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ABSTRACT

While 'optimal' frequency responses for speech intelligibility can be shown, their practical application poses many difficulties, some of which are already quite widely appreciated. Experimental work where vision supplements the audio speech signal suggests a further difficulty concerning the difference between laboratory or clinical conditions of testing and the conditions affecting the use of a hearing aid in real life. Visual information about the speaker's articulations is redundant upon the mid- and high-frequency audio information. This should shift the need for audio information to lower frequencies when lipreading.

It is shown that the performance of hearing aid users conforms to this expectation. A 'flat' and a 'rising' frequency characteristic were tested under audio and audio-visual conditions. A better score was obtained for 'flat' than for 'rising' on the audio-visual test but not on the audio test. The interaction between type of test and frequency response was highly significant. It is concluded that worthwhile applications of improved high-frequency responses in hearing aids are restricted because the majority of present hearing aid users are typically lipreading when using their hearing aids. However, a two-position tone-control switch on aids to cover 'lipreading/not lipreading' conditions is justified.

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INTRODUCTION

The question of the optimal frequency response in a hearing aid is a vexed one with a long history. It has been shown in experiments involving the identification of spoken words (usually without significant noise background) - that general optima can be found for heterogeneous clinical groups (MRC, 1947) but that optima diverging from the general ones can be found for individuals (Levitt and Collins, 1980; Skinner, 1980). The variability of standard clinical word identification tests (formulated for "speech audiometry") (Shore et al, 1960), plus the general constraints upon optima, make it difficult to show individual optima both in research studies and in practical hearing aid selection. As a consequence, determination and validation of optima are extremely time-consuming and are generally replaced by predictive prescription rules that take account of an individual's audiogram in a formula, weighting the hearing levels at each of the standard frequencies (for a comprehensive review, see Byrne, 1983). An audiogram tends to have been obtained already, supposedly for diagnosis, so it is a convenient if not necessarily the best basis for prescription. However, as the statistics of audiograms that actually occur are constrained (e.g. a predominance of gradually sloping losses), the rules cannot be conveniently tested as highly specific prescription regimes. A direct health-economic test of the overall efficiency of one regime against another would be unlikely to be worthwhile, as too many variables are involved; rather, tests are required on the groups comprising those few types of cases where the various regimes generate clearly divergent prescriptions. It is *a priori* likely that the population to be served would be well served by a standard prescription for the majority and a small number of differing types for distinct extremes of audiogram shape. The foregoing generalisations are the essential context for evaluating any proposed refinements in the domain of frequency response of hearing aids. Any particular proposal should be evaluated explicitly either as an improvement for 'the majority of typical users' or as an improvement for a specified subset. While the knowledge detailing the appropriate subset may not always be secure, at least this approach improves the chances of a favourable evaluation for a specific development.

In practice the major issue in determining frequency responses, both in general and for the individual, is the slope of the frequency response, and the related issue of the worthwhileness of providing substantial high-frequency gain. Particular cases, especially new users, prefer a frequency response with less high-frequency content than the one which gives optimum word identification (Thompson and

Lassman, 1970). One possible basis for this discrepancy is that any response peak protruding from the overall frequency response classically recommended for hearing aids, (but particularly a high-frequency peak), will exert a dominant role in overall loudness and quality. The intelligibility of speech through a hearing aid with a peaked characteristic suffers from two factors: the direct loss of normal spectral relationships, and the entailed lower tolerable gain setting for other frequency regions of the response (Haggard, 1983). Where the user has the ability to vary the gain, as is generally the case, a lower than optimum score will therefore result from achieving tolerable loudness in a hearing aid with a peaked characteristic. It is also true that if the boundaries of tolerance are pushed in respect of the high-frequency gain, the rising characteristic gives, on average, slightly greater intelligibility than a flat characteristic (Thompson and Lassman, 1969). Thus, as well as eliminating unwanted peaks from the frequency response, hearing aid technology must join with audiology and human factors to maximise the acceptability - in the long term - of the levels of high-frequency gain that are now possible and in some cases desirable.

The purpose of this article is to demonstrate a major human-factor consideration in work on frequency responses, which is a possible explanation for discrepancies between field results and laboratory or clinic results, and between real-life preferences and measured performances. That consideration is lipreading. This skill is often represented as a mixture of visual uptake and enlightened guessing in the profoundly and totally deaf. This is appropriate, but numerically the implications of lipreading as a synergy of visual uptake with impaired hearing of gross auditory features in the mildly-, moderately-, and severely-impaired are much more important.

Recent experimental studies of audiovisual speech perception (Summerfield, 1983; Rosen et al, 1981; Risberg and Lubker, 1978) support down to a considerable level of detail the old insight (Fletcher, 1929) that an impoverished audio signal for speech, with mainly low frequency content, can combine effectively with information from the speaker's face, because the two classes of information are largely complementary. (Principle 1). Fortunately this fact about speech offsets a general difficulty in loud noise and in hearing impairment, and it has presumably exerted some evolutionary pressure on the development of spoken languages.

As most present-day hearing aid users are not mildly but moderately to severely impaired, (Haggard et al 1981) they "lipread" under most circumstances, and suffer a disadvantage most notably when they cannot, particularly in conjunction with noise or reverberation. They find hearing aids useful for television and face-to-face, but often not with radio etc. For spoken communication, the typical hearing aid user will therefore inevitably use the aid as an aid to lipreading, not as an aid to hearing. (Principle 2). From these two principles we may deduce a third, that the optimum frequency response will differ between a condition that does and a condition that does not include visual information of the speaker's articulations. (Principle 3). The direction of the effect should entail less high-frequency amplification when the listener can view the speaker's face, as this information is then partly redundant. Given such viewing, it will not be worth allowing high frequency information at high gain to contribute to the overall loudness and hence to force down the gain of the complementary and also useful low frequencies when gain is adjusted for comfort. We designed an experiment to test this argument.

METHOD

Test Stimuli

The FAAF test (Four Alternative Auditory Feature Test; Foster and Haggard, 1979) and the FADAST (Four Alternative Auditory Disability and Speechreading Test; Summerfield and Foster, 1983) are four-alternative speech perception tests recorded by the same male speaker. In the FAAF test the 80 stimulus words comprise each word in 20 four-word vocabularies. The vocabulary is composed on the rhyme test principle by taking two values of each of two articulatory/acoustic features of consonants that distinguish minimally-paired real words in terms of the phoneme at a single syllabic position (e.g. mail, bail, nail, dale). The 100 FADAST trials are similarly composed except that each trial allows for one consonant confusion and one vowel confusion. The set of four response alternatives for a trial is displayed to the subject on a response sheet for the purely-auditory FAAF test and additionally as a subtitle to the head-and-shoulders video image of the speaker for the audio-visual FADAST. After an announcement of the trial number the test word is spoken, within the carrier phrase "Can you hear X clearly" for the FAAF test. There is no carrier phrase in the FADAST.

The calibration level of each test is defined as the mean peak RMS (fast meter-setting) level of the test words in dB(A). Masking noise was added to each test to avoid ceiling effects and to reduce distractions for less-than-ideal acoustical environments. The signal-to-noise ratio used was 5 dB for each test. In previous applications the FADAST has been masked by white noise, while the FAAF test has been used with speech-spectrum-shaped noise derived from the long term spectrum of speech produced by the speaker of the test. These conventions were preserved.

Each master tape, including the masking noise, was filtered with two frequency responses, one nominally 'flat' and one 'rising' (+9 dB/octave), by a body-wearable prototype of a signal processing hearing aid. Experimental stimuli for both tests were then recorded on videotape to minimise further presentation differences. At playback a Sony Videorecorder VO-1810 fed a Marantz 1072 Amplifier and Jessop Attenuator driving TDH 39P headphones (100 ohm) with MX-41/AR cushions for monaural listening. Amplification was set to a fixed calibrated level and presentation level adjusted in 5 dB steps using the attenuator.

