Acoustic distortion as a measure of frequency selectivity: Relation to psychophysical equivalent rectangular bandwidth

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(Received 18 August 1992; accepted for publication 1 March 1993)

The magnitude of cubic intermodulation distortion generated when two tones are progressively separated in frequency reaches a broad maximum when the distortion frequency falls just over half an octave below the high-frequency stimulus (f_2), when this distortion is measured with a microphone in the ear canal. For the component $2f_1-f_2$, this peak occurs at an f_2/f_1 ratio of approximately 1.2. The tuning, magnitude, and mean group delay of this distortion peak was measured for a fixed f_2 of 4 kHz at 40 dB SPL and a varied f_1 at 55 dB SPL in eight human subjects with normal hearing. The distortion peak measures were compared with the frequency selectivity at 4 kHz of the same eight subjects derived using a forward-masking notched-noise paradigm. In the six subjects from whom good, repeatable levels of distortion were measured, a significant negative correlation was found between the tuning of the distortion peak and the psychophysical bandwidth at f_2. It is concluded that the tuning of the distortion peak may provide an objective measure of frequency selectivity in the human cochlea.

PACS numbers: 43.64.Jb, 43.64.Kc, 43.64.Ri, 43.66.Dc

INTRODUCTION

Intermodulation distortion products or "combination tones" are generated as a consequence of the mixing of more than one input tone in a nonlinear device. With two-tone stimulation, the cubic distortion component, $2f_1-f_2$ is prominent in the response of the cochlea. The early psychophysical studies of cubic distortion showed a strong dependence of $2f_1-f_2$ on stimulus frequency separation, and linked distortion generation with frequency selective processes (Zwicker, 1955; Goldstein, 1967; Schroeder, 1969). Studies on the $2f_1-f_2$ acoustic distortion product generated in the mechanical response of the cochlea and propagated to the ear canal have also shown that the magnitude is strongly dependent on stimulus frequency separation. In the case of the $2f_1-f_2$ acoustic distortion, this does not take the form of a simple increase in magnitude as the stimuli converge in frequency as seen in psychophysical measures of audible distortion. Instead there is a rise to a peak in the distortion magnitude for a particular f_2/f_1 ratio of 1.2, followed by a decline as the stimulus frequencies come closer together (Wilson, 1980; Harris *et al.*, 1989; Fahey and Allen, 1985; Gaskill and Brown, 1990). This peak is often irregular, with small additional peaks and troughs, particularly for low frequency stimuli (Brown and Gaskill, 1990a). A study of the distortion peak led to the proposition that a bandpass filter operates at the frequency region in the cochlea where the basilar membrane is tuned to f_2, but the filter itself is tuned to a frequency half an octave below f_2 (Brown and Gaskill, 1990b; Brown *et al.*, 1992). It is reasonable to expect that any bandpass characteristic that can be traced to a specific region of the cochlea relates to the frequency selectivity of that region. It is also generally accepted that frequency selectivity is determined at the level of cochlear mechanics (see Pickles, 1986), so it is reasonable to make a comparison between the mechanical response of the cochlea and a psychoacoustic measure of frequency selectivity. This reasoning prompted the present pilot study in which the tuning of the distortion peak was compared with equivalent rectangular bandwidth (ERB) of an auditory filter centered on 4 kHz, measured behaviorally. There is currently no noninvasive, objective measure of frequency selectivity for the human ear and psychoacoustic measures are fairly demanding of the subjects' patience and concentration. It would therefore be useful to know whether distortion emissions could fulfill the role of an objective test of frequency selectivity.

I. METHODS

A. Auditory thresholds

The eight subjects were males aged between 19 and 34 years. Auditory thresholds in quiet were measured for each subject across the frequency range 500 to 8000 Hz at full octave intervals using a two-interval forced-choice procedure with feedback. Thresholds were estimated using a "one-up, two-down" adaptive procedure (Levitt, 1971; see Carlyon and Butt, 1992 for details). They were measured for each subject on several occasions during the 2 months over which the experiments took place. Listeners sat in an IAC single-skinned sound-attenuating booth, located inside a large sound-attenuating room, and listened through one earpiece of a Sennheiser HD414SL headset. In six subjects thresholds were also measured using the same procedure but with the insert probe used for distortion measurement (see below). The probe allows delivery of the tone bursts to the ear and also measurement of the sound level at threshold in the ear canal using the precalibrated microphone. This gives a more accurate measure of sound level at threshold than using precalibrated headphones. In all cases thresholds were within 20 dB of normal at all frequencies.

