect was not significantly different across the two populations.

Comparison of Results Across Tests

Correlations and 2-tailed p values were computed to examine the possible relations between speech recognition and psychoacoustical performance within the hearing loss group. As above, speech data were arcsine-transformed percent correct scores, and both FM
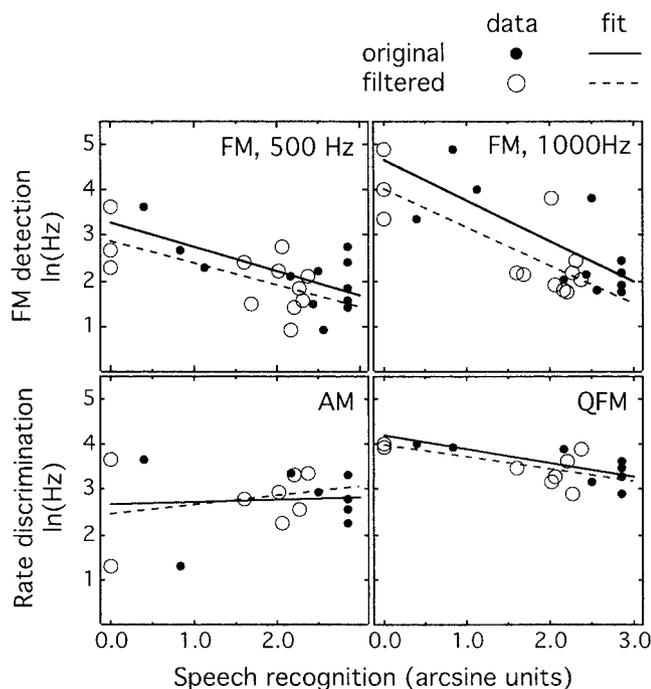
Fig. 4. Psychophysical results are plotted in units of ln(Hz) as a function of speech recognition scores for both original (full-spectrum) and filtered speech stimuli. Thresholds for individual observers with hearing loss are plotted with filled circles for full-spectrum and open circles for filtered stimuli. Solid lines show the best fit to the full-spectrum speech data; dotted lines show the best fit to the filtered speech data.

detection and AM/QFM discrimination thresholds were submitted to a natural log transform. These data are shown in Figure 4, with modulation thresholds plotted as a function of full-spectrum speech scores (filled circles) and as a function of filtered speech scores (open circles). Solid lines indicate the best fitting line for full-spectrum data and dashed lines for filtered data.

The correlation between full-spectrum speech and FM detection thresholds was significant for both 500 Hz ($R = -0.65$, $p < 0.05$) and 1000 Hz ($R = -0.76$, $p < 0.005$). A similar pattern of results was obtained with the filtered speech data: The correlation was significant for both 500 Hz ($R = -0.65$, $p < 0.05$) and 1000 Hz ($R = -0.79$, $p < 0.05$). Given the wide range of audiometric thresholds at the test frequencies, spanning 30 to 75 dB HL, it was of interest to determine the extent to which these correlations were driven by the common factor of hearing loss. The three-frequency pure-tone average (PTA), calculated as the average threshold at 0.5, 1, and 2 kHz, is often used as one estimate of audibility when assessing speech data (e.g., Dubno, Lee, Klein, Matthews & Lam, 1995; Glasberg & Moore, 1989; Horst, 1987). Partial correlations, controlling for PTA in the test ear, were performed between the arcsine-

transformed speech results and the log-transformed FM detection thresholds. This correlation for the full-spectrum speech was not significant for 500 Hz ($R = -0.48$, $p = 0.13$) but was significant for 1000 Hz ($R = -0.75$, $p < 0.01$). A similar pattern of results was obtained with the filtered speech data: The correlation was not significant for 500 Hz ($R = -0.50$, $p = 0.12$) but was significant for 1000 Hz ($R = -0.76$, $p < 0.01$).

Correlations between speech recognition and modulation discrimination, both AM and QFM, were also examined. For analyses of the AM discrimination data, the correlation was not significant for either the full-spectrum speech ($R = 0.07$, $p = 0.87$) or the filtered speech ($R = 0.27$, $p = 0.52$). The correlation was significant for QFM and full-spectrum speech ($R = -0.75$, $p < 0.05$), though correlation with filtered speech failed to reach significance ($R = -0.65$, $p = 0.08$). The correlation between QFM and full-spectrum speech was not significant in a partial correlation controlling for PTA in the test ear ($R = -0.65$, $p = 0.11$).

DISCUSSION

The differences found here between observers with normal hearing and those with hearing loss are consistent with previous findings showing that sensorineural hearing loss is often associated with a deficit in performance on amplitude modulation discrimination (Formby, 1986; Grant, Summers & Leek, 1998) and detection of low rate FM (Lacher-Fougere & Demany, 1998; Moore & Skrodzka, 2002). Observers with normal hearing performed better than those with hearing loss in all modulation conditions; this was true for observers with normal hearing tested in quiet and in the presence of background noise, suggesting that variability in presentation level was not responsible for this difference across groups. These results are consistent with the idea that sensorineural hearing loss may result in a reduced ability to encode temporal information via phase locking (Moore & Sek, 1995; 1996).

Of particular interest in the present study was whether a relation exists between the measures thought to reflect phase-locking and the ability to recognize speech. Such a relation was hypothesized on the basis of previous physiological research suggesting that neural phase-locking might be critical for the coding of speech features for sounds presented at a moderate to high level (Young & Sachs, 1979). The correlations between speech recognition and the psychoacoustical measures within the hearing loss group support the existence of such a relation. This relation was particularly robust for detection of low rate FM at a 1000 Hz carrier frequency,

in which the correlation remained significant even when audiometric threshold effects were statistically controlled for by way of partial correlation. The finding of a significant effect at 1000 Hz but not 500 Hz carrier frequency, although not predicted, is consistent with the hypothesis that degradation in fine-structure encoding is particularly evident at frequencies in which the fidelity of the fine-structure cue is beginning to fall off in the normal auditory system. The partial correlation between speech performance and QFM discrimination, though in the expected direction, did not reach significance. There was no correlation between speech performance and AM discrimination; this result does not constitute evidence against the hypothesis that temporal fine structure is an important factor in determining speech performance, however, because gross temporal features of the stimulus envelope could also serve as a cue to AM rate discrimination. Results were very similar for filtered speech and for the full-spectrum (unfiltered) speech recordings, suggesting that the role of temporal fine-structure cues may be equally influential in the full spectrum as the filtered materials.

A hypothesis of the present study was that speech recognition in observers with sensorineural hearing loss may depend on factors other than audibility (e.g., coding of temporal fine structure). This hypothesis received some support from the finding that some of the correlations between speech perception and FM detection at 1000 Hz remained significant when audibility (as represented by the PTA) was statistically controlled. In this light, it is of interest to consider whether any of the speech recognition results of the observers with hearing loss were poorer than would be expected on the basis of the PTA. It is possible to examine this question by comparing the full-spectrum speech recognition results of the observers with hearing loss to confidence intervals derived by Dubno et al. (1995). These confidence intervals, based on the data of 212 observers, allow assessment of whether speech recognition scores are consistent with audibility as measured by the PTA. Comparison of the present speech recognition results with the confidence intervals of Dubno et al. (1995) reveals that 9 of the 12 observers with hearing loss had speech recognition that was within the 95% confidence interval but that the three observers showing the poorest speech recognition (HL2, HL3, and HL5) produced results that were outside of (poorer than) the confidence interval. Inspection of Figures 2 and 3 reveals that these three observers also performed relatively poorly on the FM detection task, and two of these observers (HL2 and HL5) performed poorly on the QFM task (HL3 did not participate in the QFM task). One

caveat is that whereas the Dubno et al. confidence data are based on maximum speech recognition (PB_{max}), the present study measured speech recognition at a fixed level of 35 dB SL.

Overall, the present results provide some support for the hypothesis that sensorineural hearing loss may be related to a diminished ability to encode fine temporal information. The physiological evidence for decreased phase-locking in animal models of sensorineural hearing loss, however, is not conclusive. Although one such animal model study indicates a reduction in precision with which individual auditory nerve fibers phase-lock to a stimulating waveform (Woolf et al., 1981), other studies report normal temporal response or temporal response patterns modified by abnormalities proximal to the auditory nerve (Harrison & Evans, 1979; Miller et al., 1997). There is therefore some reason to speculate on possible ways that a reduced ability to make use of temporal information in a hearing impaired ear might coexist with a finding of normal phase-locking within individual auditory nerve fibers that are responsive to auditory stimulation. One possibility suggested by Moore & Skrodzka (2002) is that efficient interpretation of temporal information depends on a normal cochlear traveling wave (Shamma & Klein, 2000) and that the modification of the traveling wave resulting from damage to the cochlea (Ruggero, 1994) interferes with the interpretation of the temporal information.

We can suggest two other possibilities. One very general possibility is that some cases of sensorineural hearing loss are associated with a reduction in the number of inner hair cells that are responsive to sound stimuli and that reductions in performance reflect the fact that there are fewer available channels from which to extract information. This may explain why the correlation between FM detection at 1 kHz and speech data persists even after degree of hearing loss has been statistically partialed out: If the hearing loss of the current population is due to different degrees of inner and outer hair cell loss, then the degree of inner hair cell involvement in an individual observer could influence the degree to which the psychoacoustical results reflect a deficit in fine temporal information. This possibility is bolstered by findings of different consequences of inner and outer hair cell loss (Dallos & Harris, 1978; Evans & Harrison, 1975; Trautwein, Hofstetter, Wang, Salvi & Nostrant, 1996; Wake, Takeno, Ibrahim & Harrison, 1994). A related possibility concerns possible sharpening of phase-locking rostral to the auditory nerve, at least for frequencies of 1000 Hz and below, due to convergence of information from multiple auditory nerve fibers (Joris, Carney, Smith, & Yin, 1994; Koppl, 1997; Rothman & Young,

1996). Overall reductions in the number of viable auditory nerve fibers could reduce such synchrony sharpening.

CONCLUSION

The present study found relatively poor performance for some observers with sensorineural hearing loss on tasks involving the detection of low frequency FM and the discrimination of AM and QFM rate. These results are consistent with previous findings. Of particular interest in the present study was the relation between psychoacoustical measures thought to depend on the coding of temporal fine structure and speech recognition performance. Raw correlations were consistent with a relation between speech recognition and performance on the FM detection and the QFM discrimination tasks but did not support a relation between speech recognition and performance on the AM discrimination task. Correlations between speech recognition and low rate FM detection at a center frequency of 1000 Hz remained significant when threshold sensitivity was controlled for statistically. The results of this study are broadly consistent with the idea that sensorineural hearing loss may be associated with a reduction in the ability to use fine temporal information that is coded by neural phase-locking.

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