Subjects

The test subjects were obtained from records and follow-up visits at a National Health Service clinic in a middle-sized English market town. All but one had been fitted with their first hearing aid within the last year (median 3 months). Twenty-eight subjects, 12 males and 16 females, with sensorineural hearing loss unselected as to severity, asymmetry, aetiology or audiogram shape were tested. The mean air conduction hearing loss (0.5-4.0 kHz) in their normally aided ear was greater than 35 dB in all cases. The mean air-bone gap (0.5-2.0 kHz) was in 21 cases less than 10 dB. In 7 cases, however, the mean air-bone gap ranged from 11 to 17 dB. The age ranged from 42 to 69 (median 64).

Procedure

The main design comprised speech idenfication data in four conditions (two frequency responses by two test materials) undergone by each subject. The test complement is shown in Table 1; it required two sessions of one and a half to two hours per subject.

In addition to the four main conditions, subjects underwent a 40-item FAAF test "freefield" with their own hearing aid and a further FAAF test involving a switching action between the two frequency response characteristics to test this as a potential signal-processing hearing aid design (Haggard and Trinder, 1983).

The four main speech test conditions and the 'switching' condition were presented in an order counter-balanced across subjects and the order of items within tests was changed with conditions. The other tests and the questionnaire occurred in the fixed order shown in Table 1, not being part of the experimental design. They separated the components of the main design to avoid boredom for the subjects. Detailed analyses of these additional data are reported in a companion paper (Foster et al, 1983).

Uncomfortable loudness level (ULL) judgements were made before the first test with each frequency response on a passage of running speech set to the same calibration level as the test stimuli. The presentation levels were set initially according to the rule: ULL - 10 dB. In the 'rising' condition this sometimes gave a level that was reported as not consistent with comfort and ease of listening. The level was increased by 5 dB in four cases and decreased by 5 dB in two cases. For two of these subjects the parallel modification of the rule was required in the 'flat' condition also. The responses on the speech tests were ticked on result sheets by the subjects. Two subjects would have needed different spectacles for looking at the TV-monitor and reading in the FADAST. Here the experimenter ticked the sheet when the subject called out the position ("one", "two", "three" or "four") of the response word on the display.

RESULTS

The main result appears in raw form in Figure 1, the 'flat' response being significantly better than the 'rising' response ($t=13.08$; $df=27$; $p<0.001$) for the FADAST audiovisual test but not for the FAAF audio test ($t=1.23$; $df=27$; N.S.). Most importantly, the interaction is significant ($F=58.61$; $df=1, 27$; $p<0.001$). The result is only minimally modified by incorporating the presentation level as a covariate in an analysis of covariance. This rules out the possibility that the interaction might occur through the conditions differing in average intensity of presentation (derived from their particular uncomfortable loudness levels).

There are three slight differences in the composition of the two tests. We argue that none of them prevents us from interpretating the result in terms of audio-visual complementarity. The FADAST incorporates vowel distinctions as 50% of its phoneme distinctions, while the FAAF test has no vowel distinctions. The third panel of the figure however shows that the subset of FADAST consonant distinctions alone gives the same pattern of results; the crucial interaction emerges as even more significant ($F=71.30$; $df=1,27$; $p<0.001$), despite involving only half the potential stimulus information. Secondly, the high mean score for the FADAST in the 'flat' condition would usually be associated with a ceiling effect whereby any difference between conditions was less able to emerge; but it is precisely on the FADAST that the effect of frequency response *is* observed. Finally, although the voice was the same in the two tests, the masking noise slopes differed by about 6 dB/octave, being speech-shaped for the FAAF test and white for the FADAST. This would potentially restrict to some extent the relative role of mid and high frequencies in the FADAST, and possibly predispose the obtained result since the role of a band in intelligibility depends primarily upon its signal-to-noise ratio (French and Steinberg, 1947). It was therefore desirable to check the spectra resulting for each condition with the two tests and these are shown in Figure 2. Clearly, the high frequency information of the FADAST (above 4 kHz) is more masked than that of the FAAF test but the difference between the tests at mid frequencies is not great. It is therefore unlikely that the obtained effect is due to less availability of mid-frequency information for the FADAST, particularly since filtering was applied after, not before, the addition of noise.

DISCUSSION

Individual differences

Sensorineural hearing impairment is not merely attenuation by a linear filter shaped like the audiogram. Nevertheless, the question arises whether the difference in pattern of results between audiovisual and audio tests, emerging experimentally as a function of slope of frequency response, emerges also across individuals, as a function of the slope of the audiogram. We expected such a result here, having obtained it in part of a population study (unpublished; for general description see Davis, 1983) in which scores on audiovisual sentences with white noise masking were correlated with hearing losses across frequency; a significantly greater correlation emerged for low than for high audiometric frequencies. The analogous results for the present data are presented in Table 2. Patterns do emerge, different for FAAF and FADAST, the low-frequency correlation being stronger for the audiovisual FADAST and the high-frequency correlation stronger for the audio FAAF test. This confirms across individuals the result found above with experimentally controlled conditions. It also argues that audiovisually measured disability, and to some extended general communicative disability, reported by the moderately disabled should depend upon a mixture of lip-reading ability and properties of low-frequency hearing (including perhaps frequency resolution and temporal resolution as well as absolute sensitivity). This low-frequency involvement contrasts with the generally higher dependence of audio-alone measures of word identification upon *high* frequency hearing levels, a correlation replicated here and stemming from the usually greater subject variance of hearing levels at high- than at low-frequencies.

"High fidelity" aids

In a study of acoustical factors in the high frequency response of hearing aids, Lawton and Cafarelli (1978) showed higher preference ratings and an advantage of approximately 5% identification score from extended earphone frequency response or horn-approximation stepped-bore tubing. Very similar results have been obtained by L. Rigg (unpublished; see summary in Haggard, 1983) with an electronic simulation of these factors but presentation by earphone, and also by Ringdahl et al (1983). However, in an extension of the Lawton and Cafarelli laboratory study to a field trial, Rice (1983) has reported that such favourable reactions to the modified aids are unfortunately not obtained when hearing aid users rate the aids in paired comparisons on the basis of *everyday* use. Likewise informal reports from commercial hearing aid dealers do not indicate general preference or acceptance of aids with smoothed response and greater high-frequency gain. We now feel justified in interpreting this discrepancy and the older Thompson and Lassman (1970) result in terms of an effective difference in the communication conditions underlying the tasks.

In all but the most severely impaired, even a basically difficult audio-alone material can be rendered effectively easy by high presentation intensity and by a favourable signal-to-noise ratio. Even though overall difficulty may not change, the balance of influential factors becomes quite different when acoustic conditions degrade (more difficult) yet the speaker's face is visible (easier again). The mean age and impairment levels of typical UK National Health Service hearing aid users in recent years (Haggard et al, 1981) are approximately 68 years of age and 45 dB HL (0.5 to 4.0 kHz). This makes them not as a whole an ideal target group for high fidelity hearing aids. Given that the hearing loss is generally worse than 45 dB HL at higher frequencies and accompanied by loss of frequency resolution, the majority of circumstances in which a hearing aid could be used to advantage incorporate lipreading. The preference judgements were presumably based upon such circumstances in Rice's field study, and the present result helps to explain why the supposedly beneficial high-frequency audio factors could have been overridden there.

Our aim in this report is not to undermine the important and difficult work of improving the electro-acoustic quality and the specific suitability of aids delivered to hearing-impaired people. Rather we hope to indicate the tests that are appropriate for different types of aid, given the major types of user and communication circumstances likely to be involved. Thus we hope to help concentrate the limited resource of the few acoustical engineers in the field onto those specific problems in research and service delivery where the return from these refinements is likely to be greatest. The question, "Is hearing aid A better than hearing aid B?" (for a particular type of hearing loss), is still best answered by a 'difficult', rationally-designed and sensitive audio test like the FAAF. Our results show formally what hearing aid practitioners have long appreciated informally, that these psychoacoustic and electroacoustic questions are not in every case the most important questions and may sometimes receive equivocal answers. The remaining abilities, and the typical circumstances and aspirations of the user in communication determine the relative importance of psychoacoustic and electroacoustic factors.

Increasing but still modest numbers of 'young elderly' with mild hearing losses use hearing aids and attempt their use in group conversation, with the telephone etc; for such cases a sensitive audio-alone test such as the FAAF will be the appropriate arbiter of the higher quality they require. It will correctly point to a requirement for more and smoother high-frequency gain than will less sensitive measures such as those based upon audiovisual speech perception. The extent to which this benefit is material in an individual will be a continuous function of various hearing parameters and social parameters. The appropriate placement of the criterion for the decision to provide or not provide the better audio quality is not solely an audiological matter but also a health-economic matter of cost-benefit. At any rate we do not question the desirability of further technological progress for this growing sector of the aid-using population.

User adjustments

In private health services the economic term in the choice of fitting is supplied by the patient's bank balance. In public health services the responsibility is unclear and is divided. A public health service could reduce the responsibility problem (although not the cost problem, except for slight gains from bulk contracts and mass-production). This reduction would have both a technological and a procedural (audiological) component. A continuous tone control that is only convenient to set over the long term implies some *general* optimum or preferred characteristic. However a two-position switch could be provided to change the spectral slope by about 6 to 9 dB/octave. If an internal screw-trimmer tone control is put to the most positive spectral slope that the patient will *initially* tolerate with the 'low' setting of this switch, more high-frequency gain can still be available on activation of the switch, a desirable facility in habituation to an aid irrespective of the present audio/audio-visual issue. A short period of instruction would be needed, but ability/inability to see the speaker's face is a very concrete and self-evident cue upon which to base a binary aid adjustment; no appreciation of speech acoustics is required by the patient. If the screw-trimmer needs to be adjusted at follow-up, any reported behaviour in respect of the switch-position (e.g. "I prefer it always in") should help to indicate the direction of the change required. By distinguishing circumstances permitting lip-reading from those not permitting it and by encouraging the alignment of switch positions with these circumstances, a more reliable determination of the optimum or preferred trimmer setting should be obtained. The advantages would be quite general, although a less expensive aid lacking these refinements and options could be provided for those whose impairment is of a severity or form likely to make them superfluous. While it would be uneconomic to establish in routine service whether every case fitted with the switching arrangement has actually benefitted materially, at least the risk of providing a significant number of people with a single non-optimum prescription at high cost is reduced.

The apparent absolute optimality of the 'flat' condition with the FADAST in the present results does not undermine the argument for providing two (or perhaps even more) characteristics within a single aid. In the extreme, all materials must show an inverted-U relationship between identification score and spectral slope - no-one would suggest -12 dB/octave, or +24 dB/octave for general requirements! The FAAF test results indicate that the function's peak is roughly midway between 'flat' and 'rising' (i.e. about +3 to +6 dB/octave for the voice used) for the audio condition. It appears to be nearer to 'flat' (probably somewhere between -3 dB and +3 dB/octave) for the visual condition. It is this *relative* offset which argues for the switch, the absolute optima being handled by the trimmer. The companion paper (Foster et al, 1983) suggests that those optima might be efficiently predicted and hence prescribed by supplementary audiological data with new types of psychoacoustical data.

CONCLUSIONS

1. In selecting or evaluating hearing aid characteristics it matters whether an audio or audiovisual test is used.

2. The more severe the impairment, the stronger are the grounds for using an audiovisual test.

3. Broadly speaking, an audiovisual test will indicate more low- and/or less high-frequency gain.

4. Aids should therefore be manufactured with a simple position-evident switch for changing the overall spectral slope, possibly in series with a trimmer tone control.

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Table 1. Test Complement for the Study

Uncomfortable Loudness Level for running speech for each frequency response 'flat' and 'rising' (and 'switching')			
Earphone Audiovisual Tests	FADAST	100 trials x 2 frequency responses	
Earphone Audio Tests	FAAF	80 trials x 2 frequency responses	
Earphone Audio Test	FAAF	80 trials	'switching' condition
Pure Tone Audiometry	air and bone conduction		
"Freefield" Own Aid Test	FAAF	40 trials	
Hearing Aid Questionnaire	questions on impairment, handicap, disability, benefit and use of the aid.		
Electroacoustic check of hearing aid function, gain and distortion.			
Psychoacoustic Tuning Curves	levels of 50 Hz bandwidth noises at 1.25, 2.0 and 2.5 kHz which just mask a 2.0 kHz pulsed probe tone at 10 dB SL.		

Figure 1. Mean percent correct identification scores for two tests, and two frequency responses on 28 subjects. Vertical bands indicate +1 s.d.

Figure 2. Long Term Spectra for Test Materials

Each graph shows the 'long term' spectrum levels for samples of 10 test items plus noise and of noise alone. Samples were of approximately 5s duration. The FAAF test was masked by speech-spectrum-shaped noise modelled on continuous speech of the same talker and the FADAST by white noise. The nominal signal-to-noise ratio before experimental filtering was +5 dB in each case.

Table 2. Correlations between Test Scores and Audiometric Thresholds
n=28   * $p < 0.05$

Frequency (kHz)	0.25	0.5	1	2	3	4	8
FAAF 'flat'	-0.05	+0.08	+0.18	-0.32*	-0.37*	-0.33*	-0.25
FADAST 'flat'	-0.49*	-0.41*	-0.11	-0.20	-0.26	-0.09	-0.17

Figure 1

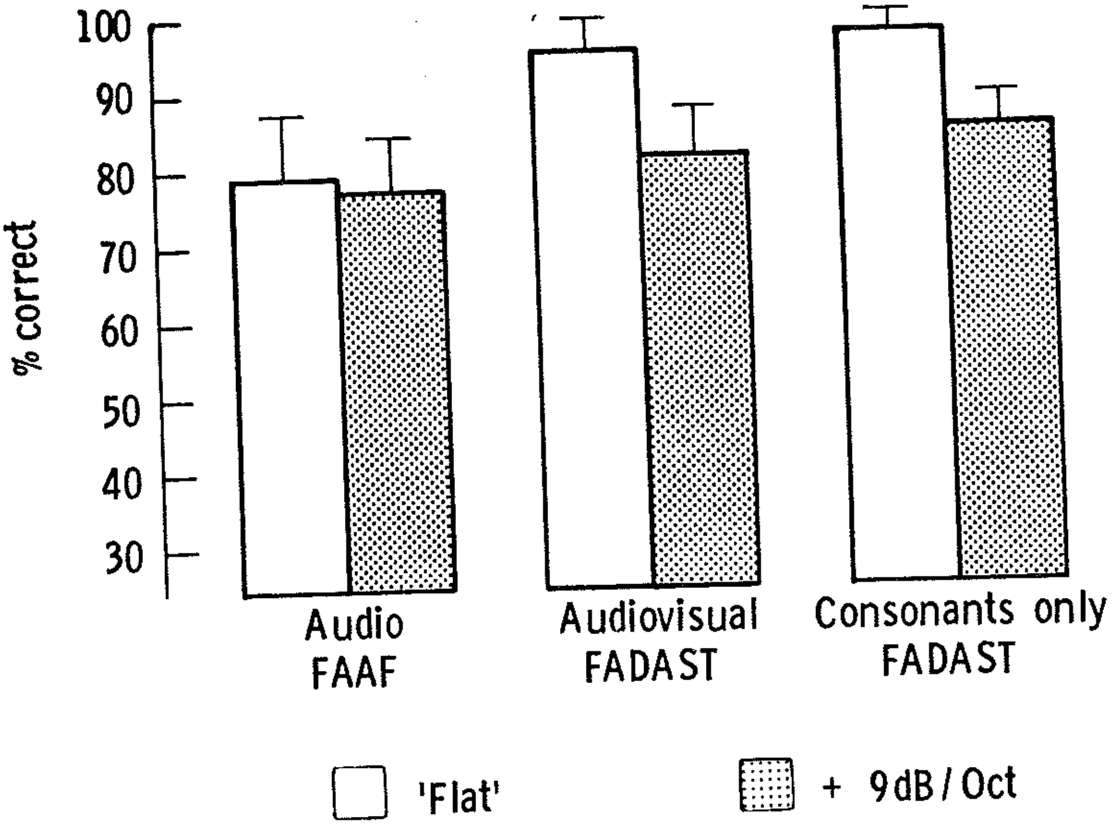
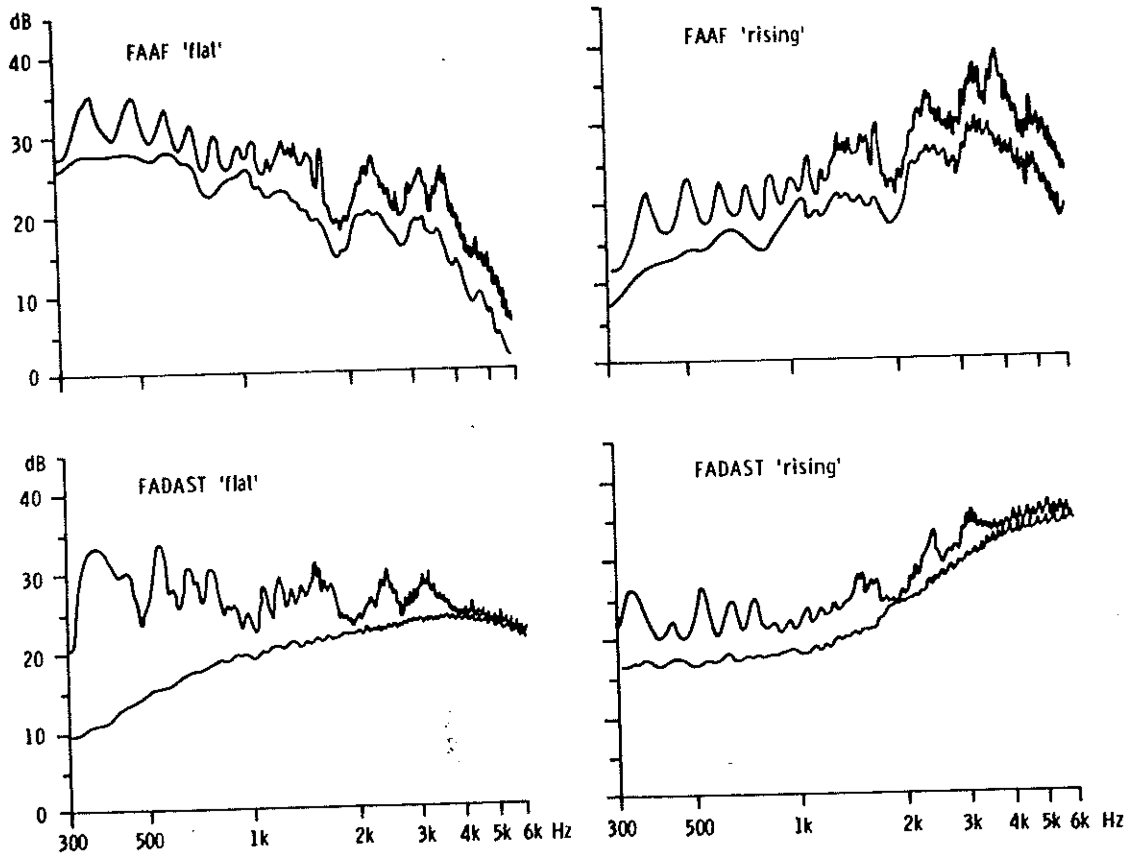


Figure 2



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