B. Acoustic distortion measurement

For distortion measurement, subjects were seated in a double-skinned IAC sound-treated room. An insert probe was placed in the meatus. This probe contained two Knowles BP 1712 miniature loudspeakers to deliver the stimulus tones (f_1 and f_2) and a Knowles EA 1843 microphone to measure the ear canal sound pressure. The magnitude and phase of the distortion emitted by the ear was measured by a "lock-in" amplifier (EG&G 5210) using a 100-ms time constant. The processed data were transferred to the computer at approximately 200-ms intervals. An artificially generated distortion signal was fed to the lock-in amplifier as a phase reference. The higher-frequency stimulus (f_2) was fixed at 4 kHz and at a level of 40 dB SPL, while f_1 was swept (at a fixed level 15 dB above the level of f_2) from 2837 to 3960 Hz. Data were analyzed on a Macintosh IIci using the software package "Excel." The phase of distortion (relative to the reference) was 'unwrapped' to give a continuous slope over several cycles of phase lag and smoothed using a 41-point moving average. An f_1 sweep was performed on all subjects on three or four separate occasions. Some examples of the magnitude and phase of $2f_1-f_2$ measured during an f_1 sweep are shown in Fig. 1. The distortion reaches a magnitude maximum approximately half-an-octave below f_2 (f_2/f_1 ratio of 1.2). Five measurements were made on each f_1 sweep as follows: (1) the center frequency of the peak; (2) the bandwidth 3 dB down; (3) the $Q_{3\text{dB}}$; (4) the maximum magnitude of the peak; (5) The mean group delay of the distortion was calculated by measuring the slope of distortion phase lag as a function of distortion frequency ($-d\phi/d\omega$). The mean of this was taken across the range of the peak. The first three measures were derived using two procedures, one completely objective and the other a "by eye" estimate. The first consisted of fitting a second-order polynomial to the data and calculating the peak frequency. The 3-dB down points on each slope and $Q_{3\text{ dB}}$ were calculated (center frequency/3-dB bandwidth). The "by eye" procedure was used because, in some cases, the distortion "peak" consisted of a complex of small peaks with steep high-pass and low-pass slopes, which made accurate curve-fitting impossible with a low order polynomial. A curve was drawn though the data and the center frequency and bandwidth 3 dB down were measured subjectively. The center frequency obtained "by eye" was similar (within 10 Hz) to that obtained objectively, so the objective measure was used. The bandwidth 3 dB down was more accurate than that obtained objectively in some subjects (the objective measure tended to overestimate the bandwidth), so the "by eye" measurement of bandwidth was used in the data analysis for all subjects. These measurements were carried out before the experimenter knew the results of the psychophysical measure, so any subjective bias was uninformed.

The five measures listed above were compared to behavioral frequency selectivity obtained as detailed below.

C. Psychoacoustic measures of frequency selectivity

Auditory filter shapes were measured using the notched-noise method described by Patterson (1976). This method was chosen because it minimizes potential artefacts, such as off-frequency listening (Patterson and Moore, 1986). A forward masking paradigm was used, so the measured filter shapes include the effects of two-tone suppression (Houtgast, 1972; Moore and Glasberg, 1981). Full details of the procedure used are given in Carlyon and Butt (1992), and are summarized here. Thresholds were measured for the detection of a 10-ms signal (5-ms raised-cosine onset and offset ramps with no plateau), presented immediately after the termination of a 300-ms bandpass or notched-noise masker, which was gated on and off with 4.1-ms raised-cosine ramps. The maskers were generated by multiplying a lowpass noise by either one (bandpass masker), or the sum of two (notched masker), sinusoids. The bandpass masker was 2000 Hz wide, arithmetically centered on 4 kHz, and had steep spectral skirts. The "notched noises" actually consisted of two 1000-Hz-wide bandpass noises. In one condition, each band was separated from 4 kHz by 5%, 10%, or 20% of that frequency. In order to measure the asymmetry of the filter (which we do not report in this paper) we also included conditions in which either the lower or upper band of noise was displaced from fs by an additional 20%. All conditions were run with a noise spectrum level of 32 dB SPL. ERBs were derived from the data in all conditions, using the computer program provided by Glasberg and Moore (1990), which provided an estimate of the "roex (p, r)" filter shape (Patterson *et al.*, 1982). Data from both symmetric and asymmetric conditions were included in the analysis and were transformed to take account of the headphone frequency response and of the slopes of growth-of-masking functions (Moore and Glasberg, 1981).[1] Slopes of the growth-of-masking functions were estimated from the difference in threshold obtained with the 32-dB bandpass masker, and that obtained in an additional condition which used a bandpass masker with a level of 12 dB SPL.

II. RESULTS

In all eight subjects, the $2f_1-f_2$ distortion level peaked for an f_2/f_1 ratio of approximately 1.2. There was intersubject variation in all measures applied to the distortion peak. When the distortion levels recorded were low, there was also considerable within-subject variation for successive measurement sessions. This was true for subjects D and F. Figure 1 shows the raw data for an f_1 sweep from three subjects to illustrate the extremes of variation. Subject A shows a notched, but still relatively sharp distortion peak which was clearly measurable above the noise floor. Subject E shows the broadest peak we measured. The level of distortion is high and consistent except for one set of readings where the subject was suffering from a head cold (dashed lines). Subject F had relatively low levels of dis-

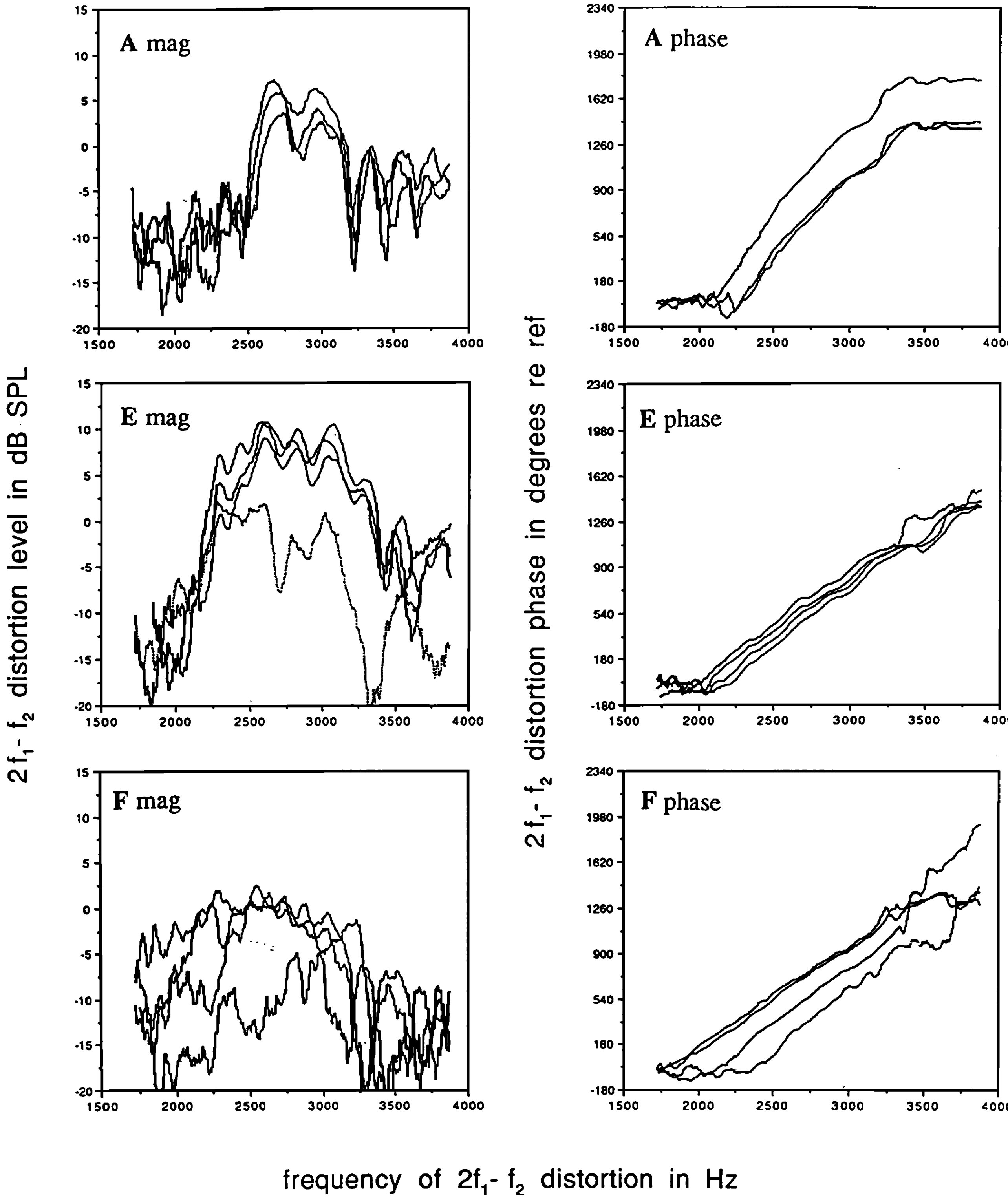

FIG. 1. The magnitude (left) and phase (right) of $2f_1-f_2$ distortion measured from three subjects as the frequency of f_1 was swept from 2837 to 3960 Hz at a level of 55 dB SPL. Here, f_2 was fixed at 4 kHz at a level of 40 dB SPL. Three traces (A) or four traces (E) and (F) for each subject measured at varying time intervals at least a week apart are superimposed. Each trace consists of 900–1000 points and has been smoothed using a 21-pt moving average. The response shown by a dashed line in E was taken when the subject had a viral infection of the nasopharynx.

tortion and gave variable results, with each of the four traces yielding very different center frequencies, bandwidths, and $Q_{3\text{ dB}}$. The phase readings of all the responses from subjects A, E, and F are shown to the right and indicate a steady trend of increasing phase lag as the distortion frequency increases. Interestingly, there was little within-subject variation in the phase of the responses, even when the magnitude was erratic, as in subject F.

Figure 2 shows the equivalent rectangular bandwidth (ERB) measurements made on two occasions. The mean

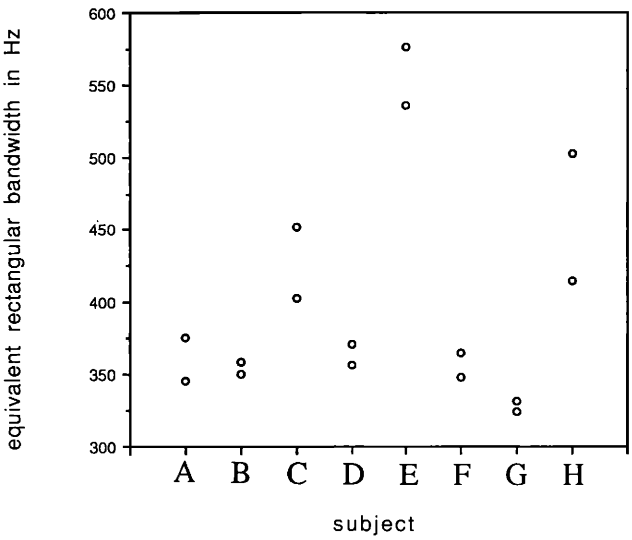

FIG. 2. The ERB measured on two occasions for each of the eight subjects. The mean of these two readings was used as the ordinate for Fig. 3.

of these two readings was compared with the five distortion measures.

The data from a minimum of three, and a maximum of four, f_1 sweeps have been averaged for each subject to give the mean data on the distortion peak in Table I. The center frequency of the peak varies between an average of 0.7 and 0.44 of an octave below f_2, and the $Q_{3\text{ dB}}$ of this peak varies between 3 and 6.5. The maximum magnitude varies between -2 and 10 dB SPL and the mean group delay between 2.25 and 3.56 ms. The ERB is shown in Hz and varies between 553 and 327 Hz. The correlation of the averaged data with the ERB is shown in Table II. There is no significant correlation between any of the five measures and the ERB when all eight subjects are included. However, it was clear from Table I that the subjects at the extreme end of the range for distortion $Q_{3\text{ dB}}$ and bandwidth coincide with the ERB extremes. If this represents a trend, then it is possible that it is being obscured by the poor data from subjects D and F. When these two subjects are excluded from the analysis, there is a significant (at the 2% level) negative correlation between $Q_{3\text{ dB}}$ and ERB. The bandwidth and $Q_{3\text{ dB}}$ data for the eight subjects are plotted against the ERB in Fig. 3(a) and (b), respectively. The mean of 3 or 4 readings is shown together with the standard deviation. The two subjects (D and F), who gave poor distortion results, are shown with filled symbols.

Although there was no significant correlation between delay and ERB, the graphs in Fig. 1 show a steeper phase slope for the more sharply tuned distortion peak in subject A than the phase slope for subject E, where the peak is broadly tuned. When expressed as delay, this difference amounts to just over 1 ms (Table I).

III. DISCUSSION

The results described indicate a correlation, which is significant at the 2% level, between the objectively measured "tuning" of the distortion peak and the equivalent rectangular bandwidth measured psychophysically in the six subjects for whom good distortion levels were measured. Where more than one measure is compared, the probability (p) must be adjusted down in level to take into account the number of correlations which are carried out. If there were *a priori* reasons for expecting each of the five measures made here to correlate equally well with ERB, then each measure would need to show significance at the 1% level ($p \leqslant 0.01$) or better. However, the measures of distortion made in this study can be separated into two distinct categories (1) those based on bandwidth: the distortion peak bandwidth 3 dB down and the $Q_{3\text{ dB}}$ (both of which are likely to correlate with the psychophysical measure of bandwidth), and (2) those which do not involve a measure of bandwidth: mean group delay, center frequency and magnitude. The probability is apportioned equally within these categories, such that $p \leqslant 0.025$ is accepted as significant for the bandwidth measures and $p \leqslant 0.0167$ for the non bandwidth measures.[2]

Mean group delay might be expected to correlate with cochlear tuning on theoretical grounds. The more highly tuned a resonance, the greater the time taken for the vibration to achieve maximum amplitude. Therefore, it might be expected that, the more highly tuned the mechanical response of the cochlea, the greater would be the mean group delay of the emitted distortion. There are, however, several reasons why this may not be evident in reality. The distortion signal represents the vector sum of components from an unknown number of sources, with consequently unknown phase relation to each other. It is only when one

TABLE I. Average data from five measures of the acoustic distortion peak ranked according to their ERB. All distortion data were calculated from individual sweeps (including $Q_{3\text{ dB}}$) to give the mean values shown. The ERB is the mean of two readings.

Subject	ERB in Hz (mean 2 measures)	No. of $f1$ sweeps	Center freq. in Hz (1)	Bandwidth 3 dB down in Hz (2)	$Q_{3\text{ dB}}$ (3)	Mag. max in dB SPL (4)	Delay in ms (5)
G	327	3	2508.3	388.3	6.567	2.667	2.47
B	354.6	4	2716.25	498.75	5.475	9.25	3.558
F	356.4	3	2556.7	700	4.184	1.167	2.34
A	360.4	3	2797	498.3	5.633	4.33	3.27
D	362.6	3	2940	658.3	4.494	−2.33	2.357
C	426.9	3	2691.67	493.3	5.633	3.167	2.866
H	456	3	2463	415	5.44	6.833	3.076
E	553.7	4	2705	812.5	3.126	6.5	2.248

TABLE II. Correlation between mean equivalent rectangular bandwidth and the five measures of the distortion magnitude peak in eight subjects (mean of 3 to 4 readings) and with subjects "D" and "F" omitted. Probability (p) is shown in parentheses.

	Correlation for 8 subjects		Correlation without subjects D and F		Significant for $p <$
	(r)	(p)	(r)	(p)	
$Q3$	−0.58	(0.13)	−0.89	(0.016)	0.025
Bandwidth	0.45	(0.26)	0.78	(0.069)	0.025
Delay	−0.25	(0.52)	−0.54	(0.27)	0.0167
Mid-peak frequency	0.01	(0.97)	0.1	(0.86)	0.0167
Maximum magnitude	0.5	(0.21)	0.44	(0.39)	0.0167

source clearly predominates that a relatively unambiguous phase reading can be made. The features evident in the amplitude waveform, which are sometimes accompanied by clear deviations in the phase slope may be indicative of "secondary" sources of distortion which will affect the mean group delay computed. This computation will also be affected by the changes in signal magnitude: the sharply tuned distortion peaks give only a narrow plateau at the peak over which mean group delay can be calculated with any precision. There may also be considerable variability in the space-coding for frequency in the human cochlea. Thus the travel time could vary because of differences in the distance travelled independently of any "tuning" effect. As pointed out in the results section, the difference in mean group delay between the most broadly peaked distortion response and a fairly typical narrowly tuned response amounted to over a millisecond, with the broader peak showing the shorter delay. This is in the expected direction (sharp tuning=long delay). It is possible that, given a sufficiently large data sample, the correlation between frequency selectivity and distortion mean group delay could improve.

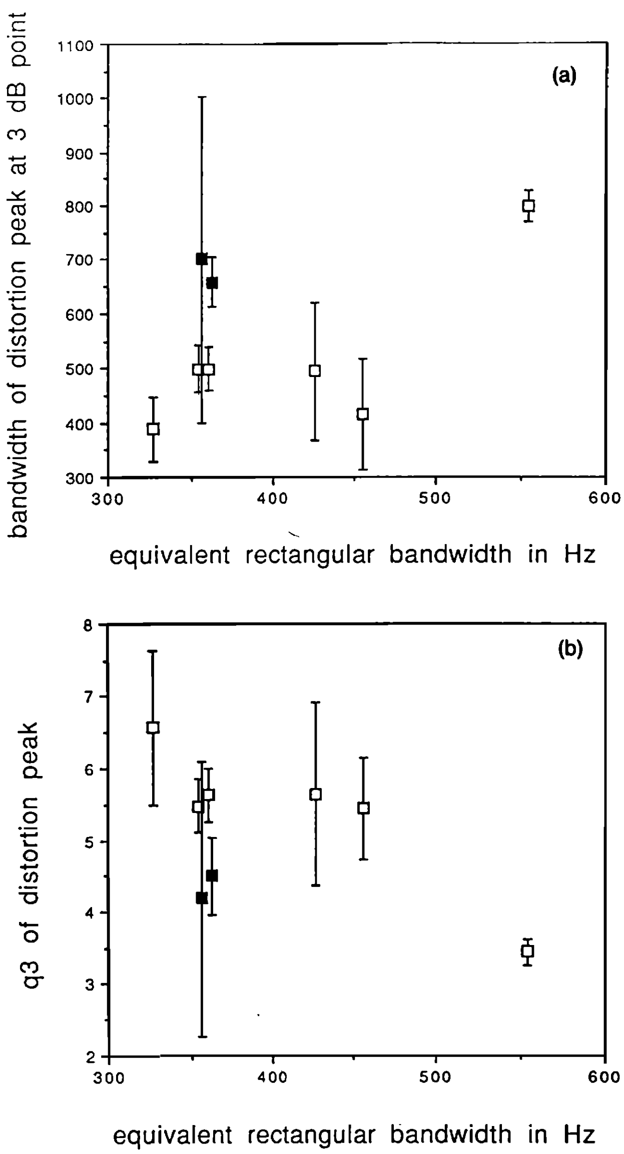

FIG. 3. Part (a) shows the relationship between distortion bandwidth and equivalent rectangular bandwidth. Part (b) shows the $Q_{3\,\mathrm{dB}}$ plotted against ERB. The ERB is the average of two measurements and the distortion data are the mean of between 3 and 4 points (see Table I). The standard deviation of the mean is shown for each point. The correlation between $Q_{3\,\mathrm{dB}}$ and ERB is significant (negative) at the 2% level.

There was no reason for predicting that the center frequency of the distortion peak would correlate with ERB. However, the finding that there is a better correlation between ERB and $Q_{3\,\mathrm{dB}}$ (which is dependent on center frequency as well as bandwidth) than between ERB and distortion bandwidth means that center frequency is more important than we had thought initially. The level of distortion measured was considered unlikely to correlate with ERB. The level of distortion is far more dependent on the state of the middle ear and outer ears (disease, effusion, scarring of the tympanum, wax) than is a psychophysical measure, since emissions depend on two-way transmission of sound through these structures.

The correlation was adversely affected by data where either the signal level was low or the noise level was high (or both, as in subjects D and F). The signal to noise ratio is a major factor in determining whether successful mechanical "tuning" measurements can be made. There must be enough data above the noise floor to allow at least a 3-dB bandwidth to be measured. Since the level of emitted distortion varies greatly between subjects, it will be necessary to improve noise rejection for future studies. We are also exploring more satisfactory and completely objective means of analyzing distortion tuning.

The stimulus conditions in this study are limited to a single f_2 with f_1 varying across an appropriate range, so we do not know if the correlation is preserved at different f_2 frequencies. The distortion generated by low level stimuli during an f_1 sweep when f_2 is held at 4 kHz shows a clear maximum. Previous work has shown that the distortion maximum generated with lower frequency stimuli is more featured, though it is still usually possible to determine a center frequency and bandwidth.

The ERB measured psychoacoustically is centered on the frequency of the probe tone at 4 kHz in all subjects. The acoustic measure of $Q_{3\,\mathrm{dB}}$, on the other hand, is derived from a center frequency, which is variable divided by the bandwidth around this peak. Why should a peak in distortion level which occurs about half an octave below f_2 relate to frequency selectivity at f_2 itself? The distortion is likely to be generated by nonlinear responses in the outer hair cells (or possibly the basilar membrane) in the f_2 region. We know from previous work, in which other cubic distortion components were measured (Brown and Gaskill, 1990b), and by inference from the work of Smoorenburg (1972), that the peak in distortion level is associated with f_2 rather than with f_1. The filter which causes this distortion peak is likely to operate at the f_2 place on the cochlear partition and this led to the speculation that the distortion peak may indicate the influence of the tectorial membrane (TM) on cochlear mechanics (Brown *et al.*, 1992). The cochlear models of Allen (1980) and Zwislocki and Kletsky (1979) both give the tectorial membrane a key role in determining frequency selectivity. In Allen's model, the tectorial membrane is tuned to a frequency about half an octave below the frequency to which the basilar membrane is tuned (f_2) at any one place on the cochlear partition. The TM, through its intimate contact with the outer hair cell stereocilia, provides a "shunt path" for vibration at frequencies below those characteristic of the place for the basilar membrane, so that the excitation pattern experienced by the inner hair cells is sharper than would be given by a basilar membrane stimulus alone (Allen, 1980). If the tectorial membrane is indeed tuned in parallel with (but at a lower frequency than) the basilar membrane, and if it is the tectorial membrane that filters the acoustic distortion before the latter reaches the ear canal, then there is a good reason why distortion "tuning" and subjectively measured frequency selectivity should correlate.

The results of this preliminary study give some indication of a link between cochlear mechanical tuning measured from acoustic distortion products and frequency selectivity measured psychoacoustically. While the precise causal relationship is unclear, the results are promising enough to prompt further study.

ACKNOWLEDGMENTS

This work was supported by MRC project grants to AMB and SAG, a Royal Society University Research Fellowship to RPC and a Wellcome grant to DMW. The sound-treated room and some equipment were provided by the Hearing Research Trust and the Wellcome Trust. We are grateful to Mahmooda Butt for help with psychoacoustic data collection, to Dr. Zoltan Dienes for statistical advice, and to Brian Warburton, who designed and built the artificial distortion source.

[1]The transformation was necessary because, in forward masking, a given change in masker level leads to a smaller change in signal threshold. Similarly, a change in notch width, which causes a change in the masker energy passing through the auditory filter centered on fs, will also be "under-represented" by the resulting change in threshold. Therefore, the thresholds reported here were transformed by the formula: $T' = B - [(B - T)/\mathrm{SLOPE}]$ where T' is the transformed threshold for a given notch width and condition, T is the untransformed threshold for that notch width, and B is the threshold for the 32-dB SPL bandpass masker for that condition. SLOPE is the slope of masking, estimated from the difference in threshold between the 32-dB and 12-dB bandpass maskers, divided by 20. We chose a two-point measure partly because of time constraints, and also because previous measures of the slope of masking (e.g., Moore and Glasberg, 1981) indicated that a two-point estimate of the slope would be sufficiently accurate.

[2]It is also possible to apportion probability unequally (Bonferroni inequality). This is done according to the formula: $1 - \Pi(1-\alpha_i) \leqslant 0.05$, where α is the probability for each of the i cases. However, this poses a problem in determining exactly what probability to apportion among disparate measures (In this study, probability could have been apportioned as follows: 0.02 for bandwidth and $Q_{3\,\mathrm{dB}}$, 0.005 for center frequency and mean group delay and 0.0002 for magnitude, on the basis of the *a priori* likelihood of a correlation occurring).

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