RELATIONS BETWEEN PSYCHOPHYSICAL DATA AND SPEECH PERCEPTION FOR HEARING-IMPAIRED SUBJECTS

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VOORWOORD

Het vervaardigen van een proefschrift zoals voor u ligt is als een lange en vaak eenzame tocht. Allen die mij gestimuleerd hebben deze tocht te voltooien en allen die de eenzaamheid onderweg doorbroken hebben ben ik bijzonder erkentelijk.

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CONTENTS

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LIST OF ABBREVIATIONS

A	: attenuation component of the hearing loss for speech
A+D	: hearing loss for speech in quiet
BM-slope	: Backward-Masking slope
$B_{\frac{1}{2}}$,B1,B2,BM,BT	: parameters for the backward-masking slopes
CB	: Critical Bandwidth
CR	: Critical Ratio
CVC-word	: Consonant-Vowel-Consonant word
$C_{\frac{1}{2}}$,C1,C2,CM,CT	: parameters for the critical ratio
D	: hearing loss for speech in noise (distortion component of the hearing loss for speech)
ΔDh	: elevation of D due to high-pass filtering
ΔDl	: elevation of D due to low-pass filtering
FM-slope	: Forward-Masking slope
F1,F2	: first and second formant positions
f1,f2	: parameters for isolated-vowel perception
$F_{\frac{1}{2}}$,F1,F2,FM,FT	: parameters for the forward-masking slopes
$G_{\frac{1}{2}}$,G1,G2,GM,GT	: parameters for the gap-detection thresholds
JND	: Just-Noticeable Difference
$J_{\frac{1}{2}}$,J1,J2,JM,JT	: parameters for the JND's for intensity
$L_{\frac{1}{2}}$,L1,L2,LM,LT	: parameters for the pure-tone thresholds
N1,N2,N3	: conditions of presentaion in noise
n1,n2	: parameters for consonant perception in noise
PTC	: Psychophysical Tuning Curve
Q1,Q2,Q3	: conditions of presentaion in quiet
q1,q2,q3,q4,q5	: parameters for consonant perception in quiet
$R_{\frac{1}{2}}$,R1,R2,RM,RT	: parameters for the dynamic range
SISI	: Short Increment Sensitivity Index
SL	: Sensation Level
SPL	: Sound-Pressure Level
SRT	: Speech-Reception Threshold
UCL	: Uncomfortable Loudness Level
v1,v2	: parameters for the perception of CVC-vowels
2AFC	: 2-Alternatives Forced Choice

CHAPTER 1

GENERAL INTRODUCTION

This thesis deals with the perception of speech by hearing-impaired subjects. Deterioration of speech intelligibility due to reduced auditory sensitivity of pathological ears is quite trivial: speech-reception thresholds can be predicted reasonably well from pure-tone audiograms in most hearing-impaired subjects. However, particularly in subjects with a sensorineural hearing loss, speech intelligibility is not only impaired by attenuation due to reduced hearing sensitivity, but also by other properties, which have deteriorated. The latter deficiencies may be regarded as a kind of distortion relative to speech-perception by normal-hearing subjects. In this study we will investigate some of these distortions and try to relate them to speech intelligibility in hearing-impaired subjects.

The appearance of distortion in the perception of speech is reflected in two commonly known phenomena:

1. Many sensorineurally hearing-impaired subjects show reduced maximum speech discrimination scores: even at high presentation levels, compensating for attenuation effects, phonemes are not discriminated entirely correctly due to distortion of the speech sounds.

2. Interfering noise has a relatively strong detrimental effect on speech intelligibility on the part of hearing-impaired subjects. Whereas attenuation affects both speech and noise without changing the intelligibility, distortion impairs the sound quality resulting in a larger signal-to-noise ratio needed by hearing-impaired subjects for speech intelligibility.

Additionally, the effects of sloping or irregular pure-tone audiograms may also be regarded as distortion. Partly, they may be responsible for the phenomena mentioned. But within the context of this study we will focus our attention especially on the effects on speech intelligibility due to the following three types of deterioration: pathological loudness perception, reduced frequency selectivity, and reduced temporal resolution.

Other important aspects of hearing impairment such as nonlinearities (e.g. combination tones and lateral suppression) and binaural interaction are beyond the scope of this study.

Pathological loudness perception is found in most cases of cochlear impairment. The dynamic range of the impaired ear may be reduced dramatically due to an increased threshold of hearing combined with a normal or even decreased uncomfortable loudness level. As mean speech levels in communication situations may vary over a range of 20-30 dB and level differences between successive speech elements cover another 20-30 dB, a reduced dynamic range will result in either inaudibly weak or uncomfortably loud parts in the perception of speech. The just-noticeable differences for intensity may also be expected to play an important role in the perception of speech cues.

It has been proved that frequency selectivity is affected in many hearing-impaired subjects. Frequency discrimination, which is assumed to be related to frequency selectivity, has also been found to be impaired. Poor frequency discrimination may violate the ability to detect changes in fundamental frequency, which carries important prosodic information in speech. The perception of rapid frequency shifts, characterizing transients in consonants and coarticulation effects, may also be affected. Poor frequency selectivity per se may harm the frequency analysis necessary in timbre perception of each complex sound. In speech perception especially the extraction of formants is important and may be reduced by excessive upward or downward spread of masking. Moreover, impaired frequency selectivity may affect an adequate separation of different voices in a multi-talker situation. Finally, a broadening of the critical bandwidth makes the hearing-impaired more susceptible to masking by interfering noise: broader bands will receive relatively more of the masking noise and this may reduce the detection and discrimination of speech sounds in noise.

Some temporal properties have also been proved to have deteriorated in hearing-impaired subjects. Reduced temporal resolution will affect the ability to follow rapid temporal fluctuations. For example, the detectability of brief silent gaps is essential for the perception of stop consonants. In addition to this, excessive forward or backward masking may cause masking of the weaker parts of the speech signal (usually consonants) when preceeded or followed by stronger components (usually vowels).

In summary, there are many indications that the intelligibility of speech on the part of hearing-impaired subjects may be influenced by properties of loudness perception, frequency selectivity, and temporal resolution. Speech intelligibility in noise may particularly be hampered by these perceptual distortions. It is striking that none of the properties mentioned is much focussed upon in clinical practice. Information about loudness perception is used only in differential diagnosis between cochlear and retrocochlear lesions. Even a practical method such as the determination of the speech-reception threshold in noise is not common practice.

It is possible that the limited number of clinical tests is dictated by the limited possibilities to compensate for a certain deficiency by means of hearing aids. Essentially, commercially available hearing aids compensate only for the attenuation component of a hearing loss. Additionally, the aids are able to adjust the maximum presentation level to the uncomfortable loudness level of the pathological ear by means of limiting circuits such as peak clipping and automatic gain control. The possibilities of compensating for pathological loudness perception are restricted to the use of the rather gross method of single-channel compression. Up to now hearing aids have been unable to compensate for impaired frequency selectivity or temporal resolution.

The aim of the present research is to find out by means of psychophysical measurements in what way deteriorations in speech intelligibility in quiet and in background noise are related to changes in auditory properties such as loudness perception, frequency selectivity, and temporal resolution. The results may deepen our knowledge about speech perception strategies in hearing-impaired subjects. A better knowledge about speech perception in pathological ears may indicate directions for future developments in hearing aid design. The results may lead to possible extensions of the routine clinical tests. Of course, a whole battery of tests will be far too time-consuming. However, it may be expected that this research will show us the most relevant tests.

In this study the results of a large battery of psychophysical tests, including some speech intelligibility tasks, are interrelated for a group of hearing-impaired subjects. The analyses are essentially correlational in nature and consequently they do not prove causal relationships. However, strong correlations between tests are at least an indication of possible common causes. Likewise, the absence of significant correlations makes a relation quite unlikely.

The choices of tests included have been dictated by rather pragmatic considerations: which tests may be expected to reflect the most important auditory properties involved in the perception of speech. On the basis of the foregoing, speech intelligibility in noise plays an important role in this study. For the tone-perception tests, the aim is a mapping of auditory sensitivity, loudness perception, frequency selectivity, and temporal resolution. Several measures of phoneme perception have also been included in order to bridge the distance between tone perception and speech perception.

The approach to the problem by means of a battery of tests is rather unusual: most studies on hearing impairment are confined to only one auditory property, sometimes in addition to audiometric threshold. Usually, normal-hearing subjects are included in order to provide a reference for the interpretation of the results. Sometimes a theoretical framework can be put forward on the basis of the results. But further consequences for the perception of speech and the social handicap are, in such a limited approach, merely speculative in nature.

The battery-approach has three advantages above these isolated studies:

1. it provides a direct comparison with speech intelligibility measures;

2. the interaction of the tests included can be taken into account;

3. possible shifts in perceptual strategy with respect to the reliance on one auditory property or another may become evident.

Instead of a group of normal-hearing subjects as a reference, individual differences in auditory properties have been used for interpreting the results.

This general introduction is followed in the next chapter by a review of the psychophysical literature on pure-tone sensitivity, loudness perception, frequency selectivity, temporal resolution, phoneme perception, and speech perception in hearing-impaired subjects. In Chapter 3 the results of a preliminary experiment including parameters of frequency resolution, vowel perception, and speech perception are reported (see also Dreschler and Plomp, 1980). Further extensions along this line of investigation are suggested on the basis of these results. In order to include the perception of consonants, the effects of presentation level and signal-to-noise ratio on phonemic confusions are investigated in Chapter 4 (see also Dreschler, 1983b). In Chapter 5 the results of the final battery of tests including tests on tone perception, phoneme perception, and speech intelligibility are presented (see also Dreschler , 1983a, and Dreschler and Plomp, 1983). In this experiment 21 sensorineurally hearing-impaired subjects participated. Finally, Chapter 6 deals with the results from Chapter 3 to Chapter 5 in relation to other studies. Also, the approach used in this thesis is evaluated.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

In this chapter the psychophysical literature with respect to hearing-impaired subjects is reviewed on the following topics: pure-tone acuity, loudness perception, frequency selectivity, temporal resolution, and phoneme perception. In view of the objectives of this study for each of these categories, especially the relations with speech perception are considered. The last section is devoted to complex relational studies on hearing-impaired subjects using series of different tests in a test battery. The aim of this review is twofold:

1. a review of the auditory properties which are affected by hearing impairment and their mutual relations;

2. a review of the tests used for these kinds of measurement in order to find the most promising tests for this study.

2.2 Pure-tone acuity

As the pure-tone audiogram is regarded as the most important clinical test on auditory impairment, there is an abundance of literature about it. In most studies the audiogram is used for diagnosing the origin of the hearing loss. In this review we will confine ourselves to some studies on the relation between audiometric thresholds and speech intelligibility.

Although speech perception is not the simple result of auditory acuity, many studies are concerned with the prediction of speech-reception thresholds from pure-tone thresholds. After the first predictive formula of Fletcher (1929), many other formulas have been proposed (for a review see Harris, Haines, and

Myers, 1956). A more recent study on 300 subjects showed that the speech-reception threshold in quiet can be predicted with a standard deviation of about 6.4 dB from hearing losses at 500, 1000, 2000, and 3000 Hz (Gjaeveness, 1969). Prediction of the maximum discrimination score from pure-tone thresholds is more complex (e.g. Young and Gibbons, 1962). Mullins and Bangs (1957) concluded that the indices of masking (parameters related to the slope of the audiogram) rather than the pure-tone thresholds themselves were related to the discrimination scores in quiet. However, Ross et al. (1965) could establish this relationschip only for discrimination scores in noise.

In view of the every-day speech situations studies on speech perception should not be confined to speech in quiet. An important study on auditory acuity and the perception of speech in noise was performed by Kryter, Williams and Green (1962). They correlated the pure-tone thresholds for 162 hearing-impaired ears, divided into six groups, with speech intelligibility scores in quiet and at various signal-to-noise ratios. By means of filtering they could prove that especially the speech frequencies above 2000 Hz contribute significantly to speech intelligibility in noise, even for severe hearing losses. They concluded that the importance of high-frequency thresholds for speech perception is underestimated. Harris (1965) arrived at similar conclusions. The results of Plomp and Mimpen (1979) and Duquesnoy (1982) show that the prediction of hearing loss for speech in noise is much more difficult than in quiet.

Plomp (1978) pointed out that the differences in prediction of speech-reception thresholds in quiet and in noise can be understood from the theory that speech-reception thresholds in quiet depend mainly on attenuation components, whereas speech-reception thresholds in noise are determined by distortion components. The origin of the hearing loss may also be a disturbing factor for a unique predictive formula. Noble (1973) concluded that the literature is inconclusive as to the predictive value in cases of cochlear disorders. Smoorenburg and de Laat (1982) provided a clear illustration that the predictive value of pure-tone thresholds for speech-reception thresholds in quiet and in noise is very poor in cases of noise-induced hearing loss. Therefore, in our opinion the predictive formulas from the pure-tone audiogram have only a limited value, and other auditory properties should be taken into account as well.

2.3 Loudness perception

Loudness perception covers various properties of the auditory system. Firstly, it is reflected in the sensation of loudness per se. Secondly, there is the discrimination of small intensity changes. Some loudness properties are coupled with other auditory functions: loudness summation is also dependent on the critical bandwidth, discussed in Section 2.4.2; loudness as a result of temporal integration is above all a temporal characteristic and is treated in Section 2.5.1.

2.3.1 Loudness sensation -

Traditionally there has been a relatively great clinical interest in the sensation of loudness in hearing-impaired subjects. On the one hand, differential diagnosis between cochlear and retrocochlear disorders is based mainly on loudness properties: an abnormally fast increase of loudness with intensity (recruitment) and pathological adaptation. On the other hand, uncomfortable loudness levels of the ear are important parameters with respect to the setting of limiting devices in the presciption of hearing aids. Because pathological adaptation may be expected to play only a minor role in the perception of fluctuating signals such as speech, this aspect will not be discussed here (for an extensive review see Scharf, 1983). However, recruitment means a reduced dynamic range and may be expected to result in deteriorated speech perception. Recruitment is a common clinical observation in subjects with cochlear hearing loss.

Mullins and Bangs (1957) did not find any significant correlation between speech discrimination scores and several measures of recruitment. Smits and Duifhuis (1982) showed (by means of a partial-masking experiment) that the dynamic range of hearing in hearing-impaired subjects can be severely reduced in conditions of masking, even in regions with almost normal hearing sensitivity. This interesting finding provides a possible explanation for relatively poor speech perception in background noise.

2.3.2 Loudness discrimination -

Another aspect of loudness perception concerns the just-noticeable difference, or difference limen, for intensity. Harris (1963) provides an extensive survey on loudness discrimination, including well-known clinical tests like the Luscher-test (Luscher and Zwislocki, 1949) and the SISI test (Jerger, Shedd and Harford, 1959). Depending upon the conditions of presentation he distinguishes tests in which loudness increments have to be detected (loudness modulation) and tests in which two loudness sensations have to be compared (loudness memory). Interpretation of the results on hearing-impaired subjects is complicated by the level-dependence of the intensity-discrimination ability.

Many studies using loudness-modulation techniques have proved that cochlear-impaired ears yield smaller just-noticeable differences for intensity than normal ears, if not at equal sound-pressure levels (SPL values), then at equal levels above the subject's own hearing threshold (sensation levels or SL values). Harbert, Young and Weiss (1969) showed an abnormally low SISI score at high levels in subjects with retrocochlear impairment, indicating reduced sensitivity for intensity differences.

Tests on the detectability of level differences between tone bursts (loudness memory tests) yield, to some extent, different results (e.g. Denes and Naunton, 1950; Hirsh, Palva, and Goodman, 1954). Buus, Florentine, and Redden (1982) suggested that these differences originate from 'memory noise' in memory tasks and/or onset cues in the SISI test, but the differences are not fully understood thus far. Fastl and Schorn (1981) reasoned that in loudness-memory tasks higher centers of the auditory pathway are involved than in loudness-modulation tasks. They advocated the use of the loudness-memory paradigm because of its small frequency and level dependencies. At 30 dB SL subjects with retrocochlear disorders showed clearly larger difference limens than all other hearing-impaired subjects.

In summary, subjects with cochlear disorders show an improved loudness-discrimination ability at equal SL values, and an almost normal one at equal SPL values. Subjects with retrocochlear disorders show larger loudness difference limens, most clearly demonstrated in loudness-memory tasks. Although there seems to be some general agreement between steep loudness function and small difference limens for intensity, there are several arguments against a direct relationship (e.g. Harris, 1963; Scharf, 1978a). Experimental evidence for the relationship with speech perception is scarce. Ross et al. (1965) failed to find significant correlations.

2.4 Frequency selectivity

As will be explained below, various psychoacoustic ways of measuring auditory frequency selectivity in hearing-impaired subjects have been applied. In the first place masking patterns of pure tones or small noise bands have been mapped, resulting in a so-called masked audiogram. For reasons of comparison with neurophysiological tuning curves the alternative approach of psychophysical tuning curves was also followed in many studies. Secondly, the critical bandwidth has been used as the major representative of frequency-resolving power. From the different measurements of critical bandwidth, especially critical-ratio and loudness-summation procedures have been applied. Auditory filter shapes were investigated by means of noise maskers with a spectral notch or comb-filtered noise maskers (noise with a sinusoidally rippled spectrum along a linear frequency scale). Finally, frequency discrimination ability has been studied.

2.4.1 Masked audiograms and psychophysical tuning curves -

The earliest method for quantifying frequency selectivity was by the measurement of masked audiograms. As early as 1924 Wegel and Lane (1924) showed, for normal-hearing subjects, masked thresholds for a tone of adjustable frequency in the presence of a fixed-frequency pure-tone masker. The curves obtained appear to be influenced by the perception of beats when signal and masker frequencies are close to each other. Therefore, bands of noise have been preferred both as signal and as masker.

For hearing-impaired subjects masking pattterns have been described by Jerger, Tillman, and Peterson (1960), Rittmanic (1962), Martin and Pickett (1970), Leshowitz and Lindstrom (1979), Florentine et al. (1980), Chung (1981a), and Tyler, Wood, and Fernandes (1982). Most studies showed excessive upward and downward spread of masking, but Martin and Pickett (1970) pointed out that conclusions about a deteriorated frequency selectivity may be erroneous, because of confounding effects of presentation level and hearing threshold in quiet. They observed large inter-individual differences not strongly related to the degree and configuration of the hearing loss. Florentine et al. (1980) measured masking patterns for narrow-band noises at 500 and 4000 Hz for different groups of hearing-impaired subjects. The sharpness of the masking patterns proved to be significantly reduced at 4000 Hz for the otosclerotic group with elevated bone-conduction thresholds, for the group with presbycusis, and for the group with noise-induced hearing losses. Chung (1981a) points out that the upward spread of masking in normal hearing may be underestimated due to combination tones, so that the effect of hearing impairment on upward spread of masking may not be as large as the comparison with normals would suggest: differences may also originate from reduced generation of combination tones. However, the increased downward spread of masking may, indeed, indicate a reduction in frequency selectivity.

Instead of "classical" masking patterns, psychophysical tuning curves (PTC) can also be measured: for a fixed-frequency probe signal the threshold of masking is determined for a masker of variable frequency. Zwicker and Schorn (1978) showed how sets of masking curves can be converted into psychophysical tuning curves (see also Verschuure, 1978). The measurement results in inverted filter shapes, which for low-intensity probe tones can be compared with neurophysiological tuning curves: at low probe-tone levels only a small number of fibers is excited. A second advantage is that the problems caused by combination tones are negligible if one uses low-intensity probe tones. However, two other problems, which limit equally the interpretability of masking patterns, remain:

1. PTC may be sharper than the actual filter due to off-frequency listening (Johnson-Davies and Patterson, 1979; Verschuure, 1978);

2. PTC measured in simultaneous masking may be broader than the actual filter due to suppression (Houtgast, 1974; Wightman, McGee, and Kramer, 1977).

Psychophysical tuning curves in simultaneous masking of hearing-impaired subjects have been described by several authors (e.g. Leshowitz and Lindstrom, 1977; Hoekstra and Ritsma, 1977; Zwicker and Schorn, 1978; Florentine et al., 1980; Tyler, Wood, and Fernandes (1982); Carney and Nelson, 1983). Generally, the following findings are characteristic:

1. in moderate sensorineural losses especially the sharp tip of the tuning curve is affected and even disappears for losses above 50 dB;

2. a shallower high-frequency slope of the PTC is observed in many hearing-impaired subjects, indicating an increased downward spread of masking;

3. severe sensorineural losses often result in very broad and irregular, sometimes even inverted or W-shaped, tuning curves.

In the studies by Zwicker and Schorn (1978) and Florentine et al. (1980), simplified tuning curves for clinical use were measured at 500 and 4000 Hz in several groups of hearing-impaired subjects. Conductive hearing loss does not influence these curves, whereas all sensorineural losses, and some otosclerotic hearing losses with elevated bone-conduction thresholds, were accompanied by reduced frequency resolution over the elevated-threshold range. Simultaneously as well as non-simultaneously measured PTCs are reported by Wightman, McGee, and Kramer (1977), and by Festen and Plomp (1983). For hearing-impaired subjects differences between these tuning curves proved to be considerably smaller than for normals. This may be due to loss of suppression in hearing impairment. Wightman et al. (1977) found support for this hypothesis by direct suppression measurements. Therefore, the most direct measure of frequency resolution seems to be the nonsimultaneous PTC. Nonsimultaneous PTCs for hearing-impaired subjects have also been measured by Nelson and Turner (1980) and McFadden and Pasanen (1980). As in the case of simultaneously masked PTCs, the tuning curves were broadened, and especially the high-frequency slope of the tuning curve proved to be shallower than in normal-hearing subjects.

Generally, the results obtained from masking patterns and PTCs are in agreement: hearing-impaired subjects show poor frequency selectivity coupled with a pronounced downward spread of masking. In a number of studies it has been pointed out that this deterioration of frequency resolution is not simply a reflection of the higher SPL values used (e.g. Wightman et al. 1977; Zwicker and Schorn, 1978; McFadden and Pasanen, 1980; Carney and Nelson, 1983; Festen and Plomp, 1983).

2.4.2 Critical-bandwidth measurements -

After the introduction of the critical-band concept by Fletcher (1940), several methods for measuring the critical bandwidth (CB) have been developed. In studies on hearing-impaired subjects, two-tone masking and loudness summation are most frequently used. In two-tone masking the threshold of a narrow-band noise, positioned between two simultaneous tones of equal sound-pressure level, is measured as a function of the frequency separation between the masking tones. Florentine et al. (1980) thus obtained increased CB estimates around 4000 Hz for sensorineural losses; the results at 500 Hz did not deviate significantly from normal values. They found corresponding results for the same subjects by means of a loudness-summation procedure in which the loudness of a narrow-band noise was matched with the loudness of a wide-band noise at various presentation levels. For comparison of groups they used the maximum loudness summation in order to bypass the substantial problems of presentation level (see also Bonding, 1979). The results of earlier studies (Scharf and Hellmann, 1966; Martin, 1974) may have been affected by level effects, as is shown by Humes (1983).

In general, the most important disadvantage of these CB measurements is that they do not provide information about the shape of the auditory filter. Therefore, de Boer and Bouwmeester (1974) used a modification of the two-tone masking experiment, in which the spectral gap between two bands of masking noise was explored with a probe tone of variable frequency. For sensorineural losses some subjects yielded quite normal masking patterns, others showed a dramatic loss of frequency resolution. Further experimentation revealed the spread of masking to be highly asymmetrical with excessive masking towards higher frequencies.

The results of Fletcher's original procedure for determining the critical band, viz. the masked threshold of a pure tone in a broadband-noise masker, have been defined afterwards as critical ratios (CR). A complete set of reference data for normal-hearing subjects was provided by Hawkins and Stevens (1950). Results for hearing-impaired subjects are described by Lightfoot, Carhart, and Gaeth (1956). They found a deviating behaviour relative to the curves predicted by Hawkins and Stevens, which was most pronounced for sensorineural losses. Especially the masking effect in the region of 2000 to 4000 Hz was above normal. Simon (1963) found increased critical ratios particularly at 4 kHz. Pick, Evans, and Wilson (1977) related CR values to critical bandwidths estimated from comb-filtered noise experiments (see below). They found a 6-dB increase in CR for each doubling of the bandwidth (an energy-detector model predicts 3 dB).

Owing to its convenience the CR measurement became popular in large relational studies (e.g. Tyler, Wood, and Fernandes, 1982; Lyregaard, 1982; Festen and Plomp, 1983). Most investigators found increased CR values in sensorineurally hearing-impaired subjects. The effect of presentation level has proved to be minimal (Scharf and Meiselman, 1977). A drawback is that the CR values also reflect changes in the detector mechanism. Margolis and Goldberg (1980) measured both CR and CB for a fixed frequency as a function of the cut-off frequency of a low-pass filtered noise masker. They found the shifts in CR and CB to vary indepently in subjects with presbycusis. This relative independence was recently confirmed by Patterson et al. (1982), who pointed out the extra role of detection efficiency in CR measurements.

Finally, an elegant method for the assesment of frequency resolution was provided by Houtgast (1977): by means of a comb-filtered noise masker with varying ripple density, information about both the critical bandwidth and the auditory filter shape can be gathered. For hearing-impaired subjects this method was used by Pick, Evans and Wilson (1977) in simultaneous masking, and by Festen and Plomp (1983) in both simultaneous and nonsimultaneous masking paradigms. The results of Pick, Evans and Wilson (1977) suggest that especially the slopes of the auditory filter are affected by hearing impairment. In the results of Festen and Plomp (1983) the reduced differences between simultaneous and nonsimultaneous bandwidths observed in tuning curves (see Section 3.3.1), are found again, suggesting reduced suppression. Pick (1977) also showed that the CB-estimates from comb-filtered noise measurements do not depend on presentation level.

2.4.3 Frequency discrimination -

A quite different aspect of frequency selectivity is frequency discrimination: the ability to detect small frequency differences. In listeners with cochlear impairment Gengel (1973) and Risberg (1978) found frequency-difference limens for pure tones to be considerably larger than normal, even when compared at equal sensation levels. The results of Hoekstra (1979), using 1/3-octave bandfiltered periodic-pulse trains and of Horst (1982) using signals with a triangular spectral envelope in background noise are in agreement with these findings. It should be noted, however, that the level of presentation is an important confounding variable.

2.4.4 Relations between measures of frequency selectivity -

From the foregoing it can be concluded that the results of frequency-selectivity measurements using different methods are in general agreement, although most of the measuring techniques are subject to confounding effects. A more detailed picture of the relationships may be obtained from studies in which two or more methods have been applied to the same subjects. Florentine et al. (1980) found significant correlations between four tests of frequency selectivity for 500 and 4000 Hz: narrow-band masking, PTC, two-tone masking, and loudness summation. Festen and Plomp (1983) showed a fair amount of coherence among the results of CR, PTC, and comb-filtered noise measurements at 1000 Hz. Pick, Evans, and Wilson (1977) found high correlations between CR and comb-filtered noise data for 500, 1000, and 2000 Hz and a moderate correlation for 4000 Hz. Tyler, Wood, and Fernandes (1982b) compared the results of CR, PTC and tone-on-tone masking at 500 and 4000 Hz and judged them to be in reasonable agreement.

The relation between frequency resolution and frequency discrimination is less clear. As Hoekstra and Ritsma (1977) pointed out, deterioration of frequency discrimination is always accompanied by broadening of tuning curves, but the reverse is not necessarily the case. This suggests that frequency discrimination is a more peripheral component of frequency selectivity.

2.4.5 Relation between frequency selectivity and threshold -

In a number of studies the relation between frequency selectivity and pure-tone thresholds has been considered. Most studies found a high correlation between threshold and frequency-selectivity measures (e.g. Pick, Evans, and Wilson, 1977; Florentine et al., 1980; Lyregaard, 1982; Tyler, Wood, and Fernandes, 1982b; Patterson et al., 1982). Wightman, McGee, and Kramer (1977) found broadened tuning curves even in regions of normal sensitivity. McFadden and Pasanen (1980) described temporarily broadened tuning curves following noise exposure without accompanying loss in sensitivity. Tyler et al. (1983) recently provided preliminary evidence of a dissociation between broad PTCs and elevated thresholds in some hearing-impaired subjects. The results of Festen and Plomp (1983) for a rather homogeneous group of hearing-impaired subjects show that the frequency-resolution parameters derived from PTCs and comb-filtered noise experiments are only moderately related to the audiometric loss. Pick and Evans (1983) found impaired frequency resolution at 4 kHz in a random sample of subjects with difficulties in understanding speech, but with normal audiograms. In conclusion, for heterogeneous groups frequency selectivity is related to pure-tone threshold, but these two properties seem to be rather independent, whereas there exists considerable inter-individual spread.

2.4.6 Relation between frequency selectivity and speech perception -

Although there is overwhelming evidence of poor frequency selectivity in sensorineurally impaired subjects, the number of studies with experimental evidence on the relation between poor frequency selectivity and speech perception is considerably smaller. In many studies only a possible relationship is speculated upon (e.g. Evans, 1978, Scharf, 1978b).

Experimental evidence can be gathered from correlations between frequency-selectivity and speech-perception parameters. Leshowitz and Lindstrom (1979) derived a parameter predicting reasonably well the speech-reception threshold in noise from the masked audiogram with a 1000-Hz pure-tone masker. Ritsma, Wit, and van der Lans (1980) concluded that broadened PTCs may influence the maximum word discrimination score, but if so, it is not the only decisive factor. Horst (1982) found a significant correlation between the sharpness of simultaneous PTCs at 2000 Hz and speech-reception thresholds in noise. These results are in agreement with the results of Bonding (1979), who concluded that PTC is a more valid measure of auditory frequency selectivity than the CB derived from loudness-summation procedures. Lyregaard (1982) found the best correlation between speech intelligibility in noise and the CR averaged over 500, 1000, 2000, and 4000 Hz, although his correlation coefficient is artificially high by the inclusion of normal-hearing subjects. Festen and Plomp (1983), using five different measures of frequency resolution for 1000 Hz, could conclude that particularly speech perception in noise is related to frequency resolution. With partly different tests, Tyler, Wood, and Fernandes (1982) came to the same conclusion. Finally, some frequency-discrimination results have also been found to correlate with speech perception parameters (e.g. Gengel, 1973; Risberg, 1978; Horst, 1982).

2.5 Temporal resolution

Temporal processing in hearing depends on several different properties of the ear. Temporal integration reflects the longest time needed to reach a certain sensation level (e.g. threshold or loudness). Temporal-masking patterns reflect the extension of masking in time. Finally, the ability to detect temporal changes in a signal is involved in gap-detection thresholds, modulation-detection thresholds, and the discrimination of differences in duration.

2.5.1 Temporal integration -

Temporal integration can be determined at the threshold in quiet and at suprathreshold levels. Suprathreshold temporal-integration power can be measured by techniques of masking, loudness balancing or stapedius-reflex threshold determination. At threshold sensorineurally hearing-impaired subjects show the ability to integrate signal energy over a period of time to be inversely correlated with hearing loss (e.g. Harris, Haines, and Myers, 1958; Elliott (1963); Wright, 1968; Young and Kanovsky, 1973; Elliott, 1975; Chung, 1981b; Tyler et al. 1982a). Gengel (1972) showed that this reduced integration power is not due to the higher presentation levels used with hearing-impaired subjects. Most studies agree that, as in normal hearing, temporal integration is smaller at higher frequencies. However, Chung (1981b) found that this frequency effect disappears for hearing losses above 40 dB. At suprathreshold levels most studies reveal a larger temporal integration than at threshold (Stelmachowicz and Seewald, 1977; Chung and Smith, 1980, Chung, 1981b). On the other hand, Hattler and Northern (1970) found no difference.

2.5.2 Temporal-masking patterns -

Temporal-masking patterns can be determined by measuring forward- and backward-masking slopes or masking patterns of intensity-modulated noise. Backward masking is thought to be the consequence of peripheral frequency selectivity, whereas forward masking is also the result of neural adaptation (Duifhuis, 1973).

For the same SPL values most subjects with sensorineural impairment yield shallower slopes in forward and backward masking than normal-hearing subjects do, although there are considerable inter-individual differences (Elliott, 1975; Danaher, Wilson, and Pickett, 1978; Nelson and Turner, 1980; Festen and Plomp, 1983). These effects can partly be explained by the lower sensation level of the masker for hearing-impaired subjects.

Zwicker and Schorn (1982) combined forward- and backward-masking measurements in the masking pattern of repeated noise bursts. In a simplified paradigm for clinical purposes they found clearly distinct results for different diagnostic groups: reduced temporal resolution at 4000 Hz for noise-induced and presbycusic hearing losses, and reduced resolution at all frequencies for retrocochlear hearing losses and losses due to Meniere's disease. Instead of Zwicker and Schorn's square-wave intensity-modulated masking noise, Festen and Plomp (1983) used sinusoidally intensity-modulated masking noise as a masker, and they measured peak-to-valley threshold differences for clicks as a function of modulation frequency. Hearing-impaired subjects showed poorer temporal resolution than normals when compared at equal SPL levels.

2.5.3 Detection of temporal changes -

Jesteadt et al. (1976) suggested that the ability to detect temporal changes is inversely related to temporal integration time. For eight out of ten hearing-impaired listeners the threshold of discrimination between two Huffman sequences (waveforms with identical energy spectra but different phase relations) was improved in combination with shortened temporal integration. This may reflect a single time constant in the auditory system, decreased by hearing losses. Others measured temporal resolution by determining the detection threshold of an interval or temporal gap in noise (e.g. Trinder, 1979; Irwin, Hinchcliff, and Kemp, 1981; Tyler et al., 1982a; Fitzgibbons and Wightman, 1982). Contrary to what could be expected from the results of Jesteadt et al. (1976) all these investigators found increased detection thresholds for sensorineurally hearing-impaired subjects, indicating poor temporal resolution, most pronounced in retrocochlear cases. This holds both for comparing the results at equal SPL values and at equal sensation levels (Irwin et al., 1981, Fitzgibbons and Wightman, 1982). Frequency-specific detection thresholds for gaps in narrow-band noise bursts showed a better temporal acuity at higher frequencies (Tyler et al., 1982a; Fitzgibbons and Wightman, 1982).

Experiments on the detection of differences in signal duration have also been performed (Ruhm et al., 1966; Tyler et al., 1982a). Higher temporal difference limens were observed in hearing-impaired subjects. Tyler et al. found marked differences in duration discrimination of pulses and of pauses.

2.5.4 Temporal resolution and speech perception -

Although the number of experimental studies on temporal resolution in impaired hearing is considerably smaller than on frequency selectivity, we may conclude that there is a marked deterioration in temporal processing. This may affect speech intelligibility in a comparable way as impaired frequency selectivity may do.

Some indications can be obtained from correlational studies. Temporal integration, especially at 4000 Hz, may be involved in the perception of speech in noise (Tyler et al., 1982a). Elliott (1975) reasoned that the detection of brief silent periods is an important factor in speech perception and, therefore, increased thresholds for gap detection may hamper speech intelligibility. Experimental evidence was provided by Trinder (1970) and Tyler et al. (1982a), who showed an inverse correlation between gap detection thresholds and maximum speech-perception parameters in quiet and in noise. They also showed the temporal difference limen to be important for speech intelligibility. The results of Festen and Plomp (1983) with intensity-modulated noise did not suggest this temporal parameter to be critical in speech perception. The role of forward and backward masking was inconclusive from their data.

2.6 Phoneme perception

Overall speech-intelligibility scores and speech-reception thresholds may be too rough measures for studying the relation between tone perception and speech perception; the same score or threshold may be the result of different perceptual strategies (e.g. Bilger and Wang, 1976). Investigation of phoneme-perception characteristics is an adequate method to reveal these effects.

Phoneme perception can be investigated in two ways:

1. by means of artificial signals, especially designed to carry some specific speech properties;

2. by analysis of the perception of consonants and vowels in natural speech.

In both cases one should distinguish between discrimination and identification.

2.6.1 Perception of artificial speech-like stimuli -

In some studies the masking effects in speech-like stimuli have been investigated in order to show the effects of impaired frequency selectivity on speech perception. Danaher and Pickett (1975) showed that the presence of a first formant in the signal could disrupt the discrimination of second-formant transitions, probably due to upward spread of masking. By separating flat and sloping audiograms, they could conclude that the discrimination of second-formant transitions is not determined by the slope of the audiogram, although there is substantial inter-individual spread. Van de Grift Turek et al. (1980) confirmed the role of upward spread of masking in some hearing-impaired subjects; they found that the identification scores of synthetic /bdg/ stimuli were considerably improved by presenting the formants at different ears.

The suggestion that reduced frequency discrimination might affect speech intelligibility is supported by the results of Pickett and Martony (1970), who found that severely hearing-impaired subjects show, even at equal sensation levels, increased thresholds for the discrimination of differences in formant frequency at 400 and 825 Hz.

The influence of temporal resolution on phoneme perception was studied by Danaher, Wilson and Pickett (1978). They measured the backward and forward masking of a first-formant stimulus on second-formant sweeps. Although in normal listeners only backward masking could be demonstrated, their sensorineurally impaired subjects showed about as much forward as backward masking. Revoille, Holden, and Pickett (1979) found that the forward-masking effect of a vowel-like stimulus upon consonant-like noise bursts in hearing-impaired subjects is considerably larger for detection than for discrimination of the noise bursts. They concluded that, in terms of speech perception, this finding implies that plosive stop consonants may be specially impaired by preceding vowels. They also observed a reduced discrimination ability for formant-transition durations.

Many studies are focussed on the perception of differences in voice-onset time, which is assumed to be crucial for the perception of voicing. By means of stimulus sets which cover a large range of voice-onset times (for example /ba/-/da/ or /ta/-/da/ continua) both discrimination and identification could be investigated. Tyler et al. (1982a) found, for hearing-impaired listeners, a significant reduction in the ability to discriminate differences in voice-onset time of artificial CV-syllables; this can explain voicing confusions in difficult listening conditions. A clear illustration of the extra abilities involved in identification tasks, compared with discrimination tasks, is provided by Parady, Dorman, and Whaley (1981). They reported on a number of severely hearing-impaired children with almost normal discrimination, but with great difficulties in the identification of voice-onset-time differences in a /ta/-/da/ continuum. Although this may seem a central phenomenon, we should not exclude a peripheral component.

In other studies modified natural-speech segments were used. Ginzel et al. (1982) found that presbycusic subjects were extremely sensitive to shortening the initial, high-frequency fricative segment in CVCV-words. This may reflect deteriorations in high-frequency temporal resolution, but unfortunately age is a confounding factor. Revoille et al. (1982) investigated the importance of different cues for the perception of voicing in final stop consonants by normal-hearing and hearing-impaired subjects. Manipulation of such cues as duration of the preceding vowel and voicing murmurs proved to impair the perception of voiced stops for many of the hearing-impaired listeners. With all listeners the use of information from vowel-consonant transitions proved to be important for final-stop voicing perception. No relations with the audiogram and the most-comfortable loudness level could be found.

In summary, the research described in this section provides useful indications of relations between impaired speech intelligibility and basic auditory properties such as frequency resolution, frequency discrimination, and temporal resolution. On the other hand, most results are based upon discrimination or detection rather than on identification. This forms a restriction for possible extrapolations to speech intelligibility in daily life.

2.6.2 Perception of vowels and consonants -

A more direct approach to phoneme perception makes use of the elements of natural speech themselves. In this case, too, the difference between identification and discrimination is encountered in the two possible ways of investigation:

1. determination of confusions in the perception of phonemes;

2. determination of subjective similarities or dissimilarities between various speech segments.

In studying phoneme perception we need parameters characterizing the differences between phonemes. In spite of the difficulty that some phoneme properties are context-dependent, many features have been derived from articulatory (Wang and Bilger, 1973) and acoustical theories (Soli and Arabie, 1979). By means of perceptual experiments the relevance of these features in phoneme perception can be established. However, these features, adopted from speech production, are based on a-priori assumptions about the way in which listeners perceive phonemes. For the interpretation of the perceptual data a-priori feature systems may not be the most adequate ones. The introduction of new techniques such as multidimensional-scaling analysis and clustering analysis makes it possible to arrive at such a system on the basis of perceptual data.

Because consonant perception must be severely affected before vowel perception deteriorates, studies on vowel perception prove to be under-represented in recent literature. In their review, Franks and Daniloff (1973) concluded that hearing-impaired subjects seem to use the same features as normal-hearing subjects.

After Miller and Nicely's (1955) analysis of perceptual confusions among initial consonants for normal-hearing subjects, the interest in this kind of analysis as a qualitative approach to speech perception has grown considerably. The confusion of consonants has also been studied for hearing-impaired subjects (Reed, 1975; Bilger and Wang, 1976; Mueller, 1979 a,b; Gutnick, 1982). The results of Bilger and Wang (1976) yielded a clear grouping of individuals into three groups in accordance with the degree and configuration of the hearing loss for tones: mild flat losses, severe flat losses, and high-frequency losses. For subjects with severe flat losses the feature nasality is not well identified, for subjects with high-frequency losses the feature sibilance is not. Gutnick (1982), too, found low-frequency features like voicing and sonorance to be very important for subjects with high-frequency losses, and not high-frequency features like frication and sibilance.

The method of (dis)similarity judgements was used by Walden and Montgomery (1975), Danhauer and Singh (1975), and Danhauer and Lawarre (1979). The same features as in the confusion experiments proved to be important. However, the relation with the audiogram could be demonstrated only in the data of Walden and Montgomery (1975). The question of whether confusion and similarity tasks reveal the same perceptual properties may be answered from the results of Walden et al. (1980), who used both methods. Their conclusion was that "those consonants which are most confused are not necessarily the most conceptually similar to the listener".

A final note concerns the lack of knowledge with respect to the effects of presentation level and the presence of noise at different signal-to-noise ratios on the confusion matrices for hearing-impaired subjects. In our opinion knowledge of these effects is a prerequisite for interpretation of the results. Moreover, the relations with basic auditory properties are only known for the pure-tone audiogram.

2.7 Complex relational studies

There are a few studies devoted to complex relationships which go beyond the scope of the separate sections given above. In these studies test batteries have been used with tests on diverging auditory properties.

Ross et al. (1965) presented hearing-impaired subjects with a battery of tests including pure-tone thresholds, speech-reception thresholds, speech-discrimination scores in quiet and in noise, difference limens for frequency and intensity, and beat-detection thresholds (aural overload test). Difference limens for frequency and intensity tended to be uncorrelated. Only a high difference limen for frequency at 2000 Hz seemed to impair speech-discrimination scores in quiet. The other significant correlations with speech intelligibility concerned audiometric thresholds and parameters related to the slope of the audiogram. From the results they concluded that the effect of their tone-perception parameters upon speech intelligibility had not been proved except for the mean and the slope of the audiogram. However, they advocated further research on this topic by means of tests on other suprathreshold phenomena.

Recently, Tyler et al. (1982 a,b) performed two complex relational studies, with the tone-perception tests performed at 500 and 4000 Hz. One study (Tyler et al, 1982b) concentrated mainly on frequency resolution (reviewed in Section 2.4) and also included temporal integration for subjects with noise-induced hearing loss. Speech intelligibility in noise proved above all to be related to the frequency-resolution parameters at 4000 Hz. In the other study Tyler et al. (1982a) measured PTCs, four measures of temporal processing (reviewed in Section 2.5), perception of voice-onset time, and speech identification in noise in a more heterogeneous population. Speech intelligibility in noise was significantly correlated with PTC-parameters at 4000 Hz and with all temporal parameters. However, after partialing out the effects of absolute threshold, only the correlations with gap detection and temporal difference limen remained significant. Correlations with voice-onset-time parameters were low, although voicing errors were observed in the speech-in-noise task.

Festen and Plomp (1983) designed a battery of tone-perception experiments at 1000 Hz (see also Section 2.4 and Section 2.5) and additionally of speech-reception thresholds in quiet and noise. It appeared that speech-reception thresholds in noise are determined above all by frequency-resolution parameters, and speech-reception thresholds in quiet by audiometric loss and forward- and backward-masking slopes.

Finally, we will focus upon the relations between frequency resolution and temporal resolution. There are some indications of a relation between poor temporal integration and high CR values (e.g. Simon, 1963; Gengel, 1972; Chung, 1981b) or broad masking patterns (Tyler et al., 1982b). Nelson and Turner (1980) showed in a small, but interesting study the co-existence of broadened PTCs and shallower forward-masking slopes in hearing-impaired subjects. For a limited number of subjects they found a positive relation between the forward-masking time constants and the sharpness of the PTC at 1000 Hz. Festen and Plomp (1983) found similar relations between forward and backward-masking slopes on the one hand and CR values and nonsimultaneous CB estimates on the other. Tyler et al. (1982a) found positive correlations between PTC tuning and gap-detection ability both at 500 and 4000 Hz. So there are several indications of relations between frequency resolution and temporal resolution. However, the results contradict the reciprocal relation between frequency and temporal resolution predicted by simple linear-filter models. Moreover, the true correlations are often obscured by a dependence on audiometric thresholds.

CHAPTER 3

PRELIMINARY EXPERIMENTS

Summary

In this chapter results are presented of a pilot study with a heterogenenous group of ten hearing-impaired adolescents. The study focussed on the effects of pure-tone acuity and frequency-resolving power at 1000 Hz on speech intelligibility in quiet and in noise. As an intermediate stage between tone perception and speech perception the perception of isolated vowels was investigated. Speech-reception thresholds in quiet proved to be related to mean audiometric loss and to the critical band as measured with comb-filtered noise. Speech-reception thresholds in noise showed high correlations with the vowel-perception parameters, the frequency-resolution parameters (both critical bandwidth and critical ratio), and the audiogram parameters. However, because of strong correlations between these parameters themselves, it was not possible to separate the effects of audiogram and frequency resolution in this group.

3.1 Introduction

This preliminary study is focussed on the following aspects:

1. the relation between pure-tone audiogram and speech intelligibility, both in quiet and in noise;

2. the relation between critical bandwidth and speech intelligibility;

3. vowel discrimination studied with similarity judgements, and the relation with speech intelligibility.

Therefore the following tests were included in our investigation:

1. to establish an auditory baseline, the tone audiogram was measured from 250 to 4000 Hz, and at 1000 Hz the frequency resolving power of the ear was determined by measuring both the critical bandwidth (CB) with comb-filtered noise and the critical ratio (CR) with a tone in white noise;

2. as an intermediate stage on the continuum from pure-tone thresholds to speech intelligibility, vowel discrimination was studied using the method of triadic comparisons;

3. speech intelligibility was investigated by measuring the speech-reception threshold for sentences (SRT) in quiet and as a function of the interfering noise level.

To examine the results, data-reduction techniques were used to extract the most relevant parameters. By means of correlation analysis, all interactions were considered.

3.2 Subjects, procedures, and apparatus

All subjects, aged 13 to 18, were pupils of a high school for the hearing-impaired. The selection was based on the audiometric data available and the subjects' readiness to cooperate. We tried to compose a group with widely diverging audiograms. The audiometric data of the ten subjects participating in the experiments are summarized in Table 3.1. The subjects are labelled by the same letters in all tables and figures.

For each subject, the measurements were spread over six months in two to five sessions varying in duration from one to five hours. To assess the reliability of the data most tests were performed twice in different sessions. Total measuring time for all tests was about 5 hours, but after each 10-15 minutes of testing a break of equal duration was given, resulting in a total of 10 hours per subject.

To make interpretation of the vowel-perception data possible, the results of a group of normal-hearing subjects were required. For this reason five normal-hearing subjects, aged 18 to 30, judged the vowel dissimilarities. For reference purposes, their pure-tone audiograms were also measured.

Ss	Sex	Better ear	Conductive or sensorineural	Fletcher index (dB)	Audiogram shape	Maximum discimination (%)	Phonemic regression
A	f	l	c	15	flat	100	no
B	f	r	sn	60	sloping	70	yes
C	m	r	sn	45	flat	100	yes
D	f	l	mixed	45	sloping	80	yes
E	m	r	sn	55	sloping	80	yes
F	f	l	sn	55	sloping	80	no
G	m	l	mixed	35	flat	100	no
H	m	r	c	30	flat	100	no
I	m	l	mixed	40	dip 2 kHz	100	yes
J	f	r	sn	70	sloping	70	yes

TABLE 3.1. Summary of audiometric data available for the ten subjects. The Fletcher index is defined as the mean loss at 500, 1000, and 2000 Hz, the maximum discrimination score has been determined with monosyllables and phonemic regression is indicated if the discrimination score for higher intensities is more than 10% below the maximum discrimination score.

All tests were performed monaurally with headphones. The ear with the lower air-conduction thresholds was selected. The speech material was reproduced over Scintrex MK-IV headphones. Both experimenter and subject were seated in a sound-proof room. All other experiments were performed with Beyer DT-48 headphones and our so-called audioprocessor. This is a hybrid system consisting of audio circuits and a PDP-11/10 computer; the audioprocessor generated the stimuli, controlled their presentation, and processed the subject's responses.

3.3 Measurements and results

3.3.1 Pure-tone thresholds -

3.3.1.1 measurement technique -

For each subject, an accurate tone audiogram was measured by means of an adaptive two-alternative forced-choice (2AFC) procedure, starting at a suprathreshold level and converging by means of an up-down strategy (2 dB down after three correct responses and 2 dB up after one incorrect response) to the 79% detection level (Levitt, 1971). With this method first a rough estimate of the threshold was obtained, after which the average level of 20 subsequent presentations was taken to be the threshold value. The timing diagram of a single presentation is given in Fig. 3.1(a). As the auditory thresholds may alter over a period of time, the threshold measurements were repeated periodically. As a measure of accuracy for each subject, the pooled intra-individual standard deviation was calculated from the standard deviations of the repeated measurements at different frequencies. In further analysis, the mean values of all replications were used.

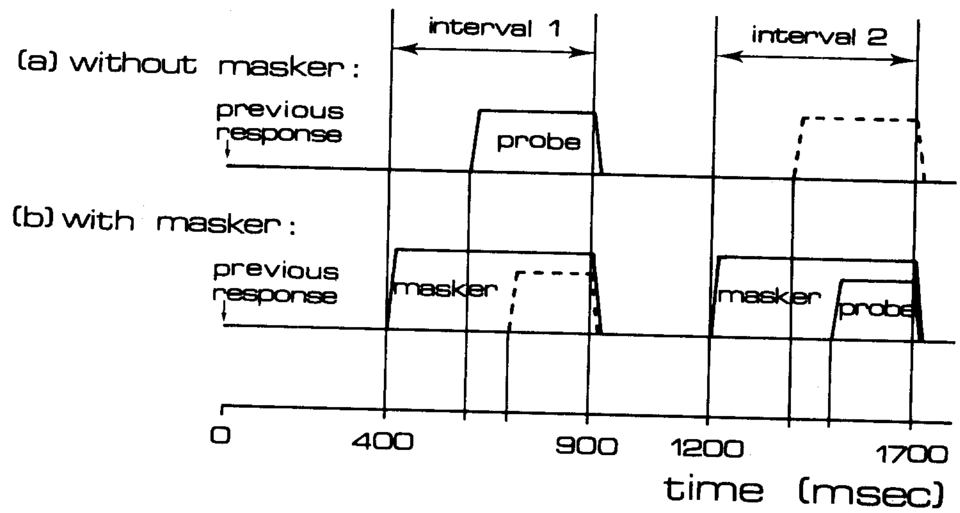


FIG. 3.1. Timing diagram of the measurement of detection thresholds by means of a 2AFC-procedure. The auditory signals were gated with a cosine-squared envelope, 16 ms in duration. Intervals were indicated by means of light signals.

3.3.1.2 results -

The mean losses (relative to ISO-389) for the hearing-impaired subjects are presented in Table 3.2(a). The inter-individual spread is considerable at all frequencies, but largest at high frequencies. Subject A seems to have an almost normal audiogram. In Table 3.2(b), the hearing losses of the normal-hearing subjects are reproduced in a similar way. The last column of Table 3.2 shows the intra-individual standard deviations, pooled over the frequencies measured. For the normal-hearing subjects, a comparable value was adopted from experiments by Festen and Plomp (1981), who used the same measuring procedure for threshold measurements at 1000 Hz.

Ss	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	St.dev.
			(a). hearing-impaired subjects			
A	9.4	16.4	11.7	-2.8	11.1	0.6
B	-0.2	51.5	75.5	85.3	99.1	4.4
C	39.0	29.3	33.0	49.0	61.9	8.9
D	5.9	17.5	57.4	66.0	77.8	5.3
E	-3.8	6.8	49.8	80.9	34.5	3.0
F	11.5	31.0	54.9	67.2	62.2	3.7
G	14.6	31.2	39.0	43.2	50.3	4.8
H	23.5	24.4	37.0	23.5	22.5	4.9
I	19.1	35.0	27.9	53.4	25.2	3.6
J	-0.2	45.6	67.5	87.1	84.9	4.4
			(b). normal-hearing subjects			
V	12.6	8.0	2.8	2.8	4.3	
W	-8.7	-7.1	-8.5	-7.2	5.8	
X	-3.1	-6.6	-0.3	-7.1	-7.4	2.8[a]
Y	-9.1	-1.7	-2.7	-3.3	1.6	
Z	-7.2	-0.5	-2.0	-8.9	17.5	

TABLE 3.2. Mean pure-tone losses and pooled intra-individual standard deviations in dB (a. indicates estimated value).

Obviously, not all hearing-impaired subjects remained constant in pure-tone acuity over the periods between the sessions. The high standard deviation for subject C is due to the last session, at which the auditory thresholds had improved considerably at all frequencies. In addition to the tone audiogram, only the retest of the vowel-perception experiment was performed during that session. Because this measurement took place at the most comfortable loudness level (see Section 3.3.3), the influence of threshold improvement may be expected to have been minimal for vowel perception itself. Pooling the intra-individual standard deviations over the 10 hearing-impaired subjects, the overall standard deviation amounts to 5.0 dB. In view of the large inter-individual differences, this level of accuracy is acceptable.

For reasons of data reduction and in order to visualize inter-individual differences, a principal-components analysis on the pure-tone thresholds was performed. The results of this analysis are listed in Table 3.3. In two dimensions, 93.5% of the total variance can be explained: 87.8% by the first dimension, on which the high-frequency losses yield high factor loadings, and 5.7% by the second dimension, on which the losses at 250 and 500 Hz load highly. Fig. 3.2 results from plotting all individuals in a two-dimensional space along the new dimensions.

For a better interpretation of these data points, lines have been drawn representing hypothetical cases in which either the mean loss at 500, 1000, and 2000 Hz or the slope of a rectilinear audiogram is varied. Because the grid obtained is approximately rectangular, descriptions in terms of mean audiometric loss and of mean audiometric slope will account for about the same percentage of the total variance. These parameters can be related moie easily to data from other studies. Therefore, the audiograms were fitted by straight lines and, the calculated values for mean audiometric loss (LM) and mean audiometric slope (LT) in the frequency region from 250 to 4000 Hz are used in further analysis.

	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	%
I	0.061	0.276	0.473	0.623	0.555	87.8
II	0.811	0.497	-0.063	-0.296	0.051	5.7

TABLE 3.3. Direction cosines for the computed main dimensions I and II relative to the original dimensions, and percentage of variance explained per dimension.

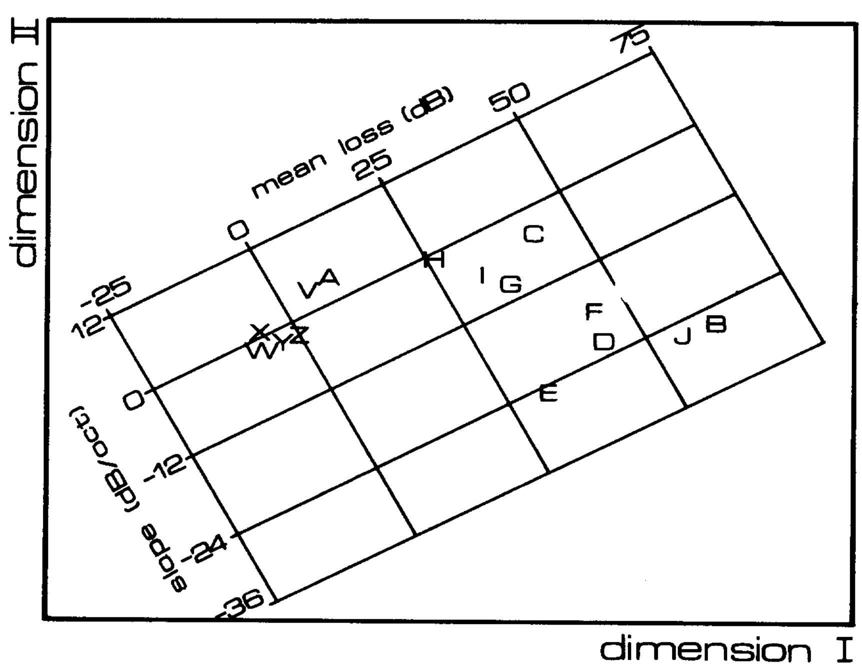


FIG. 3.2. Individual positions of the subjects in a two-dimensional space, based on a principal-components analysis of the audiograms. Dimensions I and II can be interpreted as the high-frequency loss and the low-frequency loss, respectively. The lines drawn represent hypothetical cases of rectilinear audiograms in which either the mean loss or the slope is varied.

3.3.2 Frequency resolution -

3.3.2.1 measurement technique -

The frequency-resolving power at 1000 Hz was measured in two ways:

1. an indirect measure for the critical band is obtained from the masked threshold of a pure tone in white noise relative to masker level, i.e., the critical ratio (CR);

2. a direct estimate for the critical bandwidth (CB) is derived from simultaneous-masking data with a comb-filtered noise masker.

The CR measurement was performed with a white-noise masker at different spectral densities: 35, 45, 55, and 65 dB/Hz, respectively. For subjects with a large hearing loss at 1000 Hz, this range was reduced to 50, 55, 60, and 65 dB/Hz (2 Ss) or to 55, 60, 65, and 70 dB/Hz (3 Ss). At each noise level, the threshold of a 1000-Hz tone was determined in test and in retest, using the simultaneous-masking procedure of Fig. 3.1(b), by means of the 2AFC strategy described earlier. The mean of the four measured signal-to-noise ratios (tone threshold in dB SPL minus noise spectral density in dB/Hz) was adopted as the critical ratio.

The CB measurement was performed with a comb-filtered noise masker (the spectral density of the noise had a sinusoidal shape along a linear frequency scale, relative to the mean spectral density) with a peak-to-valley ratio of 20 dB. In general, a tone with constant frequency will be masked more effectively when the masker has a peak at that frequency than when the frequency of a valley coincides with it. Because of the limited frequency-resolving power of the ear, this difference in masking effectiveness between peak and valley will diminish with smaller peak spacings. Peak-to-valley differences in masking effectiveness of comb-filtered noise maskers with peak spacings of 1000, 667, and 500 Hz were measured in simultaneous masking of a tone of 1000 Hz. A Gaussian-shaped filter with bandwidth as a free parameter was fitted to a model predicting the measured threshold differences as a function of peak spacing. The bandwidth may be assumed to be the critical bandwidth (Houtgast, 1977). One CB measurement thus required six threshold values. For both test and retest, each threshold measurement was performed twice. The measuring procedure for single threshold values was analogous to the method used in the CR measurement except that probe-tone level was fixed and masker level was varied according to the up-down strategy. With respect to probe-tone level, the subjects were divided into groups according to the a priori information about their hearing loss at 1000 Hz. The probe-tone levels were 60 (2 Ss), 80 (5 Ss), 90 (2 Ss), and 100 dB SPL (1 S). Relative to the 1000-Hz thresholds determined in this study, probe-tone level ranged from 12 to 45 dB SL. The critical bandwidth was calculated from the mean peak-to-valley differences of test and retest.

3.3.2.2 results -

Because theoretically a doubling of the critical bandwidth should be accompanied by a 3-dB increase in critical ratio, the mean values of the critical bandwidths are plotted logarithmically against the mean values of the critical ratio in Fig. 3.3. Thus plotted, the correlation coefficient between both measures of frequency resolution amounts to 0.77. Calculated regression lines are depicted too. For normal-hearing subjects the following values can be used: a CR at 1000 Hz of 18 dB (Hawkins and Stevens, 1950, 4 Ss), and a CB at 1000 Hz of 177 Hz with a standard deviation of 22 Hz, measured with a probe tone of 40 dB SPL and comb-filtered noise (Festen and Plomp, 1981, 50 Ss).

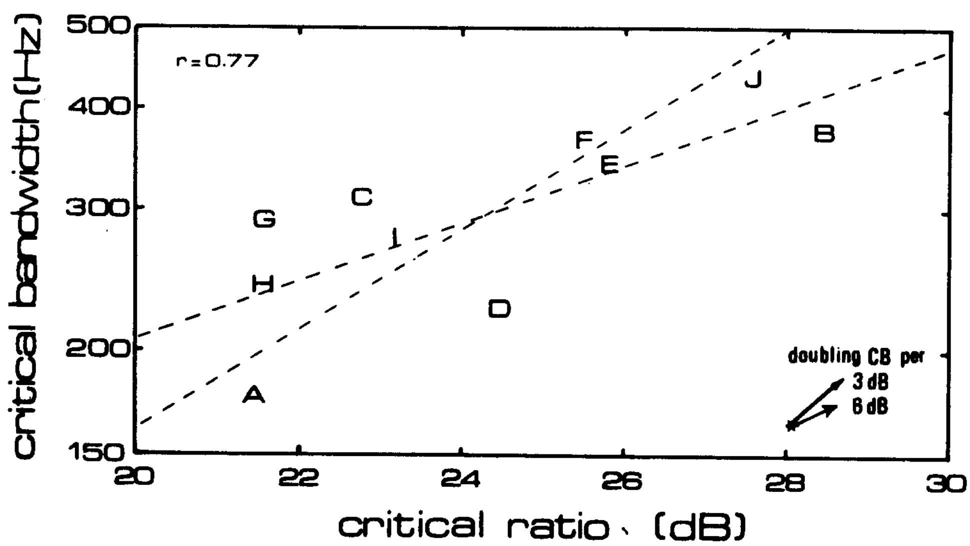


FIG. 3.3. The mean values of the critical bandwidth, logarithmically plotted versus the mean values of the critical ratio for ten hearing-impaired subjects. Calculated regression lines have been drawn in, and the directions of a doubling of the bandwidths for each 3 or 6 dB increase in CR are indicated.

The accuracy of the measurements of the frequency-resolving power is expressed in the pooled intra-individual standard deviation of a single threshold determination of a tone in noise, which is 2.3 dB in this study. In the CR measurement, no systematic effect of noise level was found. The test-retest correlation of the CR measure amounts to 0.93. In the CB measurement, the pooled intra-individual standard deviation of a peak-to-valley difference amounts to 2.7 dB. The test-retest correlation of the CB measure is 0.96.

3.3.3 Vowel perception -

3.3.3.1 measurement technique -

Vowel perception was investigated by means of the nonverbal technique of triadic comparisons. The subject had to decide for each triad of vowels which pair was most similar and which pair was most dissimilar. On the basis of the study of Pols, van der Kamp, and Plomp (1969), eight Dutch vowels listed in Table 3.4, and representing the most important differences between Dutch vowels, were chosen for this investigation.

	Dutch word	Vowel pronunciation	IPA symbol
1	hut	hurt	œ
2	hoet	foot	u
3	huut	minute (French)	y
4	hiet	free	i
5	haat	fast	a
6	hoot	note	o
7	het	hat	ɛ
8	heet	face	e

TABLE 3.4. List of words used for production of the vowels included in this experiment. Approximate British-English and French equivalents are given.

The signals were single periods of the relatively steady-state vowel portion of normally spoken words of the type h-(vowel)-t, repeated continuously by the computer. Fundamental frequency and duration were equalized to 125 Hz and 300 ms, respectively. Loudness was matched for each subject by the following procedure:

1. the subject adjusted the most comfortable loudness level for a signal consisting of all vowels in succession;

2. by adjustment the loudness of the second of each possible pair of vowels was matched to the adjusted most comfortable loudness level of the first of the pair: the order of pairs was randomized, the order within each pair was balanced with respect to the number of times each vowel was fixed or varied;

3. from the accumulated matching adjustments the best-fitting set of vowel levels was calculated for use in the triadic comparisons. All 56 triads were pre-

sented in a fixed randomized order with a break halfway.

Using simple marking (2 points for the most dissimilar pair, 0 points for the most similar pair and 1 point for the remaining pair), accumulation over all triads resulted in a matrix of dissimilarity rates. Loudness matching as well as triadic comparisons were performed twice, as test and retest, in different sessions. For reference purposes five normal-hearing subjects participated.

For each subject, the dissimilarity matrices of test and retest were added. The resulting set of dissimilarity matrices was analyzed by INDSCAL (Carroll and Chang, 1970). An assumption in INDSCAL analysis is that all subjects use the same fundamental dimensions in their judgements of the stimuli. The plot of all stimuli as a function of these dimensions is called the object space. However, the subjects may differ in the weight with which each dimension contributes to the final decision. The plot of these individual weightings for each dimension is called the subject space.

It is very difficult to develop an appropriate measure of accuracy for triadic judgements. Moreover, it is important to know how far the INDSCAL results are affected by lack of reliability. These effects can be estimated from the test-retest variability. By also performing separate INDSCAL analyses on the test and the retest set of vowel judgements, object-space loadings and subject-space weightings of test and retest can be compared.

3.3.3.2 results -

Since Pols et al. (1969) concluded that in vowel perception at least three perceptual dimensions are involved, three-dimensional INDSCAL analyses were performed. The analysis of the overall dissimilarity matrices of test and retest resulted in the object space presented in Fig. 3.4. A comparison with the well-known F1-F2 representation of vowel spectra indicated that the first two dimensions could be interpreted as the first and second formant positions (correlation coefficients between the factor loadings and the formant positions are 0.89 and 0.95, respectively). The third dimension could not be interpreted.

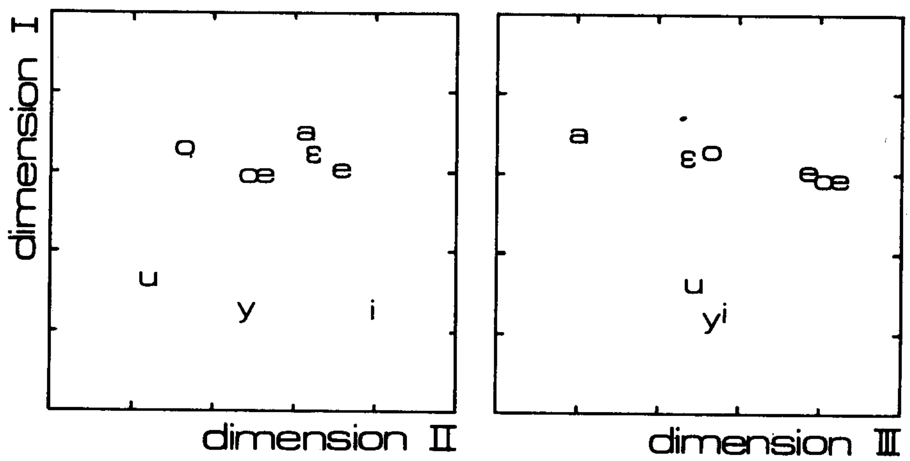


FIG. 3.4. Object space resulting from a three-dimensional INDSCAL analysis of the vowel-dissimilarity matrices.

The individual weightings of these dimensions are expressed in the subject space. Figure 3.5 shows the weighting for the first two dimensions. The weighting factors of the third dimension show that this perceptual dimension reflects the rather deviating behaviour of subject A. Therefore, the third dimension is left out of consideration in further analysis.

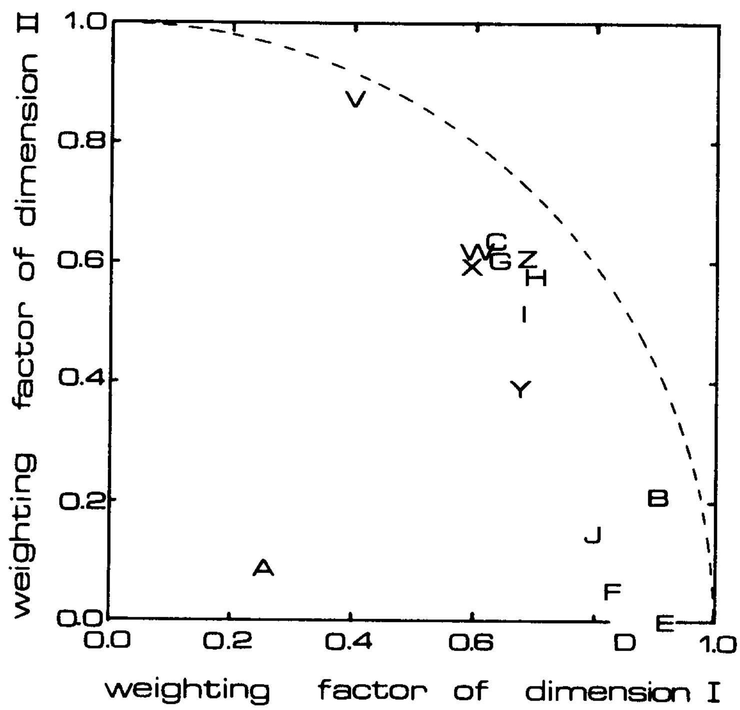


FIG. 3.5. Subject space for the first two dimensions of the three-dimensional INDSCAL analysis of vowel-dissimilarity matrices. The quarter of a circle represents the extreme case that all variance could be explained in these two dimensions.

The quarter of a circle represents the extreme position of the individual points, reached if all variance is explained by the first two dimensions. For all subjects, with the exception of subject A, this situation is reasonably well approached. The individual characteristics of vowel perception can thus be summarized by two parameters: the weighting of the first dimension, related to first-formant information (F1) and the weighting of the second dimension, related to second-formant information (F2) in comparing different vowels. The separate analyses of test and retest results yield highly similar object spaces (correlation coefficients along corresponding axes are 0.99, 0.99 and 0.93, respectively). With regard to the subject space, the test-retest correlations for the F1 and the F2 weightings for the group of hearing-impaired subjects are 0.78 and 0.82, respectively.

3.3.4 Speech-reception thresholds -

3.3.4.1 measurement technique -

Speech-intelligibility performance in quiet and in noise was investigated by means of the accurate test developed by Plomp and Mimpen (1979) for measuring the speech-reception threshold for sentences (SRT): with a list of only 13 short sentences and using a simple up-down strategy (2 dB down after a correct response and 2 dB up after an incorrect response) a threshold measurement can be performed with a standard deviation of approximately 1 dB in normal-hearing subjects. With ten lists of sentences, the SRT at each of five levels of interfering noise (including quiet) was measured twice within one session. A noise signal with the long-term average spectrum of the speech signal was used as the masker at the following levels: 28, 58, 73, 43 dB(A), and quiet, presented twice in this order. A curve was drawn to fit the five mean thresholds, following a model by Plomp (1978) and using the following monaural reference values for normal-hearing subjects: in quiet SRT equals 16.4 dB(A) and at high noise levels SRT is found at a constant signal-to-noise ratio of -5 dB. From the fitted curve two parameters emerged:

1. The D-parameter, representing the elevation of the signal-to-noise ratio for speech reception in noise relative to normal-hearing listeners. It can be interpreted as a distortion term;

2. The (A+D)-parameter, representing the threshold elevation for speech reception in quiet relative to normal-hearing listeners. It can be interpreted as resulting from attenuation (A) and distortion (D) together.

3.3.4.2 results -

The calculated values for (A+D) and D are plotted in Fig. 3.6. The pooled intra-individual standard deviation of single threshold values is 1.8 dB.

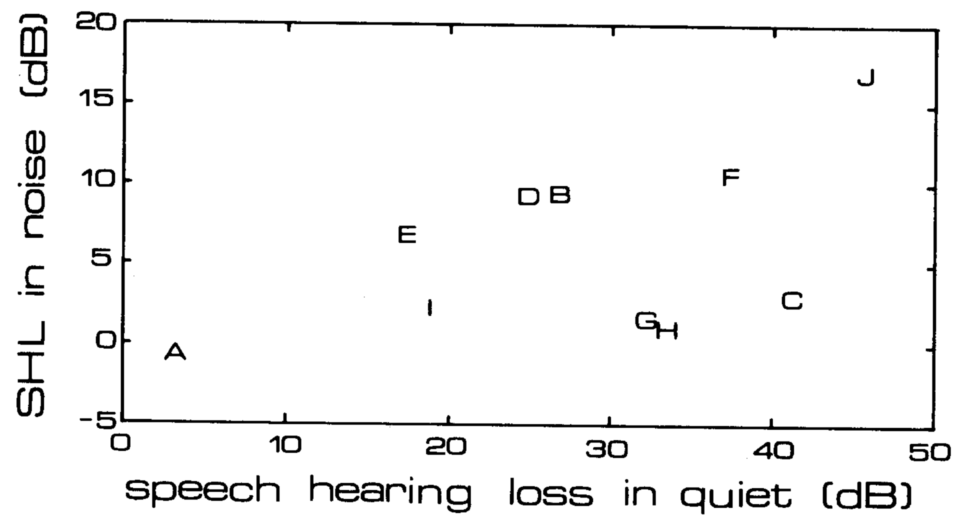


FIG. 3.6. The calculated values of speech hearing loss for sentences in noise (D), plotted versus the calculated values for speech hearing loss in quiet (A+D) according to the model by Plomp (1978).

3.3.5 Relations between test parameters -

We have seen that by using data-reduction techniques or modeling theories, all categories of measurement could be characterized by two parameters (Figs. 3.2, 3.3, 3.5, and 3.6, respectively). The relations between these parameters were analyzed in terms of correlation coefficients.

It is important to note that because of the nature of the INDSCAL analysis, the F1 weighting and the F2 weighting should be considered together. For instance, a positive correlation with F1 and a negative correlation with F2 together account for a so-called distortion in vowel perception.

In Table 3.5, the matrix of Spearman rank-correlation coefficients is given. The underlined values are highly significant ($p < 0.01$); the dashed lines indicate values which are moderately significant ($0.01 < p < 0.1$).

	LS	CR	CB	F1	F2	A+D	D
1a. mean audiometric loss (LM)	0.89	0.80	0.77	0.60	-0.16	0.55	0.90
b. mean audiometric slope (LS)		0.90	0.71	0.81	-0.37	0.26	0.87
2a. critical ratio (CR)			0.81	0.85	-0.42	0.22	0.90
b. critical bandwidth (CR)				0.50	0.02	0.56	0.79
3a. F1 weighting (F1)					-0.55	-0.03	0.69
b. F2 weighting (F2)						0.38	-0.43
4a. speech hearing loss in quiet (A+D)							0.48
b. speech hearing loss in noise (D)							

TABLE 3.5. Matrix of correlation coefficients for the 8 parameters extracted from the different types of measurement. The underlined values are significant at the 1% level, the dashed lines indicate the 10% level (n=10).

3.4 Discussion

From this study it can be concluded that, even with advanced and difficult tests, such as the CB measurement using comb-filtered noise and vowel dissimilarity judgements using triadic comparisons, reliable results can be obtained from a heterogeneous group of hearing-impaired subjects. Before discussing relations between test parameters, some aspects of the separate tests are reviewed first.

Whereas grouping and averaging of audiograms tends to obscure individual differences, a principal-components analysis of the audiograms proved to be a powerful tool of data reduction almost without loss of information about inter-individual differences. From the grid in Fig. 3.2, it can be seen that in this population descriptions in terms of mean audiometric loss and mean slope of the audiogram are equally successful. With respect to the accuracy of pure-tone thresholds, it may be necessary, when measuring more homogeneous groups, to avoid long periods between different sessions.

The accuracy of both measures of frequency-resolving power at 1000 Hz was promisingly high. At this frequency, both CR and CB had increased in most hearing-impaired subjects, as was also found by Pick et al. (1977). This corresponds to reduced frequency resolution as measured by other methods in hearing-impaired subjects. The CR measurement appeared to be level-independent at our testing levels. This is in agreement with a study by Scharf and Meiselman (1977), who reported that critical ratios are constant up to at least 80 dB SPL. Some CB measurements were performed at higher stimulus levels (subjects B, J, and F), but the correspondence with CR values did not suggest a broadening of the CB at these levels, as can be seen from Fig. 3.3. Furthermore, the increase in CR seems to be greater than 3 dB per doubling of the CB, approximately equal to the 6-dB increase for each doubling of the bandwidth Pick et al. (1977) found. In our opinion, there is a need for further investigation into the effect of sloping audiograms on the masking effectiveness of comb-filtered noise in peak as well as in valley conditions.

From the fact that INDSCAL analysis of vowel dissimilarity judgements yielded an object space with easily interpretable dimensions (Fig. 3.4), it can be concluded that hearing-impaired subjects use the same perceptual dimensions as normal-hearing subjects in vowel perception, namely the frequency positions of the first and second formants. Only the weighting of these two dimensions appeared to differ, as is reflected in Fig. 3.5. Similar conclusions were arrived at by Pickett et al. (1972), who concluded that the hearing-impaired use normal features in vowel perception but show better residual use of low-frequency information than of high-frequency information.

The SRT measurement with sentences proved to be a reliable test even in subjects with considerable losses. However, the standard deviation obtained from single thresholds was larger than that in normal-hearing subjects. This is partially due to a fundamental limitation of this test: for subjects with a maximum discrimination score below 100% it is very difficult to understand sentences entirely correctly. Splitting up the subjects into two groups according to the information of Table 3.1, the group with a maximum discrimination score below 100% yields a standard deviation of 2.2 dB, whereas the other group reaches a standard deviation of 1.3 dB. The remaining small difference from the standard deviation of 1 dB in normal-hearing subjects may be due to the small number of subjects in this study or due to the reduced verbal abilities of hearing-impaired subjects.

The mutual relations between the parameters in Table 3.5 show that the measures of the frequency-resolving power of the ear correlate highly with both audiogram parameters. Pick et al. (1977) also showed a relation between the mean loss at 500, 1000, and 2000 Hz on the one hand and both the CR and CB on the other.

The distortion of vowel perception - resulting in a high F1 weighting and a low F2 weighting - is clearly correlated with the audiogram parameters and with the CR measure. The influence of the audiogram on vowel perception can also be seen from Figs. 3.5 and 3.2: all subjects with a low F2 weighting have a sloping audiogram. However, because of the strong relationship between the audiogram and the frequency-resolving power, it is difficult to ascribe a deterioration in vowel perception to either the separate effect of the audiogram or the separate effect of reduced frequency selectivity.

Finally, the speech-perception parameters in quiet and noise show a striking difference in their dependence on the other audiometric parameters. Whereas SRT in quiet seems relatively independent of other data, SRT in noise is strongly correlated with the slope of the audiogram, with frequency selectivity, and with distortion in vowel perception. These correlates of the D parameter justify the term "distortion".

In this study, only a preliminary stage has been reached. But in our opinion encouraging results have been obtained. Further extensions along this line of investigation will be necessary to understand completely the relation between psychophysical data and speech perception. It will be important to investigate a greater number of subjects. In addition, it may be worthwhile to incorporate temporal properties of the auditory system in the experimental setup in order to relate them to dynamic properties of speech such as those involved in the perception of consonants.

CHAPTER 4

PHONEMIC CONFUSIONS IN QUIET AND NOISE

Summary

In this chapter the effects of presentation level and signal-to-noise ratio on phonemic confusions are studied for 25 hearing-impaired subjects. At three presentation levels in quiet and three signal-to-noise ratios in noise the confusions of initial consonants, vowels, and final consonants in the perception of nonsense CVC-words were determined. The group results of the different presentation conditions were analyzed by means of INDSCAL analyses. The presence or absence of interfering noise proved to be the most dominant factor: the presence of noise caused a reduced use of low-frequency information. The effects of presentation level are of secondary importance.

4.1 Introduction

There is only little knowledge about the effects of presentation level and the presence of noise at different signal-to-noise ratios on phonemic confusions for hearing-impaired subjects. In our opinion this knowledge is a prerequisite for the interpretation of phonemic confusion patterns. Therefore, it is necessary to study these effects separately before using confusion parameters in an analysis of individual data such as the one to presented in Chapter 5. In this chapter we will analyze for a group of 25 sensorineurally hearing-impaired adolescents the confusions of initial consonants, vowels, and final consonants, presented at three presentation levels in quiet and at three signal-to-noise ratios in noise. In order to avoid the use of a priori information in the interpretation of the results, we used an unbiased approach by means of multi-dimensional scaling (INDSCAL).

4.2 Procedure

4.2.1 Subjects -

Twenty-five pupils of a high school for the hearing-impaired, aged 13 to 20, participated in the experiments. All hearing losses were sensorineural (no air-bone gaps greater than 10 dB). The ear with the lower air-conduction thresholds was selected.

4.2.2 Speech material -

The confusion of initial consonants, vowels, and final consonants was studied by analysis of the responses to consonant-vowel-consonant (CVC) words. The speech material consisted of a tape with 18 lists of 50 nonsense CVC words, recorded from the same male speaker. In order to obtain connected discourse, each word was embedded in one of a set of five different carrier phrases. For the noise conditions, a continuous noise with the average spectrum of speech was used. The signals were presented over headphones (Beyer DT-48).

4.2.3 Method -

The CVC words were presented monaurally at three SPL-values around the 50% intelligibility threshold, both in quiet and in noise. In the noise conditions the SPL value of the noise was adjusted to the subject's most comfortable loudness level. All conditions were measured twice on separate days. During the first day the subject was trained in the perception of nonsense words by means of four training lists: three without and one with noise. The subject had to write down his responses and after training the responses were corrected by himself and discussed with the experimenter. With the other 14 lists, used for the actual measurements, the responses had to be typed by the listener on a screen terminal for computer processing. The responses to the first list were regarded as a training on the screen terminal: by means of this list only the most comfortable loudness level was determined. With half of the second list a rough estimate of the 50% intelligibility threshold (word score) in quiet was made, using a simple up-down strategy. With the other half the same was done in the presence of a background noise at the subject's most comfortable loudness level. With the next six lists confusion matrices were determined at the following speech levels: both in quiet and in noise at the estimated 50-% intelligibility threshold, and 5 dB above and below these thresholds. The quiet conditions will be indicated by Q1, Q2, and Q3 for increasing SPL values, the noise conditions by N1, N2, and N3. The order of conditions was randomized. During the second day confusion matrices were determined under the same conditions using the remaining six lists, again in a randomized order. So each subject produced 12 confusion matrices for each of the three stimulus categories: initial consonants, vowels, and final consonants. In further analysis. these confusion matrices were combined in different ways by adding corresponding matrix cells. The resulting asymmetric confusion matrices had to be converted into symmetric similarity matrices to enable analysis by INDSCAL (Carroll and Chang, 1970). This was accomplished by means of a procedure, suggested by Houtgast and used by Klein, Plomp and Pols (1970). In this procedure the cells of the similarity matrix, s(i,j), are calculated not only from the four confusion elements c(i,j), c(j,i), c(i,i) and c(j,j), but from the total correspondence between the response distributions for the stimuli i and j. In formula:

$$s(i,j)=s(j,i)= 0.5 * \left\{ \sum_{k=1}^{n} (c(i,k)+c(j,k)) - \sum_{k=1}^{n} \left| c(i,k)-c(j,k) \right| \right\},$$

in which the dissimilarity of the response distributions, $\Sigma|c(i,k)-c(j,k)|$, is subtracted from the total number of valid responses on the stimuli i and j, $\Sigma(c(i,k)+c(j,k))$. As an example, Table 4.1 shows the asymmetric confusion matrix and the symmetrized similarity matrix for initial consonants in one of the quiet conditions (Q3).

A. Confusion matrix

	p	t	k	b	d	f	s	g	v	z	h	w	j	l	r	m	n
p	.38	.20	.00	.06	.02	.00	.00	.02	.20	.02	.00	.06	.00	.00	.00	.00	.00
t	.04	.46	.08	.03	.21	.00	.00	.01	.04	.02	.00	.03	.00	.01	.01	.01	.00
k	.00	.09	.69	.00	.08	.00	.00	.02	.06	.01	.00	.01	.00	.00	.00	.00	.00
b	.02	.01	.01	.29	.22	.00	.01	.00	.06	.07	.00	.23	.00	.01	.01	.00	.01
d	.00	.03	.01	.06	.74	.00	.01	.00	.02	.04	.00	.04	.02	.00	.01	.00	.01
f	.02	.02	.00	.02	.02	.14	.00	.16	.46	.02	.00	.06	.00	.00	.00	.00	.00
s	.02	.06	.02	.01	.02	.00	.16	.04	.24	.36	.00	.03	.00	.00	.00	.00	.00
g	.00	.02	.00	.01	.01	.01	.00	.67	.12	.04	.07	.00	.00	.00	.01	.00	.00
v	.01	.00	.01	.01	.01	.04	.01	.10	.42	.11	.06	.15	.00	.01	.03	.01	.00
z	.00	.00	.00	.02	.08	.00	.06	.01	.03	.60	.01	.09	.03	.01	.01	.01	.00
h	.00	.00	.00	.01	.01	.00	.00	.00	.02	.00	.87	.01	.00	.01	.01	.01	.01
w	.00	.00	.00	.01	.03	.00	.00	.01	.03	.03	.00	.69	.03	.07	.00	.05	.02
j	.00	.00	.00	.02	.02	.00	.00	.00	.04	.02	.02	.10	.76	.00	.00	.00	.00
l	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.03	.01	.87	.00	.03	.02
r	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00	.91	.01	.00
m	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.02	.00	.03	.02	.55	.31
n	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.03	.00	.03	.01	.33	.55

B. Similarity matrix:

	p	t	k	b	d	f	s	g	v	z	h	w	j	l	r	m	n
p	–																
t	.39	–															
k	.22	.32	–														
b	.26	.38	.18	–													
d	.18	.36	.16	.42	–												
f	.38	.18	.14	.22	.14	–											
s	.38	.22	.20	.24	.16	.40	–										
g	.20	.12	.12	.14	.12	.36	.24	–									
v	.32	.14	.12	.32	.14	.64	.46	.34	–								
z	.16	.20	.14	.30	.24	.16	.52	.12	.28	–							
h	.04	.06	.04	.06	.06	.04	.04	.12	.12	.08	–						
w	.14	.14	.08	.34	.14	.14	.12	.08	.24	.24	.08	–					
j	.16	.12	.08	.20	.14	.16	.12	.10	.20	.22	.06	.20	–				
l	.02	.04	.00	.04	.04	.02	.02	.00	.06	.06	.06	.16	.06	–			
r	.04	.06	.04	.06	.06	.04	.04	.04	.10	.06	.06	.06	.04	.04	–		
m	.02	.04	.00	.04	.04	.02	.02	.00	.06	.04	.04	.12	.02	.10	.06	–	
n	.04	.06	.02	.06	.06	.04	.04	.02	.06	.06	.06	.14	.04	.10	.04	.70	–

TABLE 4.1. Example of the conversion from an asymmetric confusion matrix into a symmetrized similarity matrix. The matrices for initial consonants in the Q3-condition are presented. The number of presentations of each stimulus has been balanced phonetically. For this reason, response fractions are used instead of raw confusion scores. For example, for the calculation of s(p,t) = s(t,p) we need $\Sigma(c(i,k)+c(j,k))$, being 1.91, and $\Sigma|c(i,k)-c(j,k)|$, being 1.13, in order to find the value of s(p,t), being 0.39.

4.3 Results

The audiometric results from this experiment are summarized in Figure 4.1 by a plot of the mean audiometric slope from 250 to 4000 Hz versus the mean audiometric loss in the same frequency region. The mean losses range from 20 dB up to 68 dB. Both flat and sloping losses are present.

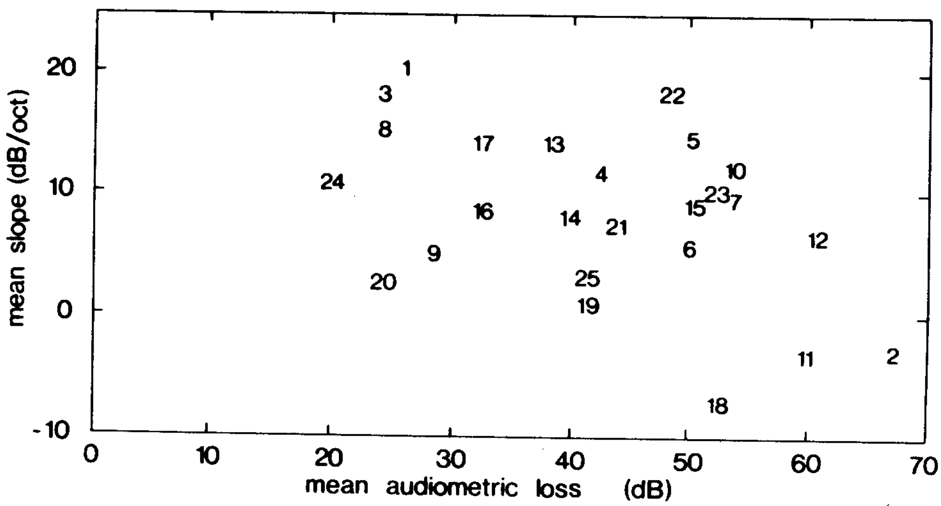


FIG. 4.1. Individual values of mean audiometric loss plotted versus the fitted values of mean audiometric slope (n=25). Each subject is represented by a number.

As described above, the results of an up-down strategy determined the presentation levels of speech and noise. In quiet the mean presentation level of Q2 was 45 dB(A), with an inter-individual standard deviation of 15 dB(A). The mean noise level, which was equal to the most comfortable loudness level, was 65 dB(A) with a standard deviation of 10 dB(A). The mean signal-to-noise ratio of N2 was +3 dB with a standard deviation of 3 dB.

The identification scores for the different conditions of presentation are presented in the last column of Table 4.2. The mean identification scores are 62% for the quiet conditions and 60% for the noise conditions. The mean slope of the performance-intensity function is shallower in quiet than in noise (2.0% per dB against 2.9% per dB, respectively). The mean identification scores per stimulus category are also presented in Table 4.2: the identification scores are highest for vowels and lowest for initial consonants, both in quiet and in noise.

Confusion matrices for corresponding conditions were added over test and retest for each subject and accumulated over all 25 subjects. The resulting six matrices (3 presentation levels, both in quiet and in noise) per stimulus category were converted into similarity matrices, in the way explained in Section 4.2.3., and subjected to INDSCAL analyses.

	Cvc	cVc	cvC	all phonemes
quiet	51%	77%	58%	62% { 51% (Q1) 63% (Q2) 71% (Q3)
noise	43%	76%	61%	60% { 44% (N1) 63% (N2) 73% (N3)

TABLE 4.2. Mean discrimination scores (phoneme score) for different stimulus categories separately and for all phonemes together. The influence of presentation level is also shown.

INDSCAL is a multidimensional scaling technique resulting in an object space and a subject space. In the object space the stimuli are plotted as a function of the fundamental dimensions used for their perception. However, the importance of these fundamental dimensions may differ from condition to condition; the weightings per condition are plotted in the subject space.

The similarity matrices of initial consonants were analyzed by means of a three-dimensional INDSCAL analysis. In Figure 4.2 the resulting object space (upper panels) and subject space (lower panels) are presented. In three dimensions 76% of the total variance could be explained. The first dimension of the object space explains 47% of the variance and differentiates between nasals, voiced and unvoiced consonants. The second dimension explains 15% and separates the stops /p/, /b/, /k/, /d/, and /t/ from the fricatives /s/, /f/, /χ/, /v/, and /z/. In the third dimension the extreme position of /s/ and /z/ points to the importance of sibilance. This dimension explains 14% of the variance.

In the subject space we can see the importance of these dimensions (from now on referred to as voicing/nasality, frication and sibilance) in the different conditions. In quiet, voicing and nasality are much more important characteristics for identification than frication and sibilance. Presentation level seems to play a minor role in quiet. In conditions with interfering noise, frication and sibilance are relatively important and the importance of voicing and nasality is smaller than in quiet. At higher signal-to-noise ratios the ratios between the weighting factors for voicing/nasality on the one hand and for frication and sibilance on the other show a clear shift towards the ratios in quiet. Obviously, at low signal-to-noise ratios especially the perception of voicing and nasality is impeded.

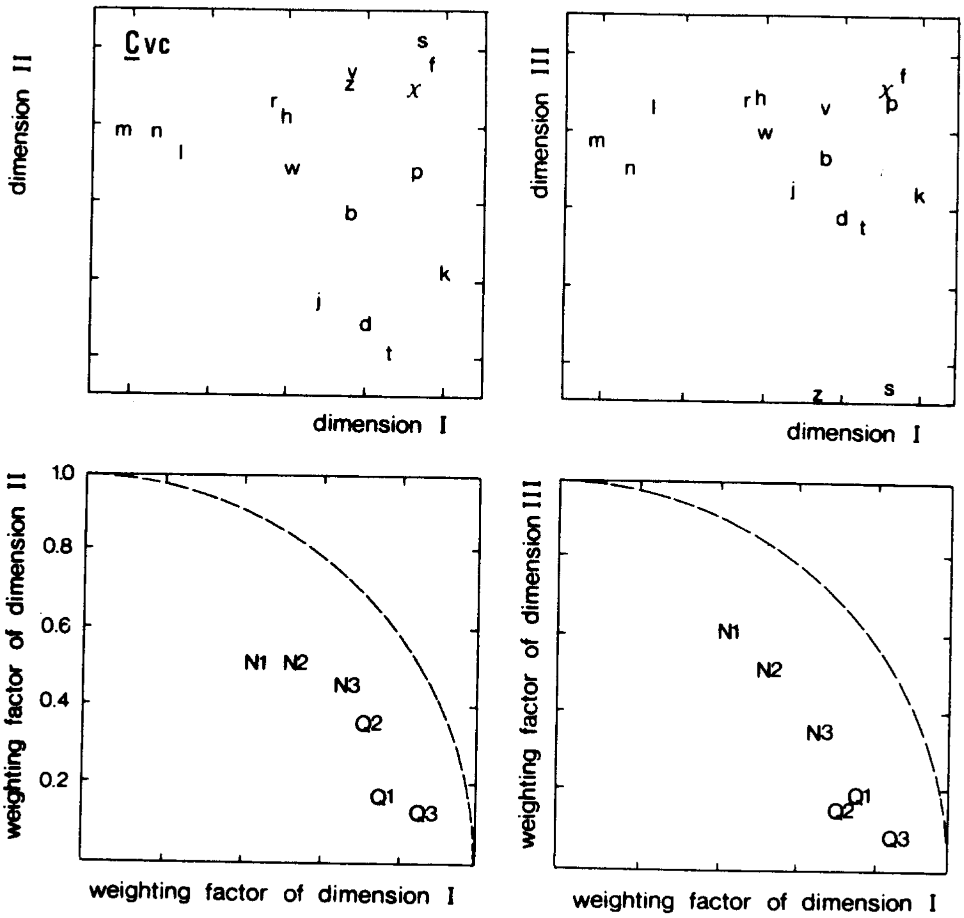


FIG. 4.2. Object space (upper panels) and subject space (lower panels) from a three-dimensional INDSCAL analysis of confusion matrices of initial consonants in quiet (Q1-3) and in noise (N1-3).

For the similarity matrices of vowels 84% of the total variance could be explained by a two-dimensional INDSCAL analysis. Figure 4.3 shows the resulting object space (upper panel) and subject space (lower panel). The first dimension explains 67% of the variance and is related to the position of the first formant (ignoring the diphtongs /ei/ and /ʌy/, r=0.97). The second dimension explains 17% of the variance and is related to the position of the second formant (r=0.84). In noise conditions we find a more important weighting factor for the second-formant position than in quiet. Thus, in noise second-formant information also becomes important for the identification of vowels. The effects of presentation level and signal-to-noise ratio are only small: at low presentation levels F2 information seems to be hardly of any importance.

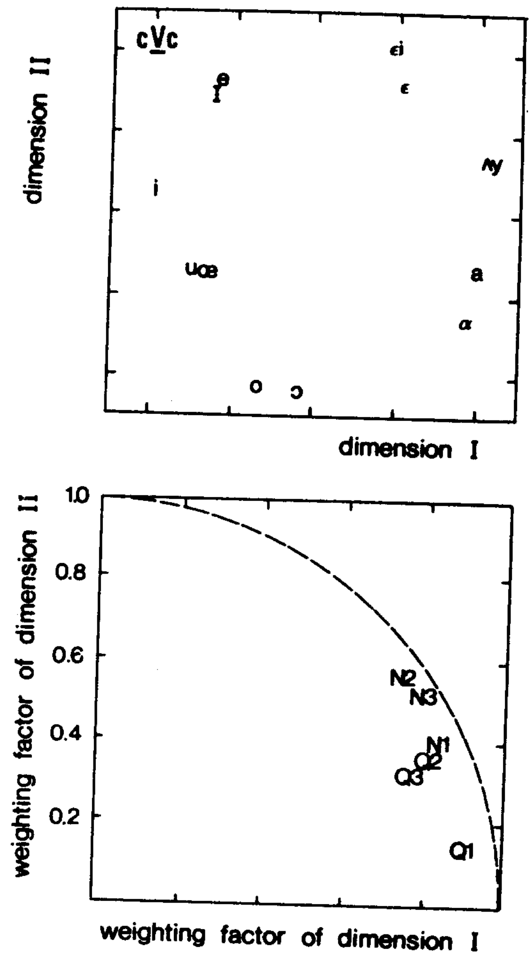


FIG. 4.3. Object space (upper panel) and subject space (lower panel) from a 2-dimensional INDSCAL analysis of vowel confusions in quiet (Q1-3) and in noise (N1-3).

For the similarity matrices of final consonants 87% of the total variance was explained by a two-dimensional INDSCAL analysis. Figure 4.4 shows the resulting object space (upper panel) and subject space (lower panel). The first dimension explains 56% of the variance and separates the voiced and unvoiced consonants. The second dimension explains 31% of the variance and seems to differentiate between nasals and non-nasals. In noise conditions the weighting of voicing is somewhat lower than in quiet. At higher signal-to-noise ratios the importance of nasality for the identification of final consonants increases.

The replicability of the results presented was tested by also performing analyses on the test and retest data separately. From these analyses the same trends emerged, showing that the results are not influeced by training effects or the set of word lists used.

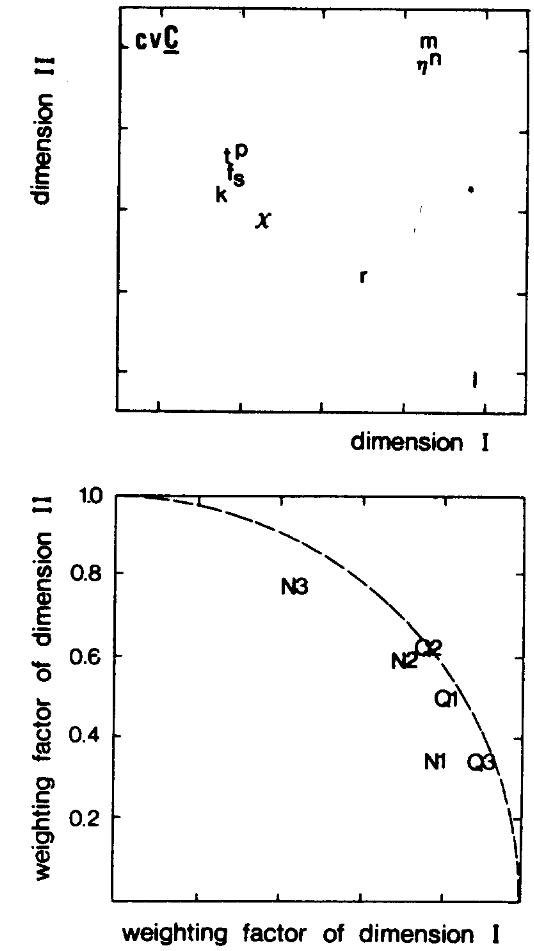


FIG.4.4. Object space (upper panel) and subject space (lower panel) from a 2-dimensional INDSCAL analysis of the confusions of final consonants in quiet (Q1-3) and noise (N1-3).

4.4 Discussion

The results show that the presence or absence of noise is the most important factor for the weighting of perceptual dimensions. The effects of presentation level and signal-to-noise ratio are of secondary importance. This is in agreement with the results for normal-hearing subjects (Dubno and Levitt, 1981).

In the perception of initial consonants the appearance of voicing and nasality is the most important cue for hearing-impaired subjects, even in the presence of interfering noise at unfavourable signal-to-noise ratios. This is also in agreement with the results for normal-hearing subjects (Wang and Bilger, 1973). However, the relative importance of the fundamental dimensions for different conditions changes in another way than in normal-hearing subjects. Soli and Arabie (1979) described an increasing voicing/nasality weighting (periodicity/burst in their terminology) and a decreasing sibilance weighting (spectral dispersion) with increasing noise level. Our results show the opposite effect as a result of addition of interfering noise and decrease of the signal-to-noise ratio. The decrease of the voicing/nasality weighting for the lower signal-to-noise ratios may indicate that the masking effect of the noise harms the low-frequency cues above all.

The perception of vowels in quiet appears to be determined by F1 information. It is possible that the information from the second formants is below threshold for the low presentation levels used in quiet. In noise, the presentation levels are higher and, although masking noise in present, F2 information becomes available.

The results for final consonants are the most difficult to explain. Unfortunately, the object-space dimensions are not clearly interpretable and they show no resemblance to those obtained with initial consonants. This may be due to the influence of coarticulation effects, which may determine the perception of especially the final consonants in CVC-words. As pointed out by Revoille et al. (1982), the perception of voicing in final stop consonants is greatly influenced by changes in the vowel-consonant transition.

In summary, for hearing-impaired subjects the addition of interfering noise impedes the use of low-frequency cues such as voicing and nasality, and stimulates the use of high-frequency cues such as sibilance and F2 position in phonemic identification. This may be the reason for the great importance of especially the high-frequency thresholds for speech perception in noise found by some authors (e.g. Leshowitz, 1977; Smoorenburg and de Laat, 1982). The reduced use of low-frequency cues in noise may be related to the masking effectiviness of the noise, which is dependent on the width of the critical bands. The increased use of high-frequency information in noise may be a compensation for the lack of low-frequency information. It may also be caused by the higher presentation levels in noise, in which a greater part of the speech spectrum is above threshold. Further investigation on individual confusions and related auditory parameters is necessary in order to reveal the underlying causes.

CHAPTER 5

RELATIONS BETWEEN PSYCHOPHYSICAL DATA AND SPEECH PERCEPTION

Summary

In this chapter the results for 21 sensorineurally hearing-impaired adolescents on an extensