THE USE OF LOW FREQUENCY RESIDUAL HEARING IN PROFOUNDLY DEAF CHILDREN

by

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INTRODUCTION

Purpose of the Research

Up to the present time it has been customary for hearing aids to reproduce approximately the same range of frequencies as the telephone (300 - 3000 cps). The aim of this investigation was to determine whether additional low frequency amplification, achieved by the provision of hearing aids with a frequency range from 80 - 3000 cps, would contribute significantly to the audition of speech among children with low-tone residual hearing.

In some earlier work the writer (Ling, 1963) had observed that the amplification of low frequency components of speech (achieved by coupling a high quality microphone externally to a conventional hearing aid) substantially improved the spontaneous voice and speech patterns of some children with residual hearing whom he was teaching. It was clear that this improvement was due in some way to better audition of speech. The present study examines in detail some of the relationships between low frequency amplification and the audition of voice and speech patterns among children with residual hearing.

For the purpose of this research, experimental hearing aids were developed to the writer's specifications by the Zenith Radio Corporation. They were identical in appearance with standard model hearing aids and could be identified visually only by their serial numbers. To ensure that the aids possessed the required characteristics and adequately reproduced low frequency components of speech, a preliminary study of the hearing aids was made. This part of the research has been fully reported (Ling, 1964b). The frequency response characteristics of the two models and their effect on the transmission of low frequency components of speech are shown in Figure 3 (p. 30) and by Ling (1964b).

General Review

Hearing Loss Found in Schools for the Deaf

Recent surveys (Huizing, 1959; Watson, 1961) show that at least 95 to 97 percent of the children enrolled in special schools for the deaf have some measurable hearing. Ewing (1962), in reviewing reports on the hearing levels of children receiving special educational treatment for deafness in Holland, New Zealand and Britain, remarked that, among children with defective hearing, the proportion of those having a profound hearing loss was greater than that found among adults with defective hearing. Ewing stressed that schools for the deaf have highly selected populations. Of 1336 cases that he reviewed, 16 percent had hearing losses averaging less than 60 decibels, 31 percent had hearing losses averaging between 60 and 90 decibels and 53 percent had hearing losses averaging more than 90 decibels (British standards). Only one case had no measurable hearing. Public Health Service (1964) data confirm similar incidence in the United States.

Hearing Aids Used : Their Characteristics

Four main types of hearing aid are presently available for use with deaf children. These are (1) the group hearing aid, (2) the speech training aid, (3) the loop induction system and (4) the individual hearing aid. Each is discussed below.

The group hearing aid is used in schools where several pupils may be taught simultaneously by one teacher. Group hearing aids are generally mains operated. The power delivered to each pupil's phones is usually controlled by wiring the output of the amplifier through attenuators attached to each child's desk. The number of microphones feeding the amplifier varies from school to school, from one per class to one per speaker.

Group hearing aids are capable of delivering a high level of intensity. In theory, since headphones and microphones can be chosen without too much regard for size, almost any desired frequency response characteristic can be made available. In practice, the frequency range is generally limited. In England group hearing aids were produced by leading manufacturers with no significant response below 300 cps and Charan (1962)reports that the low frequency response of group hearing aids at the Central Institute for the Deaf is deliberately reduced "to minimize ambient classroom noise". Few studies in which group hearing aids have been used report the characteristics of the apparatus.

<u>The speech training aid</u> is similar to the group hearing aid but is designed for use with individual children. It is generally portable. It may be either battery or mains operated and usually consists of a microphone feeding an amplifier, which in turn feeds a pair of headphones. Controls for the adjustment of gain, and often frequency response, are available. As with the group aid, size of components is of minor importance within the limits of portability, and instruments with any desired frequency characteristic can easily be designed. While this type of aid is in common use (Ewing and Ewing, 1964) it is seldom mentioned in the literature. A speech training aid reported by Guberina (1963) differs from others in this category in that it is not portable, it employs filters, is used for both the measurement and the training of hearing and has "linear transmission along with the possibility of various rates of attenuation from 1 cps so as to include the frequency range of the vibrations of the body". Guberina also uses vibration transducers in conjunction with earphones and works with these to the exclusion of body-worn individual instruments. Since only the intermodulatory products of speech occur below the fundamental of voice, the use of frequencies from 1 cps is of questionable value. The amplifier of a group hearing aid or a speech training aid may be used to power a loop induction system.

The loop induction system, which is commonly used in schools for the deaf, requires a teacher's microphone and an amplifier, the output of which is fed into a loop of wire circling the classroom. The current created by the output from the microphone goes to the amplifier and flows into this loop, creating a magnetic flux within the room. This flux, crossing a coil housed in an individual hearing aid, induces the same pattern of current, thus permitting the child to hear the teacher equally well whatever their respective positions in the classroom. It is particularly suitable for group lessons of an active type.

The intensity and frequency response available to each child depends on the characteristics of the loop amplifier, the transformer coupling and the individual hearing aid. As the induction circuit by-passes the microphone of the individual aid, better low frequency and high frequency responses can be obtained from any type of individual aid when it is used in a loop induction system. The response could, indeed, range from less than 100 cps to over 8000 cps.

Used in Europe for more than ten years, this system has been described in the American literature by Davis and Silverman (1962), by Calvert (1964) and evaluated by Bellefleur and McMenamin (1965). Loops operating on radio frequencies are in use, but have not yet been described in the literature.

The individual hearing aid is either a head-worn or body-worn instrument. Early instruments, as described by Watson and Tolan (1949) were cumbersome since they employed thermionic tubes and therefore needed at least two batteries, which could not be incorporated in the aid. Modern instruments, such as those used in this study, are transistorized and, together with the one battery required, weigh 2½ ounces and measure 2½ x 2 x ½ inches. While there are many makes and models available, individual hearing aids differ more in the amount of gain provided than in frequency response or range. Gain on one model may be as little as 30 decibels, and on another as much as 80 decibels. The frequency range generally extends from 300 cps (± 50 cps) to 3000 cps (± 1000 cps) for body-worn aids, and less for head-worn instruments. (Frequency response above 3000 cps may not be recorded accurately at present due to the characteristics of the standard 2 cc coupler employed.) Dale (1958), in describing the frequency response characteristics of the individual aids used in his study, reported only one with a significant response below 250 cps. Some degree of conformity in manufacture arose following the Medical Research Council's Report 261 (1947) in England and the Study of Design Objectives made in the United States by Davis et al (1947). The subjects in both of these studies were adults. That hearing aids designed for adults were not necessarily adequate for deaf children was pointed out by Silverman (1957) and later by Ewing and Ewing (1960). Both recommended an extended high frequency range so that most amplification was provided where hearing loss was greatest, in the hope that unvoiced consonants would be heard and intelligibility of speech thus improved. This recommendation is in marked contrast to the theory underlying the present study. Here, amplification is recommended for the frequency range over which the child hears best. Amplification of voiced rather than unvoiced phonemes and improved audibility of voice patterns are stressed by the writer as the factors most likely to contribute optimum information on speech to profoundly deaf children.

The proposal to use the low frequency residue of hearing among deaf children by extending the frequency range down to 80 cps, the lowest fundamental of the male voice, appears to have originated with the writer (Ling, 1956).

The Use of Hearing

There is an apparent dichotomy between the views of workers in special schools and classes on one hand, and workers in rehabilitation and research clinics on the other, as to the extent to which residual hearing can be used and what role it should play in the acquisition of speech and language among children with defective hearing. Those who work with deaf children in schools tend to consider hearing as a poor supplement to vision, while those who work with deaf children in the clinic situation often regard audition as the most important of the sense modalities. This apparent divergence of opinion may be acoounted for, at least partially, by the age of the child dealt with, the type of hearing aids used and the structure of the programmes offered.

Hearing as a supplementary modality. Hardy (1954), who emphasized hearing as a supplement to lipreading, stated that:

" There is incontrovertible evidence that the child who is introduced very early to sound learns to use it and to adapt to it. The idea that a deaf child must somehow learn what language is before he is permitted to use his residual hearing is consistently reiterated by some educators of the deaf. This idea lacks basis in fact - physiologic, neurologic, pathologic or psychologic. The deaf child will learn so-called 'natural language' best with the earliest possible use of sound, as does every other child"

Goldstein* introduced the Urbantschitsch auditory training method in the Central Institute for the Deaf in the late 1890s, but this method stressed the dominance of vision, using audition as a supplementary communication channel. Similarly, Hudgins (1954) stressed

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* see Goldstein, M.A. Problems of the Deaf St. Louis. Laryngoscope Press, 1933.

the advantages of the auditory training techniques he had developed in the Clarke School. Hudgins measured progress in the use of audition "in terms of the degree to which auditory perception supplements visual perception." To this end, scores obtained by pupils through lipreading were compared with scores obtained through lipreading plus hearing. What Hudgins recommended in the United States, Ewing (1957, p. 7) also recommended in England: that audition be used, but as a supplement to vision and other sense modalities. In work directed by Ewing, Clarke (1957) investigated the effect of using a group hearing aid in a school for the deaf. As in many other schools for the deaf, not all the children had individual hearing aids, and the group aid was shared between ten classes of children and a maximum of 1½ hours group training per week was available to any one child. His results, which supported the concept of "lipreading plus hearing", showed better scores after multisensory training and testing, than after testing by hearing alone. These children, however, had no opportunity to learn by hearing alone. Clarke's study may be contrasted with work later reported by Ewing (1962) in which hearing aids were worn by the children every minute of each day and hearing was the main sense avenue exploited in teaching. Though profoundly deaf, these school children taught by Lady E.C. Ewing in Manchester, by Mrs. B.I. Ingall in Woodford and by the writer in Reading, understood and controlled their use of everyday colloquial speech through hearing. Amplification in all cases was provided by individual body-worn hearing aids and through loop induction systems. In the case of the children taught by Ingall and by Ling, group hearing aids, available in each classroom, were also used in the course of teaching, some of which was "unisensory" (Ling, 1956).

Hearing as the dominant modality. The movement away from regarding vision as the most important (or only possible) sense modality was begun by Wedenberg (1951). His method was "built primarily and principally upon the auditory sense with the visual sense as a complement, in contrast to other methods based on the visual sense first with the auditory sense as a complement." The object of his work was "to create a natural synergy between the hearing sense and the seeing sense ... so that the child is unable to say 'I hear' or 'I see', but rather 'I perceive'".

Wedenberg's programme was based on data provided by Fant (1948) on the properties of Swedish speech and on the Barczi system of word presentation for deaf children, in which words which are considered easiest to hear are presented before those with components outside the child's auditory range. (Wedenberg's method was to present the words "ad concham". He later realised this was not purely auditory since it permitted the child to perceive tactile sensation from the direct breath stream on the pinna).

Support for Wedenberg's auditory emphasis in teaching deaf children was quickly provided in Holland, by Huizing (1953), who found that lipreading tended to divert the child from optimum use of residual hearing. He therefore recommended the exclusion of lipreading from the early stages of training. Further support for Wedenberg's work was provided in England by Whetnall (1953), Fry and Whetnall (1954) and Ling (1956), also in France by Perdoncini (1954; 1959). All of these workers emphasised the use of audition and suppressed visual cues in the course of training. While the cases seen by Huizing and Whetnall were mainly pre-school children who were taught by means of individual hearing aids, the pupils of Ling and Perdoncini were of school age and both group and individual hearing aids were used in their training. The communication skills in general, and the voice quality in particular, of children reported in these studies were remarkably better than those of children taught by traditional methods emphasizing vision.

Current Views on the Use of Audition

The benefits reported from the emphatic and systematic use of residual hearing have not yet changed the thinking in many schools or teacher training centres. Thus

DiCarlo (1964, pp. 106-107), whose views seem to represent those of many contemporary educators, generalised as if residual hearing could be ignored when he stated,

"Since the deaf cannot use the auditory modality ... even the modern, most powerful transistor hearing aids can only be poor supplements to the eye of the deaf child."

In contrast, unisensory (auditory) programmes have been recommended by Stewart, Pollack and Downs (1964) and Griffiths (1964). Results of these programmes have shown that unisensory training, with present standard type hearing aids can certainly be effective with many young deaf children. However, the limitations of these aids in terms of frequency range render this approach open to criticism when applied to children with extremely limited residual hearing. Auditory cues available to these children through standard model aids are likely to be inadequate for the acquisition of speech and language patterns without the help of other sense modalities.

As previously stated by the writer (Ling, 1964a) "The unthinking reductionism of a general unisensory approach on one hand and the blind optimism of a general multi-sensory approach on the other, are both likely to yield many failures. Indeed, the success of an auditory approach to the education of deaf children depends on our abilities as teachers to think critically, flexibly and constructively on the role of audition in our work and to recognise fully its possibilities and its limitations."

Rationale

The hypothesis examined in this study was that amplification of additional low frequencies, from 80 cps, would contribute significantly to the audition of speech among deaf children with low-tone residual hearing. This hypothesis was based on the following observations:

1. Low Frequency Residual Hearing in Deaf Children

Responses to low frequency stimuli are very common among even the most severely handicapped children to be found in schools for the deaf (Ewing, 1962; Huizing, 1959; Watson, 1961). That this "classical residual hearing for low tones, perhaps up to a limit of 1000 cps ... should be exploited early and exploited fully" has been recommended by Davis (1964, p. 129). While four major types of amplification are available for deaf children (see pp. 4 - 8) the frequency range and frequency response required for the full "exploitation" of low-tone residual hearing has not been seriously questioned.

2. Individual Aids and the Frequency Range of Speech

The bandwidth 300 - 3000 cps is traditionally regarded as the "speech range" since it contains the major components of all phonemes (Silverman and Taylor, 1947, p. 212). However, speech components occur as low in the frequency scale as 80 cps or so, the fundamental pitch of a deep bass voice, and go up to well over 8000 cps, the upper partials of both voiced and unvoiced phonemes (Davis, 1962; Denes and Pinson, 1963; Fletcher, 1953; Licklider and Miller, 1951; Pierce and David, 1958; Potter, Kopp and Green, 1947).

