Critical bandwidth for phase discrimination in hearing-impaired listeners

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Monaural phase discrimination was evaluated in normal-hearing and hearing-impaired listeners as a function of the frequency separation among components in three-tone complexes. The phases of the center components of 100% sinusoidal amplitude-modulated (SAM) waveforms were shifted by 90° to yield quasi-frequency-modulated (QFM) waveforms that had identical long-term spectra but different envelopes and temporal fine structure. Normal-hearing listeners can distinguish QFM waveforms from SAM waveforms as long as the modulation frequency (frequency separation between components) is less than about 40% of the carrier frequency (center component). Phase discrimination performance (d') was measured as a function of modulation frequency, and critical bandwidths for phase discrimination (CB_{phs}) were specified as the modulation frequency corresponding to a performance index (d') of 1.0. In normal-hearing ears, CB_{phs} increased with stimulus SPL. In hearing-impaired ears, CB_{phs} estimates were equal to or narrower than normal when comparisons were made at the same SPLs; CB_{phs} estimates from hearing-impaired ears were broader (better) than normal only when comparisons were made at equivalent SLs. Differences between CB_{phs} estimates in normal-hearing and hearing-impaired ears are explained by level-dependent auditory filtering and the sensation levels at which comparisons are made, without the necessity to postulate abnormal tuning in hearing-impaired ears. © *1995 Acoustical Society of America.*

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INTRODUCTION

The perception of monaural phase effects is associated with the limited frequency resolving power of the auditory system (Mathes and Miller, 1947). Mathes and Miller were one of the first to demonstrate monaural phase effects by shifting the phase of the center component of a sinusoidal amplitude-modulated (SAM) waveform by 90°, which produced a quasi-frequency-modulated (QFM) waveform with the identical long-term spectrum but with a different amplitude envelope and temporal fine structure. Both waveforms consisted of three tones separated by a frequency distance equal to the modulation frequency. They demonstrated that these two waveforms could be easily distinguished at low-to-moderate modulation frequencies, usually on the basis of a roughness or harshness cue. As modulation frequency increased and the individual components became widely separated, the two waveforms became indistinguishable. They reported this modulation frequency to be about 40% of the carrier frequency (center frequency of the three-tone complex), for frequencies between 500 and 2000 Hz at a 60-dB sensation level (SL). At lower listening levels, the range of modulation frequencies over which SAM and QFM waveforms were distinguishable was reduced. To account for these results, Goldstein (1967) proposed an auditory filter model, which assumed that all three components of the three-tone complex must interact within the same auditory filter to produce a discernible difference in the temporal envelope. Nelson (1994) defined the modulation frequency at which SAM and QFM waveforms become indistinguishable as the *critical bandwidth for phase discrimination* (CB_{phs}). He replicated the earlier findings, defined level effects in more detail, and demonstrated that Goldstein's model can adequately account for changes in CB_{phs} as a function of level by using auditory filter characteristics obtained from forward-masking psychophysical tuning curves.

Because SAM and QFM waveforms are deterministic waveforms with identical long-term spectra and only differ in envelope and temporal fine structure, they appear to be ideal stimuli with which to investigate frequency resolution in persons manifesting cochlear hearing loss. Since their discriminability presumably depends upon all three components passing through the same auditory filter, ears with abnormally broad auditory filters should demonstrate discriminability over a wider range of modulation frequencies than ears with narrower filters. Two preliminary reports have examined the discriminability of SAM and QFM waveforms in hearing-impaired ears, with somewhat conflicting results. Nelson (1978) reported that CB_{phs} measures in hearing-impaired ears were no larger and sometimes smaller than those from normal-hearing ears. More recently, in a brief report of results from a few hearing-impaired ears, Rosen (1984, 1986, 1987) found better phase discrimination performance (higher % correct phase discriminations) from hearing-impaired listeners than from normal-hearing listeners, implying better temporal resolution or poorer frequency

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resolution by the hearing impaired (broader auditory filters). Similar findings were also reported with different phase discrimination experiments (Moore and Glasberg, 1989; Schroder and Leek, 1989). In general, these reports of better phase discrimination than normal were consistent with the notion that listeners with hearing losses demonstrate broader than normal auditory filters. However, recent explorations of the strong level effects involved in phase discrimination (Nelson, 1994), and the nonlinear nature of normal frequency resolution (Nelson, 1991), indicate that further investigation is warranted.

In the present work, phase discrimination of SAM and QFM waveforms was measured as a function of modulation frequency from normal-hearing subjects and from subjects with cochlear hearing losses. CB_{phs} estimates were determined from the phase discrimination functions. Normal-hearing subjects were tested over a wide range of stimulus levels and in the presence of a background noise to reduce the sensation levels of high sound-pressure level stimuli. Hearing-impaired subjects were tested at 80 dB SPL. CB_{phs} estimates from hearing-impaired ears were then compared with those from normal-hearing ears at equivalent sound-pressure levels and at equivalent sensation levels. The results are examined in terms of the strong level effects seen in normal-hearing ears and the sensation levels at which CB_{phs} estimates are compared.

I. METHOD

A. Stimuli

Subjects discriminated between SAM and QFM waveforms as a function of modulation frequency. Examples of pairs of SAM and QFM waveforms are shown in Fig. 1 for increasing modulation frequency, with the top waveform of each pair showing the SAM stimulus and the bottom waveform showing the QFM stimulus. The SAM and QFM waveforms were constructed by summing sinusoids, which are mathematically described by

$$s(t)=\alpha[0.5\ \sin(\omega_c-\omega_m)t-\sin(\omega_c t+\theta)$$
$$+0.5\ \sin(\omega_c+\omega_m)t], \quad (1)$$

where the phase (θ) of the center-frequency component (ω_c) is 0° for SAM and 90° for QFM, the carrier frequency (F_c) is given by ω_c, the modulation frequency (F_m) by ω_m, and the overall amplitude is given by α.

Long-term power spectra of SAM and QFM waveforms are identical, consisting of three frequency components, with upper and lower components equally spaced about the carrier frequency or center component by an amount equal to the modulation frequency and with an amplitude that is half the amplitude of the center component. The sign of the center component was negative to shift the envelope by 90° so that the SAM waveform began at zero. Although SAM and QFM stimuli have identical long-term power spectra, their amplitude envelopes and their temporal fine structure differ. The SAM waveforms are characterized by large sinusoidal modulations in envelope amplitude, which go through zero amplitude every $1/F_m$ (s). The QFM waveforms are characterized by very minor fluctuations in envelope amplitude, which reach a minimum every $1/2F_m$ s.

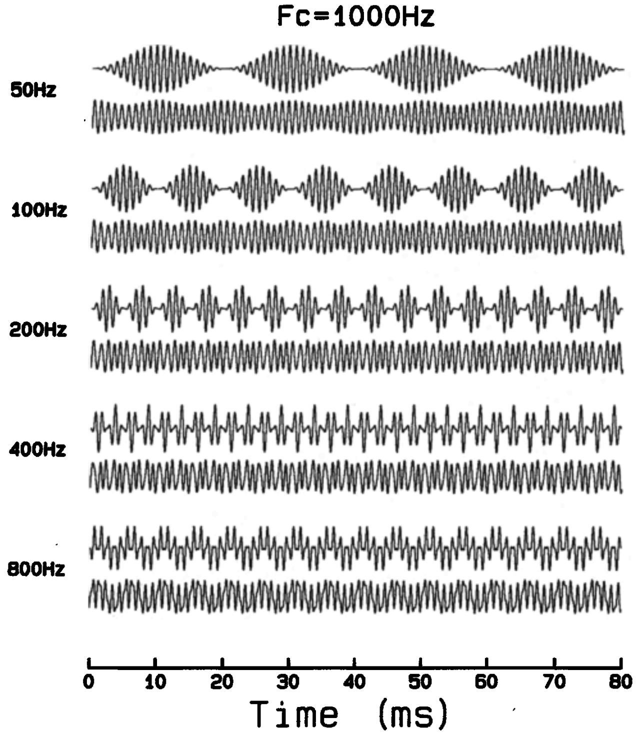

FIG. 1. Pairs of 1000-Hz SAM and QFM waveforms at different modulation frequencies calculated from Eq. (1) (from Nelson, 1994). At each modulation frequency, indicated to the left of each pair, the top waveform is the SAM stimulus and the bottom waveform is the QFM stimulus. The phase of the center component was 0° for SAM waveforms and 90° for QFM waveforms. The long-term power spectra of each pair are identical; only the envelope and temporal fine structure differ.

Waveforms were constructed digitally, converted to analog waveforms through a 14-bit digital-to-analog converter at a 20-kHz sampling rate, and then low-pass filtered with at a 9.5-kHz cutoff frequency. Stimulus levels were controlled by programmable attenuators, and the overall levels of the SAM and QFM waveforms were calibrated by a sound level meter in a 6-cc coupler. Acoustic stimuli were presented monaurally through a TDH-49 earphone in an MX41/AR cushion. Each stimulus was presented for 520 ms, including 10-ms rise and decay times. Subjects listened in a double-wall sound-treated room.

B. Psychophysical procedure

An N-interval, N-alternative, forced-choice method of constant stimuli was employed to determine percent-correct discriminations between SAM and QFM waveforms as a function of modulation frequency, an experiment inspired by a brief report in Houtsma and Goldstein (1971). The number of forced-choice intervals (N) was either four or three. Subjects listened to sounds during N sequential intervals indicated by lights; $N-1$ of the intervals contained the SAM signal and one, determined randomly from trial to trial, contained the QFM signal. Subjects indicated which interval contained the "different" signal by pressing one of N but-

TABLE I. Experimental conditions.

Normal-hearing subjects					
Expt.	Frequency (Hz)	Background	Stimulus levels	Ears	Method
I:	1000	quiet	20 SL 40 60 80 100 SPL	3	3 AFC
	1000	noise	40 60 80 100 SPL	3	3 AFC
II:	300	quiet	40 60 80 100 SPL	5	4 AFC (1–3 AFC)
	1000	quiet	40 60 80 100 SPL	6	4 AFC (1–3 AFC)
	3000	quiet	40 60 80 100 SPL	5	4 AFC (1–3 AFC)
III:	300,1000,3000	quiet	20 dB SL 80 dB SPL	3	3 AFC
	1000	quiet	80 dB SPL[a]	22	4 AFC (1–3 AFC)
Hearing-impaired subjects					
Expt.	Frequency (Hz)	Background	Stimulus levels	Ears	Method
III:	300	quiet	80 dB SPL[a]	8	4 AFC (3–3 AFC)
	1000	quiet	80 dB SPL[a]	99[b]	4 AFC
	3000	quiet	80 dB SPL[a]	7	4 AFC (3–3 AFC)

[a]Some subjects also tested at additional stimulus levels.
[b]Number of ears in each threshold decade (dB SPL): 10 (0–9); 17 (10–19); 17 (20–29); 13 (30–39); 17 (40–49); 13 (50–59); 12 (60–73).

tons, after which they received correct-answer feedback. Time between signal intervals was 250 ms. During a single listening session, a complete psychometric function was obtained for phase discrimination as a function of modulation frequency. A single session consisted of 20 trials per modulation frequency. Within a single session, different modulation frequencies were tested in ascending order from low to high. At least two sessions were conducted per presentation level to yield 40 trials per condition. If large improvements in performance were observed between the first and second session, the first was discarded and an additional session was completed. At least four sessions were conducted to yield 80 trials per condition. For the larger sample of hearing-impaired ears (in experiment III) 40 trials per condition were collected.

C. Subjects and experimental conditions

Previous research has shown that CB_{phs} is strongly dependent upon the level at which SAM and QFM waveforms are presented (Mathes and Miller, 1947; Goldstein, 1967; Nelson, 1977, 1994). When evaluating subjects with impaired hearing, it is necessary to employ intense stimuli to overcome their hearing losses; however, those intense stimuli might only be presented at low SLs because of the magnitude of the hearing loss. Consequently any differences in CB_{phs} from normal-hearing ears may be due to presenting stimuli at lower sensation levels in the hearing-impaired ear. Therefore, to examine phase discrimination in normal ears at low SLs and high presentation levels, as is the case in hearing-impaired ears, in one experimental condition a background noise was added continously during the presentation of SAM and QFM waveforms. The noise was an analog white noise with an electrical bandwidth between 20 and 20 kHz which was then modified by the frequency response of the TDH-49 earphone. It was adjusted to a level that just masked a SAM waveform 20 dB below each of four stimulus presentation levels, i.e., in the noise condition the SAM stimuli were about 20 dB above their masked threshold in the background noise. Then a SAM/QFM discrimination function was obtained at what was effectively a 20 dB SL presentation level in background noise. Phase discrimination functions were also obtained in quiet at presentation levels of 20 dB SL and at 40, 60, 80, and 100 dB SPL.

Normal-hearing subjects participated in one of three experiments, which differed in the frequencies tested, the stimulus levels tested, and whether a background noise was present to reduce the effective sensation level of the SAM and QFM stimuli. A summary of those different conditions is given in Table I. In experiment I, phase discrimination functions were obtained at a 1000-Hz carrier frequency, both in quiet and in the presence of a background noise. In experiment II, phase discrimination functions were obtained in quiet at carrier frequencies of 300, 1000, and 3000 Hz from additional subjects at 40, 60, 80, and 100 dB SPL. In experiment III, phase discrimination functions were obtained at 80 dB SPL at 1000 Hz. A subgroup of three normal-hearing subjects (three ears) were also tested at 300 and 3000 Hz and at stimulus levels that corresponded to 20 dB SL. Ages of the normal-hearing subjects ranged from 21 to 55 years. Initial data collection employed a 4AFC psychophysical procedure, which was later changed to a 3AFC procedure to minimize test time. CB_{phs} estimates compensated for this difference because they were based on d' scores, as described later. Data from some of the normal-hearing subjects in the quiet background condition were also reported in a previous publication (Nelson, 1994).

Hearing-impaired subjects participated in experiment III. All subjects were tested at 80 dB SPL. A large number of hearing-impaired subjects (N=99) were tested only at a carrier frequency of 1000 Hz. A smaller number were tested at one or more test frequencies, and in some cases at two or more of the stimulus levels specified in experiment II. Ages of the hearing-impaired subjects ranged from 19 to 71 yr. All subjects demonstrated a bilateral sensorineural hearing loss at one or more of the three test frequencies. The difference in sensitivity between ears was no greater than 30 dB in all but two subjects, who had a contralateral white noise introduced during testing of their poorer ear. Conductive hearing losses

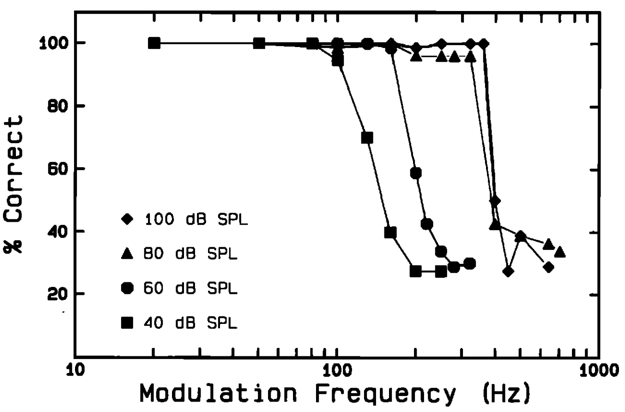

FIG. 2. Phase discrimination functions from a normal-hearing subject at a carrier frequency of 1000 Hz. Percent-correct discriminations between SAM and QFM stimuli are shown as a function of modulation frequency (frequency separation between components). The parameter is stimulus presentation level (in dB SPL). The SAM and QFM waveforms are distinguishable 100% of the time at low to moderate modulation frequencies and performance drops to chance performance (33%) at faster modulation frequencies. The modulation frequency at which the break point occurs, between perfect and chance performance, increases with stimulus level.

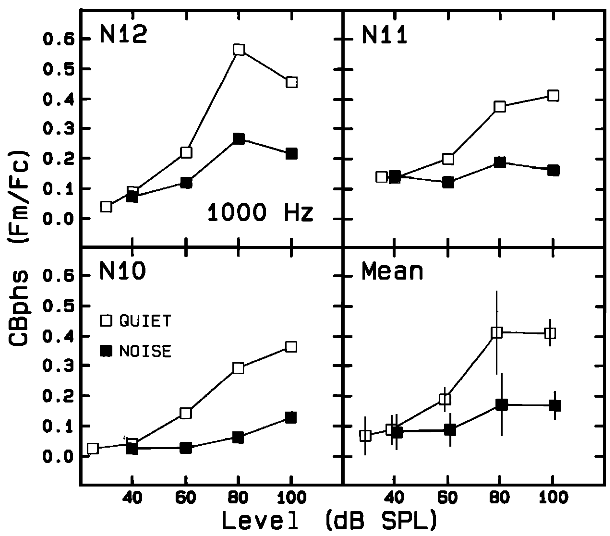

FIG. 3. CB_{phs} estimates in quiet (unfilled squares) and in the presence of a continuous background noise (filled squares) from normal-hearing subjects in experiment I. Carrier frequency is 1000 Hz. CB_{phs} is specified as the ratio between modulation frequency and carrier frequency (F_m/F_c) and plotted as a function of stimulus presentation level (dB SPL). A white noise was adjusted to mask a SAM stimulus 20 dB less intense than each stimulus presentation level, so that the stimuli were effectively at 20 dB SL in noise. Individual curves are shown in separate panels, along with the means in the lower right panel. Vertical bars are plus and minus one standard deviation. The means are offset along the abscissa for clarity. (Data in quiet also used in Nelson, 1994.)

and retrocochlear hearing losses were ruled out by an audiological test battery. All of the subjects had audiological profiles consistent with cochlear hearing loss.

D. Calculation of CB_{phs}

Phase discrimination functions obtained at 1000 Hz from the right ear of a normal-hearing subject are shown in Fig. 2. At a low presentation level of 40 dB SPL, discrimination performance was at 100% for modulation frequencies up to 80 Hz, dropped to chance levels between 100 and 160 Hz, and remained at chance levels through 320 Hz. The break between 100% and chance performance gradually moved toward faster modulation frequencies as the presentation level of the stimulus was increased (Nelson, 1994). In this subject at a presentation level of 100 dB SPL, performance remained at 100% up to 320 Hz before dropping to chance by 450 Hz. In order to quantify the break point, and compensate for differences in the method (4AFC vs 3AFC) performance scores (% correct) were converted to d' scores and the modulation frequency at which the d' score dropped to 1.0 was calculated from a linear least-squares fit to the changing portion of the curve. Fits were accomplished in linear d' and logarithmic modulation-frequency coordinates. The break point determined in this way was previously defined (Nelson, 1994) as the critical bandwidth for phase discrimination (CB_{phs}). CB_{phs} is specified here as a ratio between modulation frequency at the break point and carrier frequency (F_m/F_c). For this subject, CB_{phs} estimates were 0.138, 0.202, 0.377, and 0.414 of the carrier frequency for stimulus levels at 40, 60, 80, and 100 dB SPL, respectively.

II. RESULTS

A. CB_{phs} estimates from normal-hearing ears

CB_{phs} estimates obtained at a carrier frequency of 1000 Hz in quiet and in the presence of the background noise are shown in Fig. 3 for three normal-hearing subjects (experiment I in Table I). In quiet, CB_{phs} increased with stimulus level up to about 80 dB SPL and remained about the same at 100 dB SPL, as previously reported by Nelson (1994). In noise, where all of the stimuli were about 20 dB SL in background noise, CB_{phs} increased very little with stimulus level over that obtained at 20 dB SL in quiet. These results were consistent across individuals and are reflected in the mean CB_{phs} estimates plotted in the lower right panel of Fig. 3. Whatever cues enabled subjects to discriminate between SAM and QFM stimuli for modulation rates faster than about 0.20 F_c at 80 and 100 dB SPL, they were largely masked by the background noise.

To examine CB_{phs} changes with level at other carrier frequencies, and to provide normative data with which data from hearing-impaired subjects might be compared, phase discrimination functions were obtained from additional normal-hearing subjects at carrier frequencies of 300, 1000, and 3000 Hz, at 40, 60, 80, and 100 dB SPL (experiment II in Table I). The mean CB_{phs} estimates and standard deviations for those subjects are shown in Fig. 4 by the filled squares and vertical lines. The trend of increasing CB_{phs} with level, seen earlier at 1000 Hz, was maintained at both 300 and 3000 Hz. The plateau in mean CB_{phs} above 80 dB SPL was not seen at 3000 Hz and there was a slight decrease above 80 dB SPL at 300 Hz, but those tendencies should be treated with caution because data were only obtained from three ears at 100 dB SPL for those two frequencies.

Individual CB_{phs} estimates from additional subjects tested at 20 dB SL and 80 dB SPL are also shown in Fig. 4

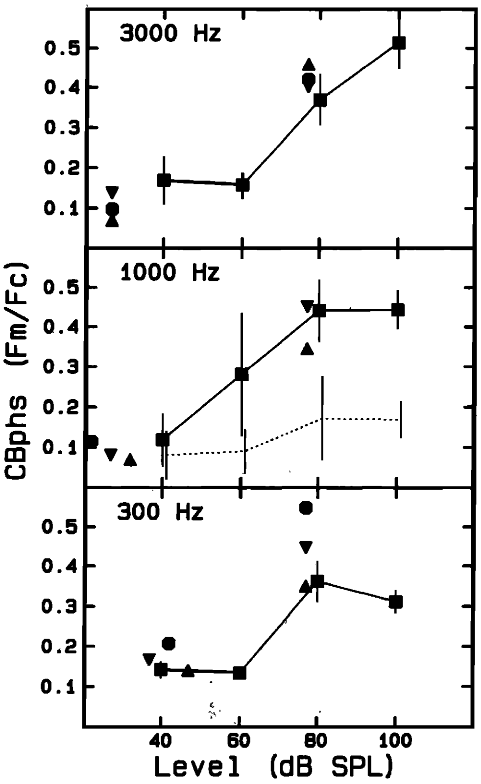

FIG. 4. CB_{phs} estimates from normal-hearing subjects in experiments II and III, as a function of stimulus level (dB SPL). Means and standard deviations from normal-hearing subjects tested at four levels (experiment II) are shown by filled squares and vertical lines, respectively. Individual CB_{phs} estimates from three additional normal-hearing subjects tested at 20 dB SL and 80 dB SPL (experiment III) are shown by the other filled symbols. The largest CB_{phs} estimate obtained at 1000 Hz from a normal-hearing ear at 80 dB SPL was $0.85F_c$ (not shown). Means for the noise condition from Fig. 3 are replotted by the dashed line. Data from individual ears and the means from the noise condition are offset along the abscissa for clarity.

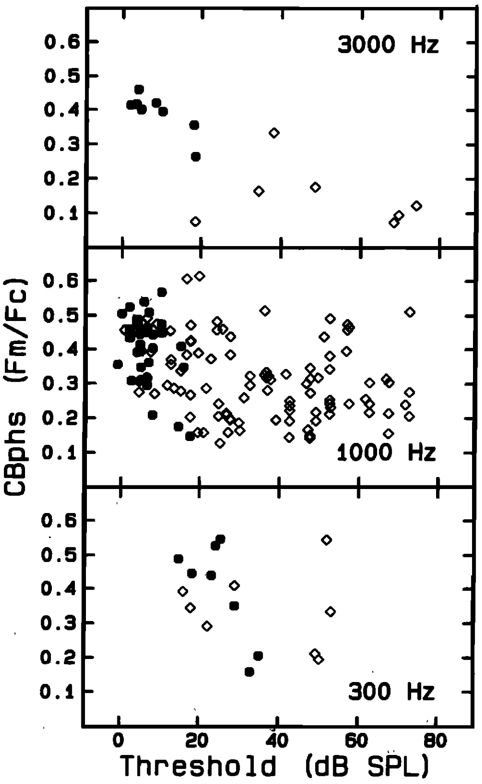

FIG. 5. CB_{phs} estimates at 80 dB SPL from normal-hearing subjects (filled circles) and subjects with cochlear hearing losses (unfilled diamonds), as a function of absolute threshold (in dB SPL) at the carrier frequency. Data from normal-hearing ears are from experiments I (quiet), II, and III. Data from hearing-impaired ears are from experiment III.

by the other filled symbols (from experiment III in Table I). Three subjects (three ears) were tested at all three carrier frequencies. The largest CB_{phs} obtained from any normal-hearing subject at 1000 Hz was 0.85 F_c at 80 dB SPL (not plotted in Fig. 4). Data from these individual subjects are consistent with the mean CB_{phs} estimates for the previous subjects: CB_{phs} increased from about 10%–15% of the carrier frequency at presentation levels below 40 dB SPL to about 40% at presentation levels at 80 dB SPL and above.

B. CB_{phs} from subjects with cochlear hearing loss

CB_{phs} estimates calculated from the phase-discrimination functions obtained at 80 dB SPL are plotted in Fig. 5 as a function of threshold at the carrier frequency. Data from subjects with cochlear hearing losses are indicated by the unfilled symbols (experiment III in Table I); data from normal-hearing subjects in quiet are shown by the filled symbols. At all three test frequencies, CB_{phs} decreased as the threshold at the carrier frequency increased. In this case, with stimuli presented at a constant SPL, CB_{phs} estimates from the hearing-impaired ears were equal to or smaller (poorer) than those from normal-hearing ears. This is contrary to what one might expect if these subjects had broader than normal auditory filters, which should cause interactions to occur among spectral components over a wider frequency range. Indeed, subjects who had thresholds greater than 60 dB SPL might be expected to reveal broader than normal auditory filters (Nelson, 1991), yet they all demonstrated CB_{phs} estimates that were equal to or smaller than normal at equivalent SPLs.

From Fig. 5, it can be seen that the CB_{phs} estimates at 1000 Hz from hearing-impaired ears with absolute thresholds above 60 dB SPL are close to the CB_{phs} range seen in normal-hearing ears in the presence of a background noise (Fig. 3). The hearing-impaired ears were operating at a lower SL than the normal-hearing ears, which suggests that a comparison of CB_{phs} estimates at equivalent SLs would be appropriate.

CB_{phs} estimates from normal-hearing and hearing-impaired ears are compared at the same SLs in Fig. 6. In this graph, CB_{phs} estimates from normal-hearing ears (filled circles) include measurements made at multiple stimulus levels, which show an increase in CB_{phs} with increased SL, as expected. At a carrier frequency of 3000 Hz (top panel), CB_{phs} estimates from hearing-impaired ears (unfilled diamonds) were all within the range of normal-hearing ears when compared at the same SL. At a carrier frequency of 1000 Hz (middle panel), CB_{phs} estimates from hearing-impaired ears (unfilled symbols) were larger (better) than those from normal-hearing ears at SLs below about 40 dB. CB_{phs} estimates are coded according to their corresponding

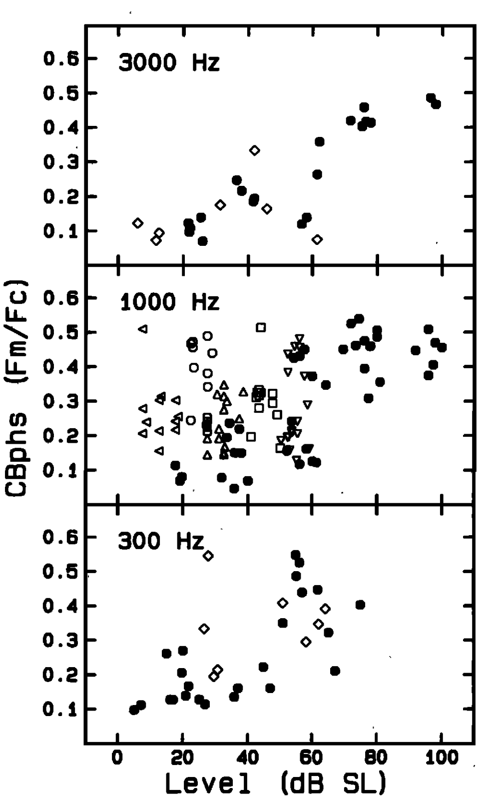

FIG. 6. CB_{phs} estimates from normal-hearing subjects (filled circles) and subjects with cochlear hearing losses (unfilled symbols), as a function of the stimulus level in dB sensation level (SL). Data from normal-hearing ears are for multiple stimulus levels [experiments I (quiet), II, and III]. Data from hearing-impaired ears were obtained at 80 dB SPL (experiment III). At a carrier frequency of 1000-Hz, CB_{phs} estimates from hearing-impaired ears were assigned (unfilled) symbols according to their corresponding sensitivity thresholds (in decades): thresholds >60 (left triangles), 50–59 (circles), 40–49 (up triangles), 30–39 (squares), and 20–29 (down triangles). At carrier frequencies of 300 and 3000 Hz, CB_{phs} estimates from hearing-impaired ears are shown by unfilled diamonds.

sensitivity thresholds, in decades. Notice that CB_{phs} estimates from ears with thresholds above 60 dB SPL (unfilled left triangles) were between 0.15 and $0.30F_c$. Because of the hearing losses, the stimuli presented at 80 dB SPL were less than 20 dB SL. The normal-hearing ears tested (in quiet) with stimuli as low as 20 dB SL had CB_{phs} estimates around $0.10F_c$ or lower. Similarly, most of the hearing-impaired subjects with absolute thresholds between 50 and 59 dB SPL (unfilled circles), and some of those with thresholds between 40 and 49 dB SPL (unfilled up triangles), revealed CB_{phs} estimates that were substantially larger than those obtained from normal-hearing ears at equivalent SLs. At a carrier frequency of 300 Hz (bottom panel), CB_{phs} estimates in one hearing-impaired ear were larger than those from normal-hearing ears at SLs below 30 dB. That subject exhibited a CB_{phs} value of $0.54F_c$, which is essentially the same as that exhibited by the best normal-hearing ear at 300 Hz ($0.53F_c$). An additional hearing-impaired subject was tested at 100 dB SPL at 300 Hz because a quiet threshold of 75 dB SPL precluded testing at 80 dB SPL (data not included in figures). That subject demonstrated a CB_{phs} estimate of $0.40F_c$, which was also larger than those from normal-hearing ears at a comparable SL (25 dB) but still within the range of normals tested at high SPLs.

Thus it appears that some hearing-impaired ears can perform "better than normal" when listening at low SLs, i.e., at low sensation levels they can perform phase discriminations between QFM and SAM waveforms at faster modulation rates than can normal-hearing ears also listening at low sensation levels. However, none of the hearing-impaired ears demonstrated CB_{phs} estimates better than normal when normal-hearing subjects listened at the same SPL.

III. DISCUSSION

Nelson (1994) demonstrated that the increase in CB_{phs} with stimulus level, between 40 and 80 dB SPL, and the plateau in performance above 80 dB SPL can be accounted for by broadening of the auditory filter with level. He employed a filter model proposed by Goldstein (1967) to quantitatively predict the changes in CB_{phs} with level seen here, using filter characteristics obtained with forward-masking tuning curves (Nelson, 1991). In that model, the discrimination between SAM and QFM stimuli was based on the power ratio of envelope maxima, after the stimuli had been filtered by an initial asymmetrical triangular filter and the resulting envelope extracted by an ideal envelope detector that is subject to temporal resolution limits (Viemeister, 1979). At low levels, e.g., 40 dB SPL, the sharp filter characteristics attenuated the sidebands in SAM and QFM stimuli, thereby reducing modulation depth when the modulation frequency exceeded the bandwidth of the filter. At high levels, e.g., 74 dB SPL and above, the filter characteristics were less steep and the bandwidth broader; therefore, attenuation of sidebands was minimal and the critical power ratio at threshold (≅1.5 dB) could be reached at much faster modulation frequencies. Nelson's CB_{phs} predictions with level fit the average data remarkably well. Essentially, level-dependent auditory filtering reduces modulation depth, more so at low than at high stimulus levels. This simple filter model can adequately explain the increase in CB_{phs} with level seen in normal-hearing subjects, including the plateau in performance at 80 dB SPL and above.

An additional assumption is required to explain the reduction in CB_{phs} seen here in the presence of a background noise at 1000 Hz in Fig. 4, where the stimuli are effectively at 20 dB SL in noise. The background noise adds variability to the otherwise deterministic waveforms of SAM and QFM stimuli, thereby making it more difficult to detect envelope fluctuations at fast modulation rates. At 80 and 100 dB SPL, CB_{phs} from normal-hearing ears averaged around $0.45F_c$ in quiet and just below $0.20F_c$ in noise. In the quiet condition, the filter bandwidths were broad because the level was high, allowing good envelope detection at fast modulation frequencies. In the noise condition, the filter bandwidths were still broad but the noise added sufficient variability to disturb envelope detection above $0.20F_c$. This may be the same phenomenon that limits CB_{phs} at very low SLs in quiet (below 30 dB SL). The decreasing filter bandwidth with decreasing sound-pressure level (from 80 to 40 dB SPL at 1000 Hz) may be the *primary* mechanism that limits the upper modulation frequency at which good envelope detection can occur. However, as stimuli approach absolute threshold increased variance near threshold could limit envelope detection even further, in which case absolute threshold would be modeled as a background noise.

In Fig. 5 there was a general trend toward lower CB_{phs} as sensitivity threshold at 1000 Hz increased. Where CB_{phs} at 80 dB SPL from normal-hearing subjects averaged about 40% of the carrier frequency ($\cong 0.40F_c$), CB_{phs} from hearing-impaired ears with thresholds greater than 60 dB SPL averaged about 25% of the carrier frequency ($\cong 0.25F_c$). All subjects listened to SAM and QFM stimuli at 80 dB SPL; therefore, as sensitivity threshold increased, the SL of the stimuli decreased. Some of the hearing-impaired subjects with more severe hearing losses (higher sensitivity thresholds) listened under conditions as low as 7.5 dB SL. As absolute threshold comes closer to the 80 dB SPL stimuli, SL is reduced and the increasing influence of absolute-threshold variance could account for reduced performance.

The most interesting finding of this study, demonstrated clearly in the middle panel of Fig. 6, was that hearing-impaired ears with substantial hearing loss exhibited CB_{phs} estimates that were higher ($\cong 0.25F_c$) than those from normal-hearing ears ($\cong 0.10F_c$), when compared at equivalent SLs. This can be understood by considering that the normal-hearing ears were operating at low SPLs where sharp filtering limits envelope detection. The hearing-impaired ears, on the other hand, were operating at high SPLs where normal auditory filtering is broader (Nelson, 1991) and envelope detection is not limited as much by auditory filtering. In this case, it is not necessary to assume that auditory filters in the hearing-impaired ears are broader than normal; they are simply operating at a higher SPL where *normal* filtering is broader. Thus the combination of increased variance near threshold and broader (normal) auditory filters at high stimulus SPLs can explain the results for both the "poorer-than-normal" performance in terms of SPL and the "better-than-normal" performance in terms of SL.

Previous reports of better-than-normal performance by subjects with cochlear hearing loss, in a similar experiment, exist in the literature (Rosen, 1984, 1986, 1987). Rosen's reports, mostly at low carrier frequencies, proposed broader-than-normal auditory filtering to explain better-than-normal performance from hearing-impaired subjects. In Rosen's experiment, three normal-hearing subjects and one hearing-impaired subject discriminated QFM from SAM waveforms, which were presented at 93–98 dB SPL. Calculations from his published results reveal CB_{phs} estimates around $0.37F_c$ on average from his three normal-hearing subjects and around $0.56F_c$ from his hearing-impaired subject. At 300 Hz in the present study, the average CB_{phs} estimate at 80 dB SPL from our normal-hearing ears was $0.36F_c$, which is consistent with Rosen's average data. However, the best CB_{phs} estimates we observed from normal-hearing ears was $0.53F_c$ at 300 Hz. As indicated in the lower panel of Fig. 6, the CB_{phs} estimate for the best hearing-impaired subject was $0.54F_c$ at 28 dB SL, which is essentially the same as the best normal-hearing subject. Had we tested a larger sample of subjects at 300 Hz, we might have seen CB_{phs} estimates with a range similar to that seen at 1000 Hz. Clearly, more research is called for at low frequencies to resolve these apparent differences.

An alternative explanation for the results presented here might be found in the excitation patterns elicited by these stimuli (Zwicker, 1970, 1976; Zwicker and Jaroszewski, 1982). Excitation patterns broaden dramatically toward higher frequencies as stimulus level increases, which should allow phase discriminations at higher stimulus levels to be made at faster modulation rates where components are farther apart on the basilar membrane. The introduction of a broad-bandwidth masking noise, as in the present study, would mask both tails of an excitation pattern more than it would mask the peak. This would reduce the effective width of the excitation pattern for a high SPL stimulus, thereby reducing the modulation rates at which discriminations between QFM and SAM stimuli could be made. Similarly, a hearing loss would reduce the effective width of the excitation pattern for a high SPL stimulus, and consequently would reduce the modulation rates at which phase discriminations could be made. This explanation would also predict a reduction in perceived combination tones as the excitation pattern is narrowed by either the background noise or a sizable hearing loss. Combination tones have been implicated as a potential cue in discriminations between QFM and SAM stimuli at faster modulation rates in normal-hearing listeners (Buunen, 1975; Nelson, 1994), and combination tones are not perceived as easily in ears with cochlear hearing loss (Smoorenburg, 1972a, b).

This research cannot affirm that the subjects in this study did or did not have abnormally wide auditory filters, because auditory filter widths were not measured directly. However, if the hearing-impaired subjects in this study did indeed have broader-than-normal auditory filters, they should have demonstrated wider CB_{phs} estimates, which they did not. To explain this in the face of wider-than-normal auditory filters, one would have to postulate that the hearing losses introduced more variance than did the background noise in normal-hearing ears, and that the increased variance overcame the improved performance expected from a broader auditory filter. This argument seems unnecessarily complex to us. Careful consideration of level effects in normal-hearing listeners, and appropriate comparisons with hearing-impaired ears at equivalent SLs, precludes the necessity of postulating abnormal tuning.

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