Davis (1962, p. 52) in discussing the frequency range of speech, states:
"Speech is a mixture of complex tones, wide-band noise and transients. Both the intensities and frequencies of speech sounds change continually and rapidly. It is difficult to measure them and logically impossible to plot them precisely." Davis continues, "For good understanding of everyday speech the range from 400 to 3000 cps is sufficient."

Many individual hearing aids, designed to give "good understanding of everyday speech" conform to Davis' range of 400 to 3000 cps. Silverman, Taylor and Davis (1962, p. 295) discuss such an aid. Many hearing aids, as stated earlier (p. 7) provide a slightly wider frequency range. The objectives of these aids, as formulated by Silverman, Taylor and Davis (1962, p. 265) are (1) "to make speech intelligible" and (2) "to deliver sounds loud enough to be heard easily, but without discomfort." The authors are thus concerned with two factors: first, intelligibility of speech, and second, its audibility. In the rationale of the present study the assumption that intelligibility rather than audibility is of primary importance to deaf children who have only a low frequency residue of hearing will be challenged and the possible contribution of frequencies below 300 cps to the audition of speech by such children will be examined.

3. The Suitability of Standard Type Aids for Adults

The conventional hearing aid was designed not for profoundly deaf children, but for adults (Davis et al, 1947; Medical Research Council, 1947; Silverman, 1957). Unlike deaf children, deafened adults have usually acquired speech and language patterns through hearing and in general have retained some hearing over the complete "speech range" of frequencies. The amplification of frequencies below 300 - 400 cps could introduce noise problems for such people and thus adversely affect the audibility of high frequency sounds by masking (Fletcher, 1953; Mullins and Bangs, 1957). Furthermore, the inclusion of low frequencies would contribute little when hearing is present over a wide range of frequencies, since information on voice factors (pitch, intonation, duration, stress, etc.), would be available in the speech range. This is demonstrated by our everyday experience with the telephone. While the true fundamental cannot be heard within the speech range it can be inferred from the overtone structures of speech (Schouten et al.,1962).

4. The Limitations of the Standard Type Aid

Hearing aids which amplify over the range 300 - 3000 cps expend much of their energy over several octaves to which the child with only low-tone residual hearing is completely deaf. With a high frequency cut-off imposed by deafness at, say, 1000 cps and a low frequency cut-off imposed by the hearing aid at 300 cps, the child with low frequency hearing has too narrow a bandwidth available to hear adequately either distinct phonemes or even voice patterns. The high frequency cut-off imposed by deafness prevents the adequate audition of consonants and thus limits the intelligibility of speech regardless of "how loud the speaker talks or how much amplification is introduced" (Davis et al.,1962,p191). The low frequency cut-off imposed by the lower limit of the hearing aid prevents the transmission of voice components below 300 cps and thus limits the audibility of speech.

5. The Contribution of Frequencies below 300 cps

Since the children in question have low-tone residual hearing, and since information of some kind is contained in any part of the speech spectrum (Miller, 1951), there is a *prima facie* case for the extension of the frequency range amplified for these children downwards to 80 cps, the fundamental pitch of a deep male voice. The contribution of this frequency range would probably be primarily in terms of the audibility of sounds and only secondarily in terms of their intelligibility. However, French and Steinberg (1947) have demonstrated that there is a slight but significant drop in articulation scores for normal listeners when components of speech below 300 cps were rejected by means of high pass filters. In other words significant information-bearing components of speech exist below 300 cps.

Ling, Rigault and Frydman (1965) in experiments with low pass filters, observed that the speech components below 300 cps allowed them to discriminate male and female speech, the relative intensity and duration of voiced phonemes, the pitch and intonation patterns of phrases and sentences; to identify the nasal or plosive characteristics of some voiced consonants and to hear the low frequency formants of some vowels. While such filtered speech was unintelligible, it was quite audible and the information available was of the type that is completely lacking in lipreading. It was concluded that such information could be made available to deaf children with low-tone residual hearing if they were provided with hearing aids offering low frequency amplification and trained in their use.

6. Masking Problems and Low Frequency Amplification

Masking problems were mentioned in item 3 of this rationale, where evidence was quoted which suggested that low frequency amplification in certain cases could detract from intelligibility. However, masking of high frequency sounds by low frequency amplification is a problem only for those who have high frequency hearing. Furthermore, ambient noise, which could be introduced by frequencies below 300 cps, is a problem only when it conflicts with the signal, thus reducing the signal/noise ratio. This ratio can, however, be controlled by adjusting the gain of a hearing aid and modifying speaker distance, voice level or both (Ling, 1964). Masking of speech by speech which apparently occurs in cases of severe high tone loss (Müllins and Bangs op. cit.), can also be overcome by ensuring that the frequency response of the hearing aid falls at 6db/8ve or more below 200 cps.

7. The Effect of Low Frequencies on Speech and Language Learning

The audibility of these low frequency components of speech should accelerate the language growth of deaf children. Studies of early language acquisition indicate that young children respond primarily to the "perceptually salient" cues such as pitch, intonation, stress, duration and rhythm (Carhart, 1947; Kagan, 1964; Lees, 1964; Miller and Ervin, 1964). These perceptually salient components of speech are generally missing from the speech of deaf children (Calvert, 1964) which suggests not only that they are inaudible, but that they cannot be perceived by the child through any other sense modality (Lenneberg, 1964).

8. The Contribution of Low Frequencies to Speech Feedback

Hearing aids with a wider frequency range would not only permit a deaf child to hear other people's voices better; it would permit him to monitor his own voice and speech patterns more effectively. The importance of providing the best possible feedback for deaf children so that they can more easily establish and control their voice and speech patterns through hearing has been discussed by Fry (1950), DiCarlo (1958) and Huizing (1964). The role of feedback in learning, monitoring and perceiving speech in normally hearing persons is discussed by Liberman (1957) and by Postman and Rosenzweig (1957). The wider implications of feedback on human behaviour are treated extensively by Miller, Galanter and Pribram (1960).

9. The Avoidance of Possible Dangers of Narrow Band, High Intensity Amplification

In the course of work with very powerful hearing aids with the standard type frequency response, the writer had noted progressive loss of hearing among his pupils. Investigating this phenomenon, Lockett and Ling (1964) concluded that the deterioration of hearing in the cases studied was probably related to the use of high gain, narrow band hearing aids. The use of less powerful aids, with wider frequency range, was suggested by the writer (Ling, 1964a) as a possible way of avoiding the risk of auditory fatigue while at the same time providing equivalent or improved transmission of auditory cues.

THE PRESENT RESEARCH

The aim of this investigation was to study the effect of low frequency amplification on the audition of speech by twelve deaf children with classical low-tone hearing residue. The investigation involved six tests and two questionnaires. The subject of each was as follows:

Test 1 Relative audibility of certain phonemes.

Test 2 Audibility of the syllabic structure of words and phrases.

Test 3 Audibility of stress within phrases.

Test 4 Audibility of pitch and intonation patterns.

Test 5 Ability to discriminate between vowels.

Test 6 Ability to discriminate between consonants

Questionnaire I Data on the children's responses to standard and experimental frequency range of amplification. Parents' reports.

Questionnaire II Data comparing results using standard and experimental frequency range. Parents' ratings.

Standardized speech tests of hearing (Davis and Silverman, 1962; Kendall, 1953; Watson, 1957; Watson and Tolan, 1949; Williams and Ling, 1958) were inappropriate for this study because they were designed for more sophisticated subjects and were, in addition, more concerned with intelligibility than audibility of speech. The tests and the questionnaires used were therefore designed specifically for this investigation. Test 1 was derived from a procedure used by Darbyshire and Fee (1963) and Test 5 from work reported by Miller (1956).

Method

In order to avoid repetition, the subjects, materials and procedures common to the whole investigation are described at the outset. The rationale, method, results and discussion for each of the six tests and the two questionnaires are then presented separately.

Subjects

Twelve subjects were selected from the fifty-eight children attending the Montreal Oral School for the Deaf. Those children with the most severe hearing impairment were chosen. All had hearing loss dating from birth in excess of 65 db at 500 cps, and residual hearing only for low tones as tested by discrete pure-tone audiometry. Pure-tone audiograms for each of the subjects are presented in Fig. 1. Pulsed-tone Békésy audiograms were later obtained for each of the subjects both to check the accuracy of discrete pure-tone thresholds and to measure possible residual hearing lying outside the range of the school's audiometer.* These are presented in Fig. 2. All subjects were noted as "of at least average intelligence", found to have normal EEG responses and considered to have no additional handicaps in the course of diagnostic reviews carried out by the Conference on Hearing and Language Disorders of the Children's Memorial Hospital (McHugh, 1962). Other relevant background data are given in Table 1.

Apparatus

Experimental and standard model hearing aids, identical in appearance, were used to provide amplification from 80 - 3500 cps and 300 - 3500 cps respectively (see Fig. 3, p. 30).

Twenty experimental model hearing aids were made available to the writer for this research. Response characteristics were obtained for each and all conformed closely to the required specifications. The five aids finally selected for this study (serial numbers 275, 413, 419, 430 and 760) conformed in both low frequency range and gain to within $\pm$ 5 cps and $\pm$ 5 db respectively with

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*My thanks are due to Mrs. M. Stephens of the Royal Victoria Hospital and Miss B. Brown of the Children's Memorial Hospital for assistance with this work.

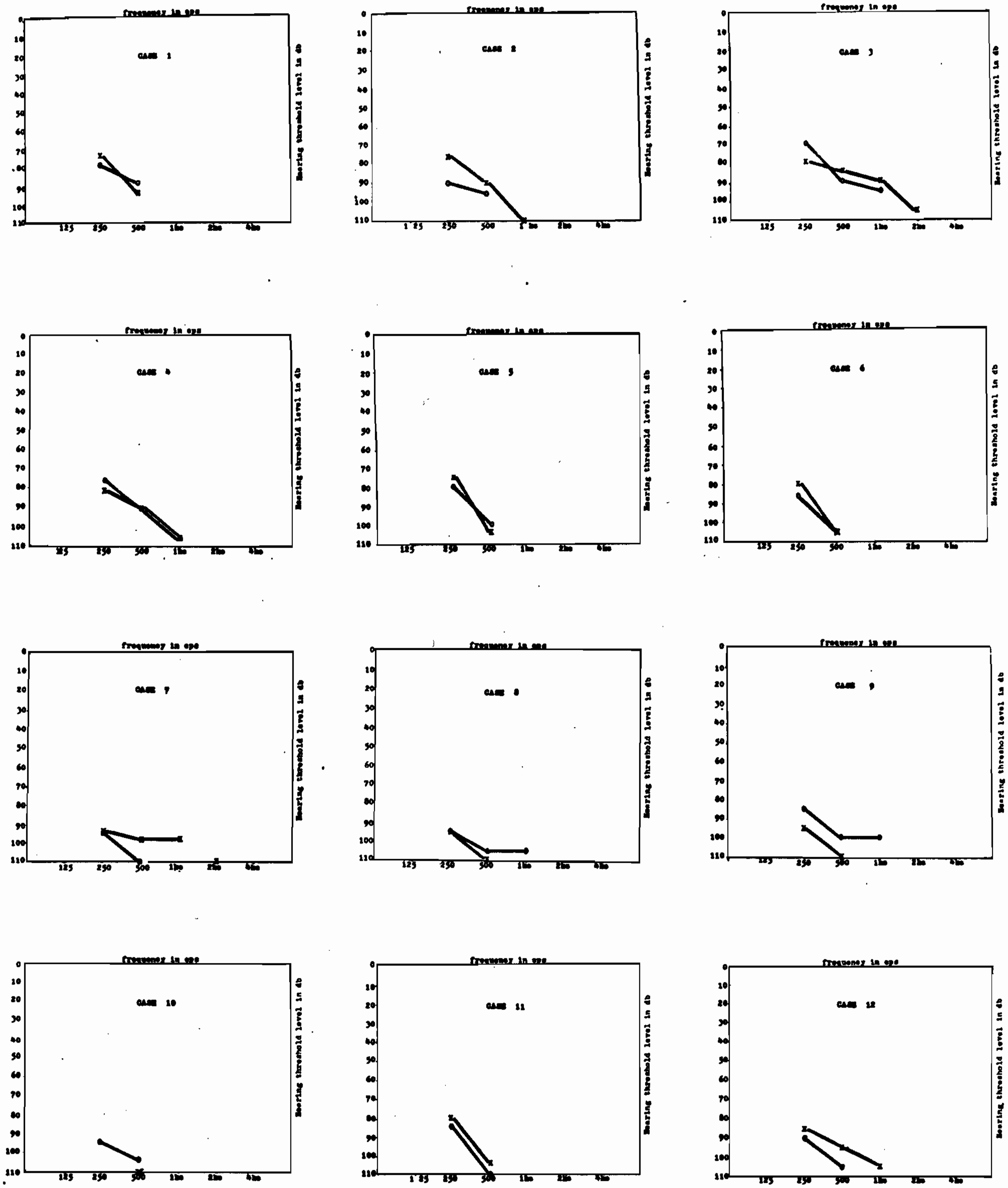

Fig. 1 Discrete pure tone audiograms
1964 ISO reference thresholds
for all twelve cases

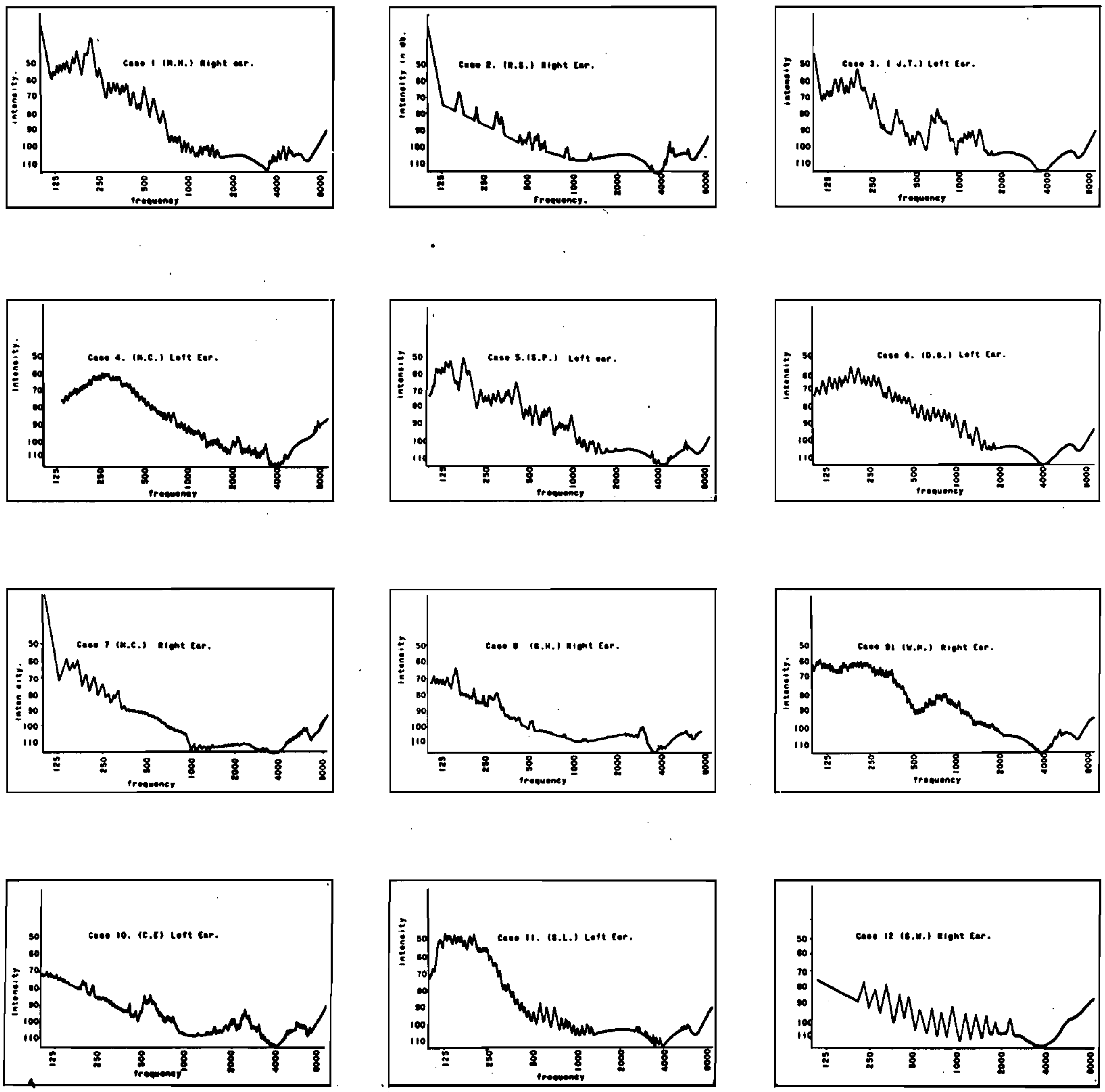

Fig. 2 Pulsed tone Békésy audiograms
of all twelve cases
(ear used in study as indicated)

Table 1

Background Data on the Twelve Subjects

Used in This Study

Case No.	Age	Years Aid Worn	Sex	Cause of Deafness	Vestibular Response (ENG)	School Grade
1	10	3	f	Unknown	Normal	3
2	8	5	m	Maternal rubella	None	2
3	12	6	f	Toxaemia in pregnancy	Normal	4
4	7	2	m	Maternal goitre	Normal	1
5	9	1	m	Virus infection at birth?	None	2
6	16	2	m	Genetic (recessive)	Normal	6
7	11	6	f	Genetic (+ anoxia?)	Normal	3
8	9	1	m	Maternal rubella	None	2
9	11	9	m	Unknown	Normal	4
10	8	2	f	Maternal rubella	None	1
11	16	2	f	Genetic (recessive)	Normal	6
12	8	1	m	Maternal rubella	Normal	1

the characteristics of the reference model presented in Figure 3. Twelve standard model aids were available, of which three conformed to the reference model within comparable limits. These models (serial numbers 182, 264 and 273) were selected for the study.

In Test 1, which measured the distance over which phonemes were audible, the hearing aid was worn by the subject on the chest and maximum available gain was used. In the remaining tests the hearing aid was held by the tester at a distance of six inches from the mouth of the speaker with the hearing aid adjusted to provide optimum gain. Optimum gain was determined by testing with the three vowels /a/, /u/ and /i/ and the consonants /ʃ/, and /s/, the gain being adjusted to permit the subject to hear the quieter sounds as well as possible without the louder sounds causing discomfort or pain. This technique permitted the operation of the aids at gain levels of 30 - 40 db. Since speech level at six inches was approximately 80 db, at least 25 to 30 db above the ambient noise level, adequate output with a high signal/noise ratio was thus ensured.

Procedure

Tests were designed to permit the relationship between the frequency range available to the subjects and

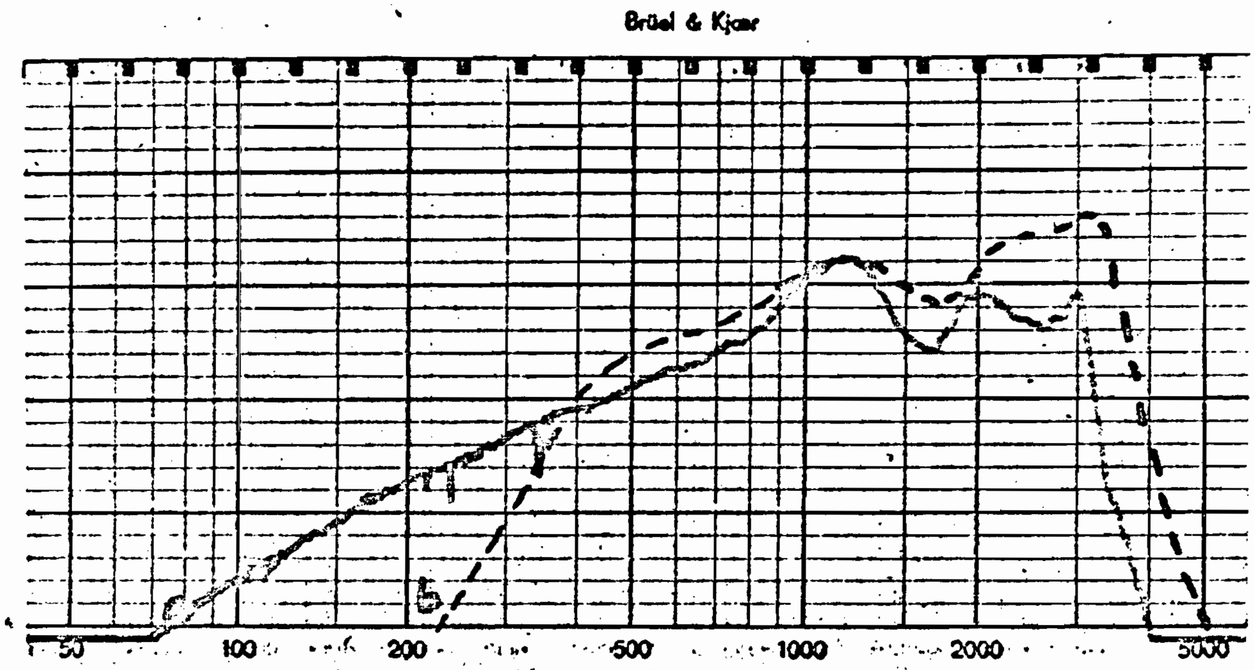

Fig. 3. The frequency response characteristics of

(a) the experimental model aid and

(b) the standard model aid.

Table 2

Experimental Design to Provide a Counterbalanced Order of Presentation for Hearing Aids and Test Series

Groups	Initial Assessment		Final Assessment	
	Hearing Aid Used	Test Series	Hearing Aid Used	Test Series
1	Exp.	1	Std.	2
2	Exp.	2	Std.	1
3	Std.	1	Exp.	2
4	Std.	2	Exp.	1

the audition of voice patterns to be examined. Subjects were divided into four groups of three and both the use of hearing aids and the presentation of test series was varied systematically as shown in Table 2.

The division of subjects into four groups of three was arranged so that the average age of subjects in each group was comparable. Attention was given to this variable because Whetnall (1955) and others consider that ability to use residual hearing decreases with age. Since four of the subjects had already worn experimental model hearing aids before the study was begun (cases 1, 5, 8 and 11), each of the four was assigned to a different group. Sex could not be distributed equally between groups.

With the exception of Test 1, which was a measure of threshold, each test was made up of two different series of items of equivalent difficulty. These tests are described in detail in subsequent pages. All tests were administered in such a way that the child received only auditory cues. All children proved able to perform adequately in each test session without undue fatigue and without extrinsic reinforcement since the children were already well adjusted to the school situtation.

A one-week period of training with each of the hearing aids was given prior to the tests. This period was considered to be adequate to permit any major differences to become evident. Since the school's routine was organized around a weekly timetable, a weekly testing schedule was also the most convenient. Training and testing with one of the hearing aids was immediately followed by training and testing with the other model. During the one-week period subjects wore their hearing aids every waking hour, with the exception of approximately ten hours weekly when the child participated in lessons on the group hearing aid in his classroom. Individual speech and hearing training work with both teachers and parents was conducted using each of the aids as a matter of routine both in school and at home. Hearing and speech training in school deliberately encompassed all items tested in this study so that bias due to practice effects was minimised.

The experimenter could tell which type of aid was being worn at any time by its serial number and also simply by listening to it. However, neither the child, his teachers nor his parents could identify the standard or experimental models as such by any means and none was told which model was being worn by the child at any time.

Statistical Methods Employed

The basic statistical problem involved in this study was to determine whether differences in scores or ratings obtained by the children when using (a) the experimental aid and (b) the standard aid reached a significant level. As these differences could not necessarily be regarded as samples drawn from a normally distributed population, non parametric methods were employed throughout.

Statistical analysis of test results. The Mann-Whitney test (Walker and Lev, 1953, pp. 434-435) was selected for analyzing the results of all six tests. This "Sum of Ranks" test was used to guard against the two-sided alternative $P(X > Y) = \frac{1}{2}$ at a .01 level of confidence. When N_1 and N_2 are 8 or larger, this statistic has a distribution which is approximately normal:

$$z = \frac{2 R_1 - N_1 (N + 1)}{\sqrt{\frac{N_1 N_2 (N + 1)}{3}}}$$

The z scores obtained (which may be verified by reference to the tables of raw scores in the text) are presented with the results of each test.

Statistical analysis of Questionnaire results. Unlike the results of the tests, tabular data obtained from the administration of the questionnaires are mainly in the form where only the presence or absence of a difference and its direction can be shown. In the analysis of data from questionnaires, therefore, a two-tailed Sign Test (Walker and Lev, 1953, p.430) was used to verify whether differences between aids reported by the parents reached a .01 level of significance. The results obtained are reported in the text.

Independent Verification of Results.

In an experiment such as this, it is notoriously easy for the experimenter, in good faith, to bias a whole set of results simply by small unconscious changes in the manner in which vocal material is presented. To check whether such bias occurred, the study was partially replicated with both live and pre-recorded material under conditions which did not permit the examiner to identify the aid used. Test 1 was carried out using the same subjects. The order of aids and presentation of live and pre-recorded material was again counterbalanced. A Sony Model TC102M tape recorder was used for both recording, during which the sound pressure level for each phoneme was monitored by reference to a VU meter, and for playback. During playback, each of the aids was suspended at a constant distance from the loudspeaker, the examiner adjusting the volume control of the recorder to determine thresholds by a method of limits. The relative audibility of phonemes was recorded in terms of the volume required for each child to hear individual phonemes. The results of this partial replication are reported on page 44.

Test 1. Relative Audibility of Certain Phonemes

In order for speech to become meaningful to children it must, first of all, be heard. Some phonemes have considerably more power than others (Fletcher, 1953, Ch. 4) and are therefore audible over greater distances for normally hearing persons. However, since only those phonemes with acoustic energy within the deaf child's frequency range of hearing are audible to the child, whatever their power may be, and since the frequency range of the hearing aid changes the child's effective range of hearing, a difference in audibility of phonemes could be expected between children using standard and experimental model hearing aids. Indeed, preliminary trials using the two types of hearing aid indicated that the experimental aid effectively increased the distance over which voiced speech sounds were audible to them. This result might be predicted from consideration of the line spectra in Fig. 4 which indicates that the low frequency range of the experimental aid encompasses the lower formants of /u/ and /i/ and the lower harmonics of /a/, while the standard model fails to transmit some important powerful components of the vowels /u/ and /i/.

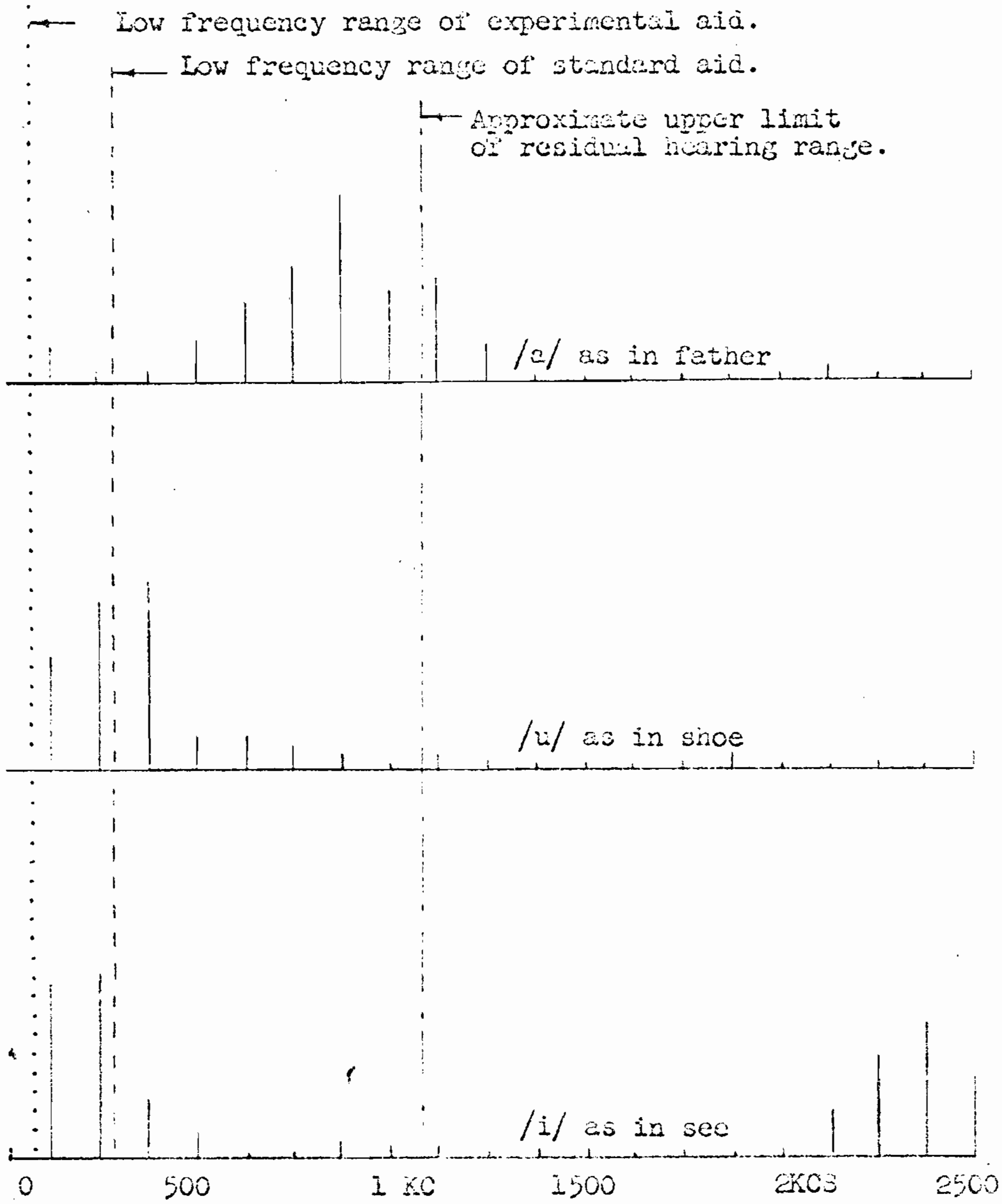

Fig 4 Line Spectra showing the energy distribution of the vowels /a/, /u/ and /i/ in relation to the frequency range of the standard and experimental hearing aids and the approximate upper limit of the residual hearing range.

Method

Apparatus and Materials

The stimuli used for this test were the five speech sounds /a/,/u/,/i/,/ʃ/ and /s/. The method of presentation employed was an adaptation of the technique normally used in obtaining pure tone thresholds in audiometry with very young deaf children. This method was selected because the children concerned were familiar with the procedure through periodic hearing tests and daily checks on hearing aids. Thus the children were trained to respond when the sound was just audible by making some definite movement such as placing a peg in a peg-board, posting a shape in a form box or simply raising a finger. The stimuli were presented at intervals of predetermined irregularity to establish threshold in terms of distance for each sound. The distance was increased or decreased by the examiner moving towards or from a point where the child was seated.

The stimuli were presented in the order given and, in each case, the distance at which responses were obtained to 50% of the presentations was recorded as representing threshold.

The sound levels of stimuli were monitored by constant reference to a VU meter incorporated into a Grason-Stadler type 260B amplifier fed by a microphone held at a constant distance of six inches from the mouth of the speaker. Each of the sounds was spoken with the same amount of effort and it was noted that the variation in level during the course of presentation of any one phoneme was never greater than 2 db.

The variation of sound level with distance in the room used for the testing was measured with Bruel and Kjaer equipment* as follows. A type 4134 ½-inch microphone was placed in the position the children occupied during the tests. The sound level at the microphone, which was connected with a cathode follower and type 2603 amplifier, was automatically graphed by a type 2305 level recorder. The system as described was calibrated with a Bruel and Kjaer piston phone type 4220. The voiced phonemes, monitored as for the experiment, were then spoken at logarithmically spaced distances from the microphone. Under perfect acoustic conditions the sound pressure drops by six decibels every time distance is doubled. In this classroom, due to reverberation, and approximately 55 to 60 db background noise, sound pressure dropped considerably less with distance, as shown in Table 3.

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*The writer is grateful to Dr. R.P. Gannon for the loan of this equipment and assistance with the measurement of room acoustics.

Table 3

The mean sound pressure levels of the vowels /a/, /u/ and /i/ recorded in the classroom used for Test 1

Distance (feet)	Sound levels of each vowel (decibels)		
	a	u	i
¼	90	88	86.5
½	83.5	81	79
1	77.5	77	77
2	72	73	72.5
4	69	67	66.5
8	65.5	65	64
16	64	63.5	63
32	63	63	61.5

Note: Figures given represent the mean of four trials. Variation of actual voice level for each vowel within and between trials did not exceed 2 db.

Table 4

Comparison of audibility of phonemes using experimental and standard aids

(results are given in feet)

Group 1

Case	Phoneme	Exp.	Std.
1	a	45	45
	u	45	35
	i	45	32
	ʃ	1	1
	s	¼	¼
2	a	40	35
	u	35	20
	i	22	9
	ʃ	3	5
	s	½	¼
3	a	45	45
	u	45	45
	i	27	7
	ʃ	12	5
	s	½	½

Group 2

Case	Phoneme	Exp.	Std.
4	a	45	45
	u	45	35
	i	45	30
	ʃ	1½	1½
	s	½	½
5	a	45	40
	u	45	15
	i	45	3
	ʃ	20	6
	s	1	½
6	a	45	45
	u	45	45
	i	45	15
	ʃ	4	1
	s	½	½

Group 3

Case	Phoneme	Exp.	Std.
7	a	45	36
	u	40	36
	i	33	15
	ʃ	3	7
	s	1	½
8	a	45	45
	u	45	15
	i	45	2
	ʃ	2	2
	s	½	½
9	a	45	45
	u	45	35
	i	30	15
	ʃ	3	12
	s	1	3/4

Group 4

Case	Phoneme	Exp.	Std.
10	a	45	45
	u	45	45
	i	45	24
	ʃ	4	3
	s	1	½
11	a	45	45
	u	45	35
	i	40	9
	ʃ	1	1
	s	0	0
12	a	45	45
	u	45	20
	i	45	4
	ʃ	45	6
	s	1	½

Results

The sound /a/ was amplified adequately by both aids. Under the acoustic conditions of this test (see Table 3) comparison of results would be unreliable when differences only slightly larger or smaller than 45 feet are involved.

Analysis of other results, which are presented in Table 4, shows that:

The sound /u/ is more audible through the experimental aid. The difference in audibility is significant beyond the .01 level of confidence. ($z = 3.10$)

The sound /i/ is very much more audible through the experimental aid. The difference in audibility is significant beyond the .01 level. ($z = 3.79$)

The sound /ʃ/ is not heard significantly better with one aid rather than the other. ($z = .176$)

The sound /s/ is not heard well with either aid and there is no significant difference in audibility of this sound when either aid is worn. ($z = 1.47$)

Discussion

The significantly better scores obtained for vowels /u/ and /i/ with the experimental aid support the hypothesis that children with low frequency residual hearing would find the voiced components more audible when the low frequency range of speech was amplified. The results also support observations made during preliminary trials. The results not only showed that the experimental aid increased the distance over which these vowel sounds could be heard, but, perhaps more important, reduced the differences in their relative audibility. Fletcher (1953, p. 85) has shown the ratios of sensation levels for the vowels /a/, /u/ and /i/ to be approximately 100 : 96 : 89 for normal listeners. Comparing the mean distances over which these sounds were audible to the subjects in this study the ratios for the standard aid appeared to be approximately 100 : 65 : 25, and for the experimental aid approximately 100 : 86 : 78. (See Table 4)

Hearing voiced sounds (including other voiced phonemes such as l, r, w, v, or z) at approximately equal intensity (i.e. at an approximately equal distance) is clearly important for, unless all voiced phonemes are almost equally audible, auditory experience for the child with residual hearing can be both bizarre and unstable. From these results it may be inferred that, with a standard aid, such a child standing at the opposite side of a large room from a speaker would hear only something of the last word of the sentence, "We keep two cars." In the middle of the room, he would hear something of the last two words. Close to the speaker he would hear something of all four words, the first two close to threshold, the last one at a shout. Only when very close to the speaker could the number of syllables, their duration and rhythm, their pitch and intonation, possibly be identified. In contrast, the wider frequency range of the experimental aid permits greatly improved audibility of speech; and greater stability of auditory patterns with distance must result.

With the significantly better relative audibility of voiced phonemes provided by low frequency amplification, the attention of the child can be more readily attracted and sustained (Table 20, p.95). The increased stability of the auditory experience within the distances involved in home life should offer considerably better opportunities for early language acquisition and the spontaneous development of good voice patterns.

While audibility of voiced sounds was significantly better for children with low-tone residual hearing using the experimental aid, the audibility of the unvoiced sounds was not significantly affected. Because unvoiced sounds carry more information than the low frequency components of voiced sound (Fletcher and Galt, 1950; Miller Heise and Lichten,1951), no marked increase in the actual discrimination of speech can be predicted from this test.

The partial replication study described on page,35 fully confirms the results presented above. For live voice, the results were identical. For pre-recorded speech, all five phonemes were heard significantly better with low frequency amplication.

Test 2. Audibility of Syllables

The Syllable as a Component of Speech

There has been considerable discussion among linguists as to the definition of the term <u>syllable</u> (Heffner, 1960, p. 306; Meader and Muyskens, 1962, p. 30). It is used here, as by Hughes (1962), to describe the peaks of acoustic energy or sonority which occur in words, phrases and sentences. In this sense, the words 'pear', 'apple' and 'banana' have one, two and three syllables respectively.

The Syllable in Relation to This Study

It is clear that if a deaf child is unable to hear certain syllables he will be unable to identify their components or reproduce them in his speech. The frequency, rate and duration of syllables are the basis of speech rhythm, which has been shown by Hudgins (1937) to be of great importance in both the perception and production of speech by deaf children. Since the speech of the deaf children used in the present study lacked rhythmic structure, it was decided to test to what extent syllables were audible to the group and whether the experimental hearing aid increased such audibility. This measure has not been included in any speech test of hearing known to the writer. Most speech tests of hearing are concerned either with the recognition of phonetically balanced monosyllabic words, spondees or sentences, and not with the audibility of acoustic peaks. In identifying the number of syllables heard, the complexity of the task increases with the number of syllables used and the speed at which they are presented. Two forms of test were therefore prepared, one using words of up to three syllables, the other using phrases of three or more syllables.

Many phrases, quite distinctly different in rhythm, are frequently confused by a child who has become visually biased through early training in lipreading. Examples of common errors are, "How are you?" and "How old are you?" Even more frequently, phrases such as "I did go" and "I didn't go" are confused. Better audibility of syllables would clearly offer many advantages to both child and teacher.

Method

To test audibility of syllables in words, two lists of twenty-five words of one, two or three syllables were constructed. The number of syllables in the words was

Table 5

Stimuli used in test for audibility of syllables in words

Series 1	Series 2
cat	elephant
father	boy
grandmother	mother
garden	house
crocodile	tadpole
socks	overcoat
bed	pajamas
robin	duck
steering-wheel	engine
birthday card	candle
purse	handkerchief
lemonade	water
cigar	pipe
cake	apple pie
pear	banana
salt	vinegar
radio	cushion
letter	pen
paper	wool
dollar bill	nickel
airplane	train
nurse	policeman
daisy	rose
teddybear	balloon
bulldozer	truck

Table 6

Stimuli used in test for audibility of syllables in phrases

Series 1	Series 2
on the path	over the bridge
high in the sky	deep in the water
up there	over there
shut the door	open the window
look at the boat	see the big airplane
here's a man	this is a lady
yes please	no thankyou
I'm hungry	I want a drink
I'm thirsty	I am thirsty
it's time for bed	it's bedtime
how are you?	how old are you?
I'm five	I am five
I'm a boy	I am a boy
I can't	I cannot
I've a ball	I have a ball
it's hot	it is hot
I'll go	I will go
I don't like it	I do not like it
I did not	I didn't
would you?	wouldn't you?
have you?	haven't you?
I don't want to	I do not want to
you did	you didn't
we didn't go	we did not go
I'd like one	I would like one

distributed unsystematically throughout each list as shown in Table 5.

To test audibility of syllables in phrases, two lists of twenty-five phrases, each containing three, four or five syllables were constructed and the number of syllables per phrase distributed throughout each list in unsystematic order as shown in Table 6.

Each item was read speedily and without undue stress or intonation to each child in the order given. The child's task was to identify the number of syllables contained in each item. The children were permitted to tap the rhythm of the words or phrases if they found this to be helpful. No time limit was imposed between items.

Results

Results of the tests for audibility of syllables within (1) words, and (2) phrases, are presented in Tables 7 and 8 respectively.

The improvement in the audibility of syllables in words was significant beyond the .01 level ($z = 3.22$) as it was in phrases ($z = 2.86$) when children used the experimental model hearing aid.

Discussion

The results of these tests support the hypothesis that the syllabic structure of both words and phrases is more audible to children with low-tone residual hearing when low frequency amplification is provided.

The poorer scores achieved on phrases than on words is probably related to the length of the stimulus pattern rather than to any intrinsic differences in the acoustic properties of words and phrases.

That the number of syllables present in both words and phrases was significantly more easily identified by the subjects when they were wearing the experimental aid indicates that there were more cues available to the children when better low frequency amplification was available. What acoustic cues were missing when the standard aid was used is a matter for speculation.

It is highly unlikely that the unstressed syllables were completely inaudible to the subjects wearing the standard aids since hearing aids were held within six inches of the tester's mouth, thus providing an input level to the aid of approximately 80 db. Most errors occurred in words containing the neutral vowel /ə/ (for example, 'elephant', 'pajamas', 'mother', 'lemonade') which occurs in unstressed syllables. It is also likely that, with the standard aid, syllable boundaries tended to be blurred through the

Table 7

Audibility of syllables present in 25 words

(Figures indicate the number of correct responses obtained using experimental and standard aids)

Group 1

Case	Experimental	Standard
1	20	16
2	19	14
3	25	18

Group 2

Case	Experimental	Standard
4	19	15
5	23	17
6	21	22

Group 3

Case	Experimental	Standard
7	18	18
8	22	13
9	23	22

Group 4

Case	Experimental	Standard
10	25	17
11	25	17
12	24	21

Table 8

Audibility of syllables present in 25 phrases

(Figures indicate the number of correct responses obtained using experimental and standard aids)

Group 1

Case	Experimental	Standard
1	16	13
2	13	10
3	25	12

Group 2

Case	Experimental	Standard
4	19	18
5	18	16
6	23	21

Group 3

Case	Experimental	Standard
7	20	19
8	22	12
9	21	21

Group 4

Case	Experimental	Standard
10	24	13
11	22	9
12	21	17

weakening of possible cues such as changes in intensity ratio, pitch, duration and onset characteristics. In the four examples given above, the voiced consonants /l/, /m/, /ð/ and /m/ respectively were involved and as syllable boundary markers they are obviously not so effective as stop consonants (e.g., ro<u>b</u>in, ci<u>g</u>ar, ta<u>d</u>pole, can<u>d</u>le). Words in which syllables were bounded by stop consonants rarely caused errors. The blurring of syllable boundaries involving voice continuants may be inferred from spectrographs (Ling, 1964b). In these spectrographs, cues for the identification of the two syllables in the word 'father' are shown to be greatly reduced by the standard aid but not by the experimemtal model.

If, as appears to be the case, the blurring of phoneme boundaries was responsible for failure to identify the number of syllables, it does not follow that the low frequency amplification provided by the experimental aid would be advantageous in this respect for children with low-tone residual hearing in other acoustic conditions. With an input to the hearing aid of 80 db and a room noise level of 55 db, the signal to noise ratio would be 25 db. Under such conditions no masking would occur. However, with an increase in distance the signal to noise ratio would be reduced, the effects of reverberation would be increased and the resultant masking effect would probably destroy some of the phoneme boundaries made audible by low frequency amplification under test conditions.

Test 3. Audibility of Stress

Stress as a Component of Speech

The importance of stress in expressing both the emotional tone of speech and its precise meaning is well known. Jones (1943) stated that,

"Stress is almost always linked to something else, generally intonation, so that it is extremely difficult - perhaps impossible - to disentangle it from general prominence in which other attributes (timbre, length, intonation) also take part. It has in fact been shown that, when other attributes are eliminated, stress alone is not very effective as a means of distinguishing words."

Stress was used by Jones to mean two things: (1) the general prominence particular words receive in a sentence, and (2) an increase in intensity to produce this prominence.

Fry (1955) showed that duration and intensity ratios are both cues for judgment of stress but that duration is a more effective cue than intensity. Bolinger (1958) showed that intensity was less important than intonation. Fry (1958) ran three experiments to determine which three of the four possible characteristics (duration, intensity, fundamental frequency and formant structure) contributed most to stress. He concluded that frequency changes may outweigh the duration cue altogether and that duration and intensity both act as cues, but confirmed his previous (1955) findings that duration was more important than intensity in perceiving stress.

Stetson (1951, p. 214) pointed out that, "Since the stress increased the tension, it is natural that the increased chest pressure, compensated by an increased tension in vocal folds, raises the pitch. The stress may fall, however, on a syllable with a low pitch because of the intonation pattern and especially at the end of the declarative phrase."

Lehiste and Peterson (1958) proposed the theory that the perception of linguistic stress is based upon judgments of the physiological effort involved in producing stressed vowels, a theory which has relevance in teaching deaf children to perceive and produce stress.

The importance of stress in learning language is emphasized by Brown and Bellugi (1964, p. 141). In the analysis of tape recordings of a mother's speech and the child's responses, they noted that "the heavier stresses fall, for the most part, on the words that the child retains ... in the transcribing of the tapes, the words of the mother that we could hear most clearly were usually the words that the child reproduced." They concluded that differential stress appeared to be the main cause of the child's differential retention of early language patterns.

Stress Patterns and This Study

Silverman (1957, p. 401) suggested that stress could be perceived by some profoundly deaf children through the use of residual hearing. However, among the children used in this study, speech was notably lacking in stress. All words were sounded with virtually equal emphasis with the possible exception of those words which were most difficult to pronounce.

The voiced sounds of speech are not likely to be equally audible to a deaf child due to their formant structure, and it could therefore be predicted that stress would not easily be perceived by deaf children who heard some unstressed vowel as much louder than a stressed vowel whose main formants lay outside their range of hearing. While it may be concluded from the literature that intensity may be a relatively unimportant cue in stress, the perception of duration and intonation presuppose adequate intensity for audition, and it therefore appeared reasonable to test the hypothesis that additional information, provided by the experimental aid in the low frequencies, would lead to better audition of stress.

Method

To test audibility of stress, two identical lists of twenty-five phrases were constructed. One word was stressed within each phrase. The position of the stressed word within each phrase was varied throughout each list in unsystematic order, as indicated by the words underlined in Table 9.

Cards measuring four inches by eight inches, on which the stimulus phrases were typed in bulletin-sized print, were prepared.

The lists were read to the child in the order given in Table 9, in accordance with the stress marking indicated. The child's task was to identify, by pointing at the appropriate word on each card in turn, which word in each phrase was stressed. (The cards were treated to prevent finger marking). Each child was given adequate practice using similar cards immediately prior to the test to ensure that the purpose of the task was clear. (All children had sufficient reading skills to cope with the simple vocabulary used).

Results

The results of this test of audibility of stress are presented in Table 10. Eleven of the twelve children

Table 9

Stimuli used for testing audibility of stress in speech

Series 1	Series 2
don't do that	don't *do* that
where are you?	where are *you*?
what do *you* want?	what *do* you want?
I'm going *home*	*I'm* going home
it's *too* hard	it's too *hard*
that's my *coat*	that's *my* coat
wash your face	wash your *face*
show me your *nose*	show me *your* nose
a black *man*	a *black* man
a *little* boy	a little *boy*
open the *door*	*open* the door
a *big* smile	a big *smile*
that's my *book*	*that's* my book
where have you *been*?	where have *you* been?
on the *top* shelf	*on* the top shelf
here it is	here it *is*
I *don't* know	*I* don't know
down the hill	down the *hill*
please give me one	please *give* me one
when did you go home?	when *did* you go home?
have you any *more*?	have you *any* more?
how *many* are there?	how many *are* there?
I've only got one	I've only got *one*
I *don't* want any	I don't *want* any
it's really *hot*	it's *really* hot

Table 10

Audibility of stress within 25 phrases

(Figures indicate the number of correct responses obtained using experimental and standard aids)

Group 1

Case	Experimental	Standard
1	17	8
2	18	12
3	20	9

Group 2

Case	Experimental	Standard
4	18	18
5	23	17
6	21	19

Group 3

Case	Experimental	Standard
7	17	13
8	23	14
9	25	21

Group 4

Case	Experimental	Standard
10	21	6
11	20	9
12	25	12

were able to identify stressed words better with the experimental aid than with the standard aid. This improvement in ability to hear stress which results from low frequency amplification was significant beyond the .01 level of confidence. ($z = 3.30$)

Discussion

The results obtained confirm the hypothesis that the additional information provided by amplification from 80 cps permits children with low frequency residual hearing to identify stress in words and phrases significantly more accurately than when speech is amplified from 300 cps. That this improvement is related to the relative audibility of phonemes (see Test 1) is suggested by the consistent pattern of errors made by the children. With amplification from 300 cps their responses were inevitably correct for the item "it's too <u>hard</u>" and equally inevitably incorrect for the item "it's <u>too</u> hard". With low frequency amplification this was not so. It was apparent that, with the standard aid, words which were loudest to the subject (i.e. those containing central vowels) appeared to them to be stressed, regardless of any duration or pitch cues present. Whether the significantly better results obtained with low frequency amplification were due to the identification of intensity, pitch or duration, or a combination of these cues, remains a matter for speculation and further experiment. No clue is provided from the results.

Test 4. Audibility of Pitch and Intonation

The Role of Pitch and Intonation in Speech

Of intonation in speech Marouzeau (1949) states, "On considère volontiers l'intonation dans l'énoncé oral comme un appoint, qui a pour effet de nuancer l'expression, de souligner les effets et les intentions, en somme, comme un jeu et un luxe. Elle est plus que cela. Elle représente un moyen d'expression autonomme au même titre que les procédés lexicographiques, morphologiques ou syntaxiques, auxquels elle se surajoute, et qu'elle peut même supplanter."

The importance attributed to intonation by Marouzeau has been widely supported by other modern linguists and phoneticians. Isamu (1954) describes its function in differentiating requests and commands, Bolinger (1955) its contribution to meaning through stress, Fries (1945, pp. 20 - 23) its importance in acquiring English as a foreign language, Lee (1960) its role in expressing negation and subjective states and Stockwell (1960) its place in a generative grammar of English.

Siertsema (1962) distinguishes intonation as one of three frequency based variables - first, the formant structure which is heard as "quality" or timbre, secondly the fundamental frequency heard as the pitch of the voice, and thirdly, the variation of fundamental frequency which is heard as intonation.

Pitch and Intonation in Relation to Deafness

The ability to perceive pitch and recognise pitch change (the basis of intonation) has been the subject of a considerable number of investigations. The relation of pitch to frequency in normally hearing subjects was quantified by Stevens, Volkman and Newman (1936) in the construction of the mel scale. No similar work has been attempted for deaf subjects, since sensori-neural hearing loss tends to be associated with poor pitch discrimination (Bradley, 1959; Meurman, 1954; Schubert, 1951).

DiCarlo (1962) reviewed work on pitch perception carried out with deaf children and studied the relationships between frequency discrimination, speech reception threshold and speech discrimination scores. He concluded that, "even deaf children with severe hearing impairment, who possess good frequency DLs at 500 and 1000 cps, may benefit greatly from amplification and a systematic program of auditory training." The writer's previous work (Ling, 1959) indicates that among profoundly deaf children the skills involved in making frequency discriminations often improve with auditory training and experience.

Pitch and Intonation in this Study

For the purpose of this study, intonation is defined as a variation of fundamental pitch of voice, (cf. Siertsema, op. cit.) Thus a male speaker may have voice patterns one octave below those of a female speaker and their fundamental pitch may be said to differ by one octave, but providing their speech has the same tune, or relative pitch change, they may be said to have the same intonation patterns.

Children with residual hearing rarely acquire natural intonation patterns and frequently have an abnormal fundamental pitch of voice, whether or not they wear standard hearing aids or have received training on high fidelity group hearing aids in the course of classroom work. Their experience with the latter is generally of insufficient duration for good intonation patterns to be acquired through awareness of their own and others' voices. Spectrographic analysis (Ling, 1964b) indicates that standard hearing aids provide them with an inadequate band of frequencies for the recognition of pitch and intonation. However, much clearer intonation patterns can be seen in the spectrographs taken through the experimental aid and it would appear reasonable to postulate that, providing the children have adequate training and experience in using the additional low frequencies, better judgments of pitch and intonation could result.

Method

To test audibility of intonation, two lists of eighteen three-syllable phrases were constructed. These were arranged in three groups of six for presentation within the range of (1) an 8ve, (2) a 5th and (3) a 3rd. Each group contained, in predetermined order, the six possible types of intonation pattern within a three syllable phrase (see Table 11). The phrases were spoken rather than sung since (1) intonation patterns in everyday speech occur not simply through pitch differences between words, but through pitch changes within words, and (2) the intervals used are present as harmonics of the voice, and movement of pitch to these intervals is therefore more likely to be heard by naive listeners than presentation at these intervals.

The child's task was either to identify the intonation by pointing in turn to colored rods associated with the pitch of the sounds heard, or to reproduce the intonation pattern directly by imitation.

Table 11

Stimuli used for testing audibility of intonation

	Series 1		Series 2	
1	Hello-there	1	A big boy	Intonation range = 8th (128 - 256 cps)
2	How are you?	2	At-five then	
3	What's-the time?	3	How many?	
4	I don't-know	4	A white dress?	
5	Bye bye Dad	5	Who-said that?	
6	Do-you know?	6	My big-car?	
7	Good gracious!	7	What-is it?	Intonation range = 5th (128 - 192 cps)
8	Some-more please	8	Where-are you?	
9	That's not true	9	Here I am!	
10	A big boat?	10	What was that?	
11	Is that so?	11	A hot-bath?	
12	Can-I go?	12	Who-said 'no'?	
13	A-hot bath?	13	Why do that?	Intonation range = 3rd (128 - 160 cps)
14	That's not fair!	14	Over there?	
15	A white-dress?	15	Which one-is?	
16	A cold-day!	16	Brown paper?	
17	No-I'm not!	17	In-the box!	
18	A blue sky?	18	I have none!	

Results

Results for the test of audibility of intonation are presented in Table 12. Not all children were able to hear intonation patterns whether the range of intonation covered was an 8ve, a 5th or a 3rd.

There were relatively few correct responses (a mean of 2.5 per child with the experimental aid and 1.25 with the standard aid from a possible 18), but better scores were consistently achieved with the experimental aid. No differences in scores were significant, however. ($z = 1.50$)

Discussion

Results of the tests do not confirm the hypothesis that extended amplification from 80 cps would make intonation significantly more audible for children with low frequency residual hearing than amplification from 300 cps.

The results do, however, confirm the experience of the children's teachers that the 8ve interval presented the least difficulty and the 3rd the most.

That only gross differences in intonation were audible to most subjects indicates that, while the identification of speakers by pitch (male v. female) may be facilitated by low frequency amplification, the intonation patterns used in everyday life, which rarely exceed an

Table 12

Audibility of intonation patterns:

correct responses from 6 items per set

Group 1				Group 2			
Case	Set	Exp.	Std.	Case	Set	Exp.	Std.
1	8ve	3	3	4	8ve	2	2
	5th	0	0		5th	1	0
	3rd	0	0		3rd	0	0
2	8ve	2	1	5	8ve	0	0
	5th	1	0		5th	0	0
	3rd	0	0		3rd	0	0
3	8ve	2	0	6	8ve	3	2
	5th	0	0		5th	4	2
	3rd	0	0		3rd	1	1

Group 3				Group 4			
Case	Set	Exp.	Std.	Case	Set	Exp.	Std.
7	8ve	0	0	10	8ve	1	0
	5th	0	0		5th	0	0
	3rd	0	0		3rd	0	0
8	8ve	3	2	11	8ve	0	0
	5th	0	0		5th	0	0
	3rd	0	0		3rd	0	0
9	8ve	3	1	12	8ve	3	1
	5th	0	0		5th	0	0
	3rd	0	0		3rd	0	0

interval of a 5th, can not be spontaneously recognised. Cases 1, 5, 8 and 11, who had worn experimental aids prior to this investigation, scored poorly which indicates that the identification of tonality in speech may not occur spontaneously in deaf children of this age. The extent to which the recognition and use of intonation could be fostered by formal training could be the subject of an interesting study.

The formal, routine training of these children prior to testing included discriminating between the higher and lower pitched vowels of a series of stimulus pairs. Results obtained by the children on this simpler task are presented as supplementary information in Table 13.

Table 13

Results of test for audibility of pitch

(1 signifies correct responses at level of confidence p .05 for the individual child; 0 signifies failure to identify pitch by this criterion)

Group 1

Case	Set	Exp.	Std.
1	8ve	1	0
	5ve	0	0
	3rd	0	0
2	8ve	1	0
	5th	1	0
	3rd	1	0
3	8ve	1	0
	5th	0	0
	3rd	0	0

Group 2

Case	Set	Exp.	Std.
4	8ve	1	1
	5th	0	0
	3rd	0	0
5	8ve	1	0
	5th	0	0
	3rd	0	0
6	8ve	1	1
	5th	1	1
	3rd	1	1

Group 3

Case	Set	Exp.	Std.
7	8ve	1	1
	5th	1	1
	3rd	0	0
8	8ve	1	1
	5th	0	0
	3rd	0	0
9	8ve	1	1
	5th	0	0
	3rd	0	0

Group 4

Case	Set	Exp.	Std.
10	8ve	1	1
	5th	0	0
	3rd	0	0
11	8ve	1	0
	5th	1	0
	3rd	0	0
12	8ve	1	1
	5th	0	0
	3rd	0	0

Test 5. Ability to Discriminate between Vowels in Words

Vowels in Speech

Sounds articulated in such a way that the breath stream flows essentially unhindered along the median line of the vocal tract are classified as vowels (Moulton, 1962, p. 6). Two vowels articulated in such a way that there is a smooth transition from one to the other form a diphthong (Wise, 1957). The number of vowels and diphthongs used varies from language to language and from dialect to dialect (Gleason, 1961). The vowel resonance is produced by a succession of damped natural vibrations caused in the vocal cavities by the periodic flow of air from the glottis. The tongue, lips, palate and pharynx all contribute to shape these cavities which resonate at particular frequencies and give each of the vowels their particular characteristics (Chiba and Kajiyama, 1958; Denes and Pinson, 1963; Fant, 1960; Joos, 1948). The frequencies at which these cavities resonate are determined by the size of their apertures. Each vowel resonates at several different frequencies and these points of maximum resonance within each vowel are called formants. The three major formants (designated F_1, F_2 and F_3 respectively) for the average male speaker saying the vowels /u/, /a/ and /i/ are:

$F_1 = 300$, $F_2 = 870$, $F_3 = 2240$ cps (u, as in shoe)

$F_1 = 730$, $F_2 = 1090$, $F_3 = 2440$ cps (a, as in father)

$F_1 = 270$, $F_2 = 2290$, $F_3 = 3010$ cps (i, as in key)

For the average female speaker the formants are slightly higher for both vowels and diphthongs (Fairbanks and Grubb, 1961). The fundamental pitch of voice, the larynx tone (designated F_0) is also generally higher for women than for men.

Since speech is a continuously varying process, vowels, like other phonemes, are modified by their relative position in a sequence of sounds. Moreover, formants for any given vowel are likely to change to some extent within a given sample of speech from any one speaker (Pike, 1962). It is for this reason that tests of hearing for vowels are so constructed that the vowel to be identified is placed in a stressed position and the "speech environment" of the vowel is carefully controlled (Holbrook and Fairbanks, 1962; Potter and Steinberg, 1950).

Experiments by Broadbent and Ladefoged (1960) show clearly that systematic modification of the "speech environment" of the vowel can produce systematic change in the identification of the vowel. In the experiments reported, 'bet' and 'bit' were heard according to the modifications of the carrier phrases which were used to introduce the stimulus word. These vowels are, of course, close to each other in formant structure. Vowels having formants widely separated in frequency are not so readily confused, since their 'colour' (timbre) is very different. Carpenter and Morton (1962) have shown that vowels are consistently categorized by listeners by their 'vowel colour' rather than simply by their formant peaks.

Vowels in Relation to Deafness

Severe limitation in the frequency range available to a child, such as that imposed by deafness, standard hearing aids or both, render most vowels partly or wholly inaudible (see Test 1). The effect of such limitation on the speech of deaf children was studied by Angelocci, Kopp and Holbrook (1964) by means of spectrographic analysis. In comparison with normal controls, the deaf children's speech had higher mean fundamental frequencies (F_0), a wider range of amplitude and a wider frequency range of formants. Only 32 percent of the deaf children's vowels could be identified, probably due to the gross overlapping of formant areas.

The importance of vowels in deaf children's speech has traditionally been secondary to that of consonants. Green (1894) in an otherwise excellent book on the teaching of speech to deaf children, largely ignored vowels. Bell (1916, p. 100) stated that, "Vowels are of secondary importance to consonants" even though much of his work on vowel sounds anticipated the work of modern phoneticians. Haycock (1942) was exceptional in emphasising the "modifying influence of consonant on vowel, and vowel on consonant" and in recommending that syllables and words rather than phonemes were the basic units of speech.

Vowel Sounds and This Study

All of the subjects in this study could produce the full range of vowel sounds required for normal speech. These had been taught through hearing, through a combination of hearing and vision, or through touch in combination with hearing and vision. None could discriminate all fourteen vowels through hearing alone. Since vowels rarely occur in isolation, the subjects had been taught to identify and use vowels within familiar words.

Since many more cues for the discrimination of vowels should be available to children with residual hearing when low frequency amplification is provided, vowels used within familiar words were used to test the hypothesis that deaf children with low frequency residual hearing can discriminate between vowels more effectively when amplification from 80 cps, as opposed to 300 cps, is provided.

Method

The stimuli used for this test were two lists of words familiar to the subjects. Each list contained the fourteen most common vowels and diphthongs in American English. Each vowel occurred twice in each list in unsystematic order. The word lists used are given in Table 14. To provide an adequate speech environment for identification, the carrier phrase "Are you ready?" preceded each item.

Before each list was administered, practice was given with similar material until the subjects were fully aware of the nature of their task, which was to say what word was heard. The subjects were told that the word would be marked correct providing the vowel was correct, thus 'brick', 'dish','chick' or 'hit' would be considered correct for the stimulus word 'kick'. It was stressed that the subjects had to respond to every word, guessing if not sure of what was heard.

Results

The results of the test for the discrimination of vowels are summarised in Table 15.

The difficulty of the task for the subjects is reflected in the low scores achieved. Better scores were obtained with the experimental aid than with the standard

Table 14
Word lists used for testing discrimination of vowels

Series 1	Series 2
who	the
car	pen
see	dish
a	do
four	what
cat	girl
book	come
show	he
play	barn
hot	say
bird	foot
bit	tore
cut	two
hen	man
the	curl
hat	moon
far	not
more	she
bed	a
hut	sat
shoe	should
cot	tar
no	horse
way	day
we	fish
fir	much
sit	bone
put	fed

Table 15

Discrimination scores for vowels

(Figures show number of correct responses from 28 items for each subject using experimental and standard model hearing aids)

Group 1

Case	Experimental	Standard
1	10	10
2	11	4
3	17	9

Group 2

Case	Experimental	Standard
4	20	15
5	9	2
6	10	6

Group 3

Case	Experimental	Standard
7	11	12
8	15	9
9	20	13

Group 4

Case	Experimental	Standard
10	15	15
11	15	6
12	18	5

aid. The difference between these scores is significant beyond the .01 level of confidence ($z = 2.66$).

Discussion

The results of this test support the hypothesis that children with low frequency hearing can discriminate between vowels more effectively when amplification from 80 cps, as opposed to 300 cps, is provided.

Analysis of the results by the use of confusion matrices (Figs. 5a, 5b and 5c) show that (1) long and short vowels were less frequently confused by the subjects when they were using low frequency amplification, (2) front and back vowels were more frequently confused with central vowels when subjects were using the standard aid, (3) vowels with low F_1 frequencies in common (e.g. /u/ and /i/) tended to be confused under both conditions of amplification and (4) subjects made fewer random errors when they were using low frequency amplification, particularly in the discrimination of back and central vowels which have marked low frequency components.

While the results are significantly better with the use of low frequency amplification than with amplification from 300 cps, they are not so good as one would predict from Miller's (1956) study (See Fig. 5c) in which subjects were required to discriminate vowels on F_0 and F_1 cues, i.e. with low

	u	ʊ	oʊ	ɔ	ɒ	ɑ	ʌ	ə	ɝ	æ	ɛ	eɪ	ɪ	i
u	18			1		2					1			2
ʊ	1	8	1	1	1	3	1	5		1	1		1	
oʊ	7		6	2		2		2			1			4
ɔ	1			12	1	5		1			2			1
ɒ		1	1		18		1	2						1
ɑ	2		1			18					1			2
ʌ	1		1				17		1		1			3
ə		2				4		19			1		1	1
ɝ			3		1	1		1	10		2			3
æ	2				1	1	3	3		11			1	2
ɛ	2	1	4			7	1	1		1	9	1	1	2
eɪ	1			4		2	1	3			3	4		1
ɪ		1	1	1	1	4		3			2		13	
i	9		1					1			1			8

A. Experimental aid.

	u	ʊ	oʊ	ɔ	ɒ	ɑ	ʌ	ə	ɝ	æ	ɛ	eɪ	ɪ	i
u	13		2	1		1	1	3						3
ʊ		7	1		2	2	3	2			2		2	3
oʊ	2		4	2		7	4	1	2		1			1
ɔ	6		1	8		6	1	2						
ɒ	3		1		9	4	3	3						1
ɑ	4		2	2		13		1						2
ʌ	3	1	3	1	1	4	6	1		1	1		1	1
ə	3		2	1		2		14			1			1
ɝ			1		2	5		4	6	1	1	1	1	2
æ	3		2	3		4		5		4			2	1
ɛ	3		2	1		1	2	6	1	1	5			2
eɪ	3		1	2		3	2	4	1			4	1	3
ɪ	2		1				2	5		1		1	8	2
i	11					1	3	2	1		1			5

B. Standard aid

	u	ʊ	oʊ	ɔ	ɒ	ɑ	ʌ	ə	ɝ	æ	ɛ	eɪ	ɪ	i
u	80								1					27
ʊ		37							1		12		69	1
oʊ			87	1					8			16		
ɔ				25	12	14				46		1		2
ɒ				4	14	4	12			69	9			
ɑ					4	56				44				
ʌ					1		49				50			
ə														
ɝ	33			4					60		3	12		
æ					12	15			1	91				
ɛ		3	2				10		3		87		15	
eɪ	8	1			1	1			13			94	1	1
ɪ		12				1							103	87
i	28					1								

C. 670 cps low pass filter from Miller (1956)

(Schwa (ə) omitted by Miller; the diphthongs (aʊ) and (ɪʊ) omitted by the writer).

Fig. 5 Confusion matrices of vowels as spoken (ordinates) and as heard (abscissae) frequency amplification extending up to 670 cps. Since Miller's subjects were sophisticated listeners and those in this study were not, further assessment of the ability of children with low-tone residual hearing to discriminate vowels after extensive training with amplification from 80 cps is suggested.

Test 6. Ability to Discriminate between Consonants

Consonants in Speech

Some contemporary phoneticians (e.g. Halle, Hughes and Radley, 1957; Ladefoged, 1962) have come to regard many consonants not so much as entities in their own right but as ways of stopping and starting vowels. Thus, for example, the unvoiced consonants /p/, /t/ and /k/ have unique influence on the vowels that precede or follow them. In other words, each of these consonants modifies the characteristic formants of vowels in a particular way according to the movement of the tongue and/or lips as they take up or leave their stop positions. Both F_1 and F_2 of all vowels fall in pitch when stopped by /p/. However, F_1 falls and F_2 rises in pitch for all vowels stopped by /t/ and /k/, the latter consonant causing a sharper rise in pitch than the former. These features permit a normal listener to identify these consonants by their vowel transitions even when the consonants themselves are not sounded. Thus, if the words 'tap', 'tat' and 'tack' are said without plosing the final consonants, they can still be recognised. In this manner, so called "high frequency phonemes" can be identified by vowel transitions which occur at much lower frequencies. It may therefore be inferred that persons having high-tone hearing loss but adequate hearing for F_1 and F_2 vowel transitions could learn to discriminate between consonants in minimal pairs (such as cat and cap).

Consonants and Residual Hearing

Data reported by Liberman (1957), in a review of results obtained from work on speech perception, indicate that many cues by which consonants are discriminated by normal listeners are also available to children with low frequency residual hearing. These cues, which should be adequate for discrimination both between and within some classes of consonants are summarized below.

1 Frequency location under 1000 cps
2 Intensity ratios of sounds heard
3 Presence and duration of voicing
4 Onset characteristics of low frequency phonemes
5 Extent of F_1 and some F_2 formant transitions
6 Direction of transitions
7 F_1 loci
8 F_2 loci for consonants articulated with back vowels
9 Duration of transition
10 Silence before F_2 transitions from back vowels
11 Nasal resonance

Discrimination between classes may be illustrated by the consonants /b/ (a plosive) and /w/ (a semi-vowel); though they have the same frequency location (point 1) and are of similar intensity (point 2) they may be discriminated by the duration cue (point 3) and the onset characteristic (point 4). Similarly, discrimination <u>within</u> classes may be illustrated by contrasting cues for /b/ and /p/ (both plosives); both generate the same formant transitions (points 5 and 6), but /b/ is voiced and /p/ is not (point 3).

Contrasted with lipreading, which makes so many sounds look alike (p,b,m; t,d,n; k,g; s,z; f,v; etc.) and which provides no cues on voice factors, the use of low-tone residual hearing would appear to offer better cues both for speech recognition and speech feedback (Hudgins, 1949; Hudgins and Numbers, 1942; Thomas, 1963; Woodward and Barber, 1960). However, the current methods of teaching consonants do not usually conform with acoustic theory (Ling, 1963) but rather with visual, analytic methods which have resisted change. Thus DiCarlo (1964, p. 94) states, "With a deaf child we cannot use this (auditory) sense modality except as it is reflected in other senses."

Consonants in this Study

In this study, syllables in which consonants precede or follow vowels were used since consonants are always taught in a syllabic context in the Montreal Oral School and the subjects were familiar with listening for and reporting consonants in syllabic form. While recognition and feedback cues due to the use of audition have helped the subjects in this study in the articulation of consonants in syllables, words and running speech, very few were able, prior to the administration of the test, to discriminate either between classes of consonants or within classes of consonants.

The hypothesis to be tested, that additional frequencies from 80 - 300 cps can be shown to contribute to the discrimination of consonants by children with low-tone residual hearing through the presence of additional low frequency cues, is highly speculative. The effective use of low frequency residual hearing is new to these subjects and, as pointed out by Templin (1957), ability to discriminate between all elements of speech increases in normally hearing children up to, and beyond, eight years of age. For children with low frequency residual hearing, it is likely to take much longer than eight years to reach really high standards of auditory discrimination.

Method

The stimuli used for this test were two lists of syllables. Each list contained the twenty-two most common initial consonants and the twenty most common final consonants. The consonants were distributed in unsystematic order throughout the lists, as shown in Table 16.

Before each list was administered, practice was given with similar material until each subject was fully aware of the nature of the task, which was to say what syllable was heard. Each subject was told that only the vowel /I/ would be used throughout the test and each subject was also told whether to listen for an initial or final consonant. The carrier word "ready" was used for each item.

Results

The results for the test of discrimination of consonants is summarized in Table 17. The difference between scores with regular and low frequency amplification was not significant. ($z = 0.21$)

Discussion

The results obtained did not support the hypothesis. In view of the nature of the auditory skill required for this task this is not surprising, as the time available for

Table 16

Syllabic stimuli used for testing discrimination of initial and final consonants

Series 1		Series 2	
Initial	Final	Initial	Final
ZI	Id	gI	Iʒ
bI	In	jI	Ib
SI	Iz	sI	Ig
WI	Ip	tI	Is
tI	It	wI	In
dʒI	Il	tʃI	Itʃ
MI	Ib	ðI	Im
kI	Iʃ	zI	Id
NI	It	hI	Id
ðI	Iv	bI	Iθ
ʃI	Iʒ	mI	Iŋ
θI	Ig	lI	If
lI	If	ʃI	Ik
dI	Ik	dʒI	Ip
rI	Id	rI	Iz
jI	Is	pI	Iʃ
hI	Im	vI	Ið
pI	Iθ	dI	Il
gI	Ið	kI	It
tʃI	Iŋ	fI	Iv
vI		nI	
fI		θI	

Table 17

Discrimination scores for consonants

(Figures show the number of correct responses from 42 items for each subject using standard and experimental aids)

Group 1

Case	Experimental	Standard
1	6	9
2	19	5
3	1	1

Group 2

Case	Experimental	Standard
4	6	4
5	0	0
6	1	2

Group 3

Case	Experimental	Standard
7	3	2
8	0	0
9	16	10

Group 4

Case	Experimental	Standard
10	2	2
11	0	0
12	0	0

the children to learn to identify the presence of cues which had not formerly been available to them was too limited.

The responses of some of the subjects indicated that a carefully programmed training schedule involving broad discrimination between classes, then finer discrimination within classes, would have helped subjects to identify available cues more easily. Certainly more information would have been obtained if two forms of test had been prepared, (1) discrimination between classes of consonants, and (2) discrimination within classes.

The task would probably have been easier for the subjects if the back vowel /u/ had been used rather than the front vowel /I/. Only one formant of /I/ could have been audible to these subjects in this test, whereas with the vowel /u/ both F_1 and F_2 would have been more audible and hence more information would, at least theoretically, have been available. Since both formants of the vowel /u/ are in the low frequency area, this might well have helped to focus attention on low frequency cues.

In view of the discrepancy between results theoretically possible and results actually obtained, the need for further research on the ability of deaf children to discriminate consonants is strongly indicated.

THE QUESTIONNAIRES

In order to (1) collect additional data, (2) determine whether any differences in the children's responses relative to the frequency range of amplification used were evident to the parents, and (3) compare parents' observations with the results obtained from Tests 1 - 6, two questionnaires were designed and administered. The items included on each questionnaire are presented in

Table 18

Items presented on questionnaire I

1 Serial number of aid and type ...

2 Gain control setting ...

3 At what distance can you attract your child's attention through hearing? ...

4 Does the child show discomfort or intolerance to any sounds? ... Specify ...

5 Is the child aware of any incidental sounds using this hearing aid? ... Specify ...

6 Does the child like the hearing aid? ...

7 Does the child control the loudness of his voice (a) better ... (b) worse ... or (c) the same as usual ... using this aid?

8 Can the child control the pitch of his voice (a) better ... (b) worse ... or (c) the same as usual ... using this aid?

9 Is communication with the child (a) easier ... (b) more difficult ... or (c) the same as usual ... using this aid?

Table 19

Items presented on questionnaire II

With which aid:		1st	2nd	Neither
1	did you feel the child heard better?	...	...	...
2	did the child voice most often?	...	...	...
3	was loudness of voice controlled better?	...	...	...
4	was rhythm imitated better?	...	...	...
5	was pitch controlled better?	...	...	...
6	was intonation imitated better?	...	...	...
7	were vowels imitated better?	...	...	...
8	were consonants imitated better?	...	...	...
9	was communication with the child easier?	...	...	...
10	any additional remarks?			

Tables 18 and 19.

The first six items on Questionnaire I were designed to elicit information pertinent to the aid in use and the child's responses to it. The remaining items asked the parents to compare the child's responses when using the aid (whether experimental or standard) to the responses made by the child before this study was begun.

All items on Questionnaire II were concerned with the comparison of the child's responses to sound - particularly to speech - during this study, i.e. when wearing the experimental and standard model aids.

Procedure

Questionnaire I was explained to the parents (usually the mother) at the beginning of each child's training and testing schedule. Parents were told that the child would try two hearing aids, each for one week; that the two aids, though identical in appearance, in fact had different characteristics; that both were "experimental models"; and that the purpose of Questionnaire I was to provide information about the child's reactions when wearing each aid. Parents were asked to complete Questionnaire I immediately before each series of tests were administered. In other words, Questionnaire I was administered twice - once after the experimental aid had been worn for a week. (As shown in Table 2, p. 31, cases 1 - 6 used the experimental aid first and cases 7 - 12 last).

Questionnaire II was completed by the parents of each child immediately following the completion of the testing programme, i.e. after the child had used both hearing aids and completed both series of tests. Parents were told that the object of this questionnaire was to provide an opportunity for them to compare the two experimental hearing aids.

Results

Questionnaire I

Data obtained from items 1 - 4 of Questionnaire I are presented in Table 20.

The amount of gain required by the children did not differ significantly between aids having standard and low frequency characteristics.

Considerable variation existed between the distances at which parents found they could call their children and attract their attention. Figures given by parents were the "average distance the child could be called during the whole week." When low frequency hearing aids were used the distances at which the children responded

Table 20

Data on use of hearing aids

(Replies to items 1 - 4 of questionnaire I)

Case No.	Serial No. of Aid Used		Optimum Gain Setting		Distance can be called (ft)		Any Intolerance to Aid?
	Exp.	Std.	Exp.	Std.	Exp.	Std.	
1	419	273	4	4	3	3	no
2	430	272	4	4	10	3	no
3	413	264	4	4	20	10	no
4	275	273	6	6	6	0	no
5	419	273	5	7	4	0	no
6	275	264	4	6	20	20	no
7	275	182	6	7	20	10	no
8	760	264	6	4	6	0	no
9	413	182	4	4	40	15	no
10	419	182	5	5	6	6	no
11	760	264	7	7	12	7	no
12	430	182	5	5	15	5	no

were significantly greater than those noted when the standard aid was used. This improvement in "response distance" permitted by low frequency amplification is significant beyond the .01 level of confidence.

There was no intolerance of sound or discomfort caused by sound reported in respect of either aid.

Data obtained from item 5 of Questionnaire I is presented in Table 21. Significantly more incidental sounds in the environment were heard by the subjects when using low frequency amplification ($P < .01$) than amplification within the standard range.

In response to item 8 of Questionnaire I, nine of the twelve children were reported to control the pitch of their voices better when using low frequency amplification while no change in the control of voice pitch was reported when using the standard model. This difference is significant beyond the .01 level of confidence, in favour of low frequency amplification.

In response to item 9 of Questionnaire I, nine of the subjects were reported to communicate more easily when using the experimental aid than previously, but no such difference was reported when children used standard aids. Thus, low frequency amplification appears to be significantly better ($P < .01$) than amplification from 300 cps in promoting ease of communication between parents and children.

Table 21

Incidental environmental sounds heard by subjects with experimental and standard model hearing aids

Case	Experimental Hearing Aid	Standard Hearing Aid
1	Doorbell, airplanes, T.V., telephone bell, traffic, radio, environmental speech.	None
2	Doorbell, airplanes, T.V., telephone bell, traffic, radio, dishwashing, humming, environmental speech	Light switch
3	Doorbell, airplanes, T.V., telephone bell, traffic, dog barking.	T.V.
4	Airplanes, traffic, TV., music.	Traffic
5	Airplanes, traffic, T.V., bouncing ball, children running upstairs.	None
6	Doorbell, airplanes, T.V., telephone bell, traffic, dog barking, knocking.	Doorbell, airplanes, T.V., telephone bell traffic, dog barking knocking.
7	Doorbell, traffic, T.V.	Doorbell, airplanes, T.V.
8	Traffic, T.V., door bang	None
9	Doorbell, telephone bell, traffic, airplanes, T.V., dog bark, child crying, conversation & laughter outside room	Airplanes, traffic, T.V., dog barking.
10	Airplanes, traffic, T.V., dog bark, bird chirping, telephone bell.	Telephone bell, traffic, dog barking.
11	Doorbell, traffic, T.V., dog bark.	Doorbell, airplanes, T.V., dog bark, crash.
12	Traffic, T.V.	Traffic, T.V.

Table 22

Replies to question 8 of Questionnaire I "Does the child control the pitch of his voice, better, worse or the same as usual using this hearing aid?"

Case	Experimental Aid	Standard Aid	Difference
1	better	worse	+
2	better	worse	+
3	same as usual	same as usual	0
4	better	same as usual	+
5	same as usual	same as usual	0
6	same as usual	same as usual	0
7	better	same as usual	+
8	better	same as usual	+
9	better	same as usual	+
10	better	worse	+
11	better	worse	+
12	better	same as usual	+

Note: In answering this question, parents were comparing the child's responses using experimental and standard aids each with the hearing aid formerly worn by the child. The replies show that significantly better control of pitch results with low frequency amplification ($p < .01$).

Table 23

Replies to question 9 of Questionnaire I "Is communication with the child easier, more difficult, or the same as usual when wearing this aid?"

Case	Experimental Aid	Standard Aid	Difference
1	easier	the same	+
2	the same	more difficult	+
3	easier	the same	+
4	easier	the same	+
5	the same	the same	0
6	the same	more difficult	+
7	the same	the same	0
8	easier	the same	+
9	easier	easier	0
10	easier	the same	+
11	easier	more difficult	+
12	easier	the same	+

Note: In answering this question comparisons were invited between responses of the child when wearing each of the hearing aids (experimental and standard) with responses made with the hearing aid regularly worn by the child. The difference is significant at the .01 level of confidence.

Questionnaire II

Results obtained in response to Questionnaire II are summarized in Table 24.

Two items of Questionnaire II elicited responses of statistical significance. These were items 1 and 9, which were questions of a similar nature. Eleven of the twelve parents considered the experimental aid to be the better one and the same number reported that their children appeared to communicate better when the experimental aid was used. These results were both significant beyond the .01 level of confidence and support the hypothesis that low frequency amplification contributes significantly to the audition of speech by deaf children with residual low-tone hearing.

Only seven parents commented on item 10 of Questionnaire II. They all stated that the one week's period of observation with each aid was too short for them to make adequate observations.

Discussion

The results from both questionnaires support the hypothesis tested in this study and in particular confirm the results obtained in Tests 1 and 4. That improvement in the children's control of voice pitch when using

Table 24

Analysis of answers given to questions asked

in Questionnaire II

Questions asked	Reply	Case number											
With which aid -		1	2	3	4	5	6	7	8	9	10	11	12
did you feel hearing was better?	Exp	x	x	x	x	x	x		x	x	x	x	x
	Std							x					
	Neither												
did the child voice more often?	Exp										x		
	Std							x					x
	Neither	x	x	x	x	x	x		x	x		x	
was loudness of voice controlled better?	Exp		x						x				
	Std							x					
	Neither	x		x	x	x	x			x	x	x	x
was rhythm imitated better?	Exp		x						x	x			
	Std												
	Neither	x		x	x	x	x	x			x	x	x
was pitch controlled better?	Exp		x						x	x			
	Std												
	Neither	x		x	x	x	x	x			x	x	x
was intonation imitated better?	Exp		x						x				
	Std												
	Neither	x		x	x	x	x	x		x	x	x	x
were vowels imitated better?	Exp		x			x			x	x		x	
	Std												
	Neither	x		x	x		x	x			x		x
were consonants imitated better?	Exp		x										
	Std												
	Neither	x		x	x	x	x	x	x	x	x	x	x
was communication with child easier?	Exp	x	x	x	x	x	x		x	x	x	x	x
	Std							x					
	Neither												

Note: In Questionnaire II, the words experimental or standard were not used. Aids were referred to as "the first aid" or "the second aid".

amplification from 80 cps was reported indirectly in reply to item 8 of Questionnaire I, but not directly in reply to item 5 of Questionnaire II, is surprising. The questions were, of course, dissimilar and the replies may reflect the parents' feelings that, while they were able to report the children's responses to sound, they were not competent to judge the difference between two hearing aids. The parents' reluctance to judge may be inferred from replies to item 10 of Questionnaire II, where insufficient time was pleaded by seven parents as a reason for making few positive judgments in favour of one aid rather than the other.

It may, however, be true that an improvement in hearing could not reasonably be expected to produce an immediate improvement in the speech of deaf children, particularly those participating in this study, since the speech skills the children had acquired were mainly learned not through audition but through visual and somaesthetic experience.

Parents' observation of the children's hearing responses, however, made without any knowledge of which of the two aids was in use, provided completely independent evidence in support of low frequency amplification at a high level of statistical significance.

GENERAL DISCUSSION AND CONCLUSIONS

General Discussion

The purpose of this discussion is to examine the pertinent features of this investigation as a whole, together with their implications. In addition, since this is the first study concerned with low frequency amplification, a number of issues which require clarification through further research will be considered.

The Population

Only those deaf children with a classical low-tone residue of hearing were chosen for this study because this group, having the most impaired hearing among the pupils found in schools for the deaf, benefits least from the standard frequency range of amplification. Four points of major interest, which emerge in connection with the subjects and their hearing, are discussed below.

1 The proportion of deaf children with residual hearing

Only one in five children - or approximately twenty percent - was deaf enough to qualify for this study. Since the subjects studied benefitted significantly from the use of amplification, it could be that the majority of children in schools for the deaf, who are less deaf, should benefit more. Only one child in the school had too little residual hearing for inclusion in the group studied. The implications of these observations are (a) it is quite realistic to fit very young deaf babies, even those who make no response to hearing initially, with hearing aids providing low frequency amplification and to expect hearing responses to occur in almost all cases after training, and (b) it is reasonable to expect most deaf children, if provided with low frequency amplification in infancy, to develop natural voice patterns through normal feedback mechanisms. These implications constitute hypotheses for further investigation.

2 Low frequency amplification and children with less severe hearing loss

Some eighty percent of the children in the Montreal Oral School for the Deaf (and probably most other schools for the deaf) have better hearing than the subjects participating in this study. Most of these children also have abnormal voice patterns. Because the audition of voice patterns among children in this investigation were significantly improved with low frequency amplification, it would appear worthwhile to repeat this study using subjects with less impaired hearing, who have either flat or sloping audiograms extending up to 4000 cps. In view of the possible masking of high frequency cues, particular note should be made of the effect of low frequency amplification on their audition of consonants. Such a study would have important implications for the theory of 'unisensory' training of very young deaf infants, where it may be difficult to establish reliable threshold measurements before a hearing aid becomes essential, i.e. while the child is passing through the possibly critical period of optimum communication readiness.

3 The possible origin of low-tone residual hearing.

Audiometric and electronystagmographic data obtained on the children in this study provide the basis for interesting speculation on, and the investigation of, the origin of low-tone residual hearing. In four cases, vestibular response was absent (Table 1, p. 28) and their low frequency responses could only stem from touch, vibration, or from intact cochlear structures. Békésy audiometry (Fig.2, p. 27), however, revealed hearing in these and in other cases for certain high frequencies which are beyond the sensation range for touch and vibration. The presence of some intact basal structures in the cochlea may therefore be inferred.

As pointed out by Gannon (1965)* low frequency hearing could imply either intact apical structures or, alternatively, inact basal structures responding in synchrony with a low frequency stimulus. Thus apical structures,

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* The writer is grateful to Dr. R.P. Gannon for arranging the electronystagmography and discussing with him the results and implications of this work.

which would normally respond to low frequencies, need not, theoretically, be present for a picture of classical low-tone hearing to emerge. By masking the high frequency "islands of hearing", present in these cases, with a suitably wide band of noise low frequency responses should be eliminated if a "line busy" theory of masking holds good and if apical cochlea structures are in fact absent. Further research in this areacould well contribute to the theory of hearing.

4 The contribution of high frequency "islands of hearing"

The subjects who had high frequency islands of hearing did not respond consistently or significantly better than others on any of the tests administered. However, on inspection of the Békésy audiograms (Fig. 2, page 27) it may be seen that, for the most part, such islands occurred above 3,500 cps, the upper limit of the characteristic determined for the two aids. A research project designed to compare the responses of such children to amplification over the ranges 80 to 1500 cps, and 80 to 8000 cps would determine whether such islands could contribute significant cues.

The contribution of such islands of high frequency residue would have implications (a) relating to the theory of hearing and the problems discussed in the preceding paragraph, and (b) of importance in determining the frequency response characteristics of hearing aids required for such subjects. Because high gain levels for high frequency sound tend to cause positive feedback (acoustic howl) there would be a practical advantage in cutting high frequency amplification if, for particular cases, it were shown that high frequency islands did not contribute either to the intelligibility of speech or its audibility.

The Experimental Design

Inspection of the results of all six tests and both questionnaires shows that the design of the research (Table 2, page 31) was satisfactory and that no significant bias occurred between or within tests, questionnaires or modes of amplification. Greater improvement in scores due to low frequency amplification tended to be obtained by children in Groups 1 and 4 than by children in the other two groups. However, these groups were opposite with respect to order of presentation of hearing aids and test series. This difference between groups appears to be related to discrepancies between hearing levels, revealed by the comparison of discrete pure tone and Békésy audiograms (Figs. 1 and 2), which were not expected. A better balance between groups could probably have been achieved if Békésy audiometry had been used as a criterion in the selection of subjects for groups.

The Stimuli

All six tests were carried out with a male voice (the writer's). While the formant frequencies (F_1 and F_2) for females and children are only slightly higher than for males, their fundamental (F_0) voice pattern range is generally an octave or so higher. It follows that the results of this study do not warrant generalizations on the audition of female and child voice patterns by deaf children with low-tone residual hearing. It may be inferred from the spectrographs published by Ling (1964b) and the distances at which the children responded to their mothers' voices in this study (Table 20, page 95) that the overall trends towards better audition of voice revealed in this study would be present, but perhaps less marked, if female or child voices were used for the stimuli rather than male voice. Because deaf children, like normally hearing children, spend a great deal of time with female speakers (mothers and teachers) and need to hear their own and other children's voices in order to learn to talk, an empirical study, using a similar group of deaf children to assess the effect of low frequency amplification on the audition of female and child voice patterns, is of great importance.

The Tests and Questionnaires

The main hypothesis of this investigation was that amplification of additional low frequencies, from 80 cps, would contribute significantly to the audition of speech among deaf children with low-tone residual hearing. It was clearly supported by the results of this study.

Test 1

In constructing this test the writer selected the three vowels /a/, /u/ and /i/ because he considered them to be a representative sample of the voiced phonemes. In other words he considered that if, under given conditions, these three sounds were of approximately equivalent audibility for deaf children with low frequency residual hearing, approximately equivalent audibility for all other voiced sounds could be assumed. This assumption requires verification. The adequacy of the sample should also be queried. For example, nasal sounds have lower formants than any other voiced sounds and /n/, having its first formant around 180 - 200 cps should perhaps be added to the sample, particularly if this test is repeated using female or child voice as the stimuli, since under these conditions F_0 and F_1 frequencies might well coincide.

Because the audibility of phonemes is a basic requirement for communication by speech and hearing, this test has particular applicability in the selection of suitable hearing aids. One important implication of this study, and one which would serve as the hypothesis for further investigation, is that the greatest ease and accuracy in communication for hearing impaired subjects results when the frequency response range and characteristic of the hearing aid is adjusted so that relative loudness of voiced phonemes approximates to their normal intensity ratios in speech.

Tests 2, 3 and 5

Results on all three tests significantly favoured the use of low frequency amplification. Since voiced sounds were involved in these tests the significant results could be accounted for in terms of the improved relative audibility of voiced phonemes measured in Test 1 and discussed above.

Test 6

Results from this test were inconclusive. As stated earlier, this test could have failed to show differences that do, in fact, exist, because F_2 of the vowel /I/, with which the consonants were combined, was outside the children's range of hearing (See Fig. 4 page 37).

Differences between responses under the two conditions of amplification used in this study might well show if the consonants were combined with vowels having both first and second formants within the frequency range of the child's audition, i.e. mid or back vowels. Recent work by Hutton, Curry and Fay (1965) suggests that, even for normal listeners, consonant confusions are less frequent with back or mid vowels.

It is, of course, impossible for a deaf child with only low-tone residual hearing to hear the major components of most of the high frequency, unvoiced consonants and it is unrealistic to expect a child to detect and identify all of these consonants entirely in terms of their effect on adjacent vowels. Wedenberg (1963) in cooperation with Johansson (1963), attempted to overcome this problem by using frequency transposition. Consonant components occurring at 3000 - 6000 cps were transposed below 1500 cps and thus were heard significantly better by severely deaf listeners. However, some distortion of the vowels occurred. Similar interference with vowels was reported for transposition experiments carried out by Raymond and Proud (1962). The joint implications of these studies and the present study are that, providing the severely defective hearing mechanism can handle the information involved, a combination of frequency shifted speech and low frequency amplification would be more advantageous than either separately.

The Questionnaires

Both questionnaires yielded independent corroborative evidence significantly in favour of using additional low frequency amplification with deaf children having low-tone residual hearing. When completing the questionnaires the parents had no knowledge of the characteristics of the hearing aids in use. In spite of the children's short period of exposure to the hearing aids and the parents' limited training in evaluating their children's performance in speech and hearing, the questionnaires were completed with confidence.

Suggestions for Further Research

The following topics, discussed above, have been found, in the course of this study, to require further research.

1. The effect of using low frequency amplification in the early management of young deaf babies.

2. The effect of providing amplification of frequencies below 300 cps on the audition of speech among deaf children with less impaired hearing, with particular

reference to its effect on discrimination within and between classes of consonants.

3. The origin of low-tone residual hearing; the relative contribution of auditory, vestibular and tactile mechanism to sensation levels.

4. The contribution of high frequency "islands of hearing", noted in the course of Békésy audiometry, to the audition of speech.

5. The effect of low frequency amplification on the audition of female and child speech patterns by deaf children with low-tone residual hearing.

6. The validity and reliability of using approximate equivalent audibility of voiced phonemes as a criterion in the selection of hearing aids.

7. The ability of subjects with residual hearing to make discriminations in time, frequency and intensity relationships between sounds, with particular reference to their ability to hear consonants in relation to vowel formant transitions and their capacity to utilize frequency shifted speech components.

Conclusions

The following conclusions, drawn from the preceding discussion, summarize the statistically significant advantages found in using low frequency amplification (range 80 - 3500 cps), as opposed to standard amplification (range 300 - 3500 cps), with deaf children having only low-tone residual hearing.

1. There is an improvement in the relative audibility of voiced phonemes.

2. The syllabic structure of both words and phrases is more audible under good signal/noise conditions

3. Primary stress in phrases is more audible. This improvement in audibility is probably related to the improved relative audibility of phonemes.

4. Ability to discriminate between vowels is improved.

5. The independent judgments of parents also demonstrated the superiority of low frequency amplification in terms of (a) the greater range of sounds to which their children respond, (b) the greater distances at which they can attract their attention, (c) the better control of pitch in their children's voices, and (d) the greater ease with which they are able to communicate with them.

SUMMARY

The effect of amplifying frequencies below the main speech range (300 - 3000 cps) on the audition of speech by twelve deaf children with classical low-tone hearing residue was explored by comparing the results obtained with two individual hearing aids; an experimental model with a frequency range from 80 - 3500 cps and a standard model with a frequency range from 250 - 3500 cps.

While the subjects' audition of consonants (particularly unvoiced phonemes) was poor with either aid, significantly better results were obtained with the experimental than the standard aids on tests designed to measure the relative audibility of voiced phonemes, the audibility of syllabic structure, the awareness of stress, and the discrimination of vowels. Independent data obtained by questionnaires confirmed the superiority of low frequency amplification in these cases.

Because the utmost use of audition is essential for the adequate development of speech and language skills in deaf children, the more general use of hearing aids of the experimental type, which amplify a wide range of sound from 80 cps upwards, is recommended for all auditory rehabilitation work with deaf children who have low-tone residual hearing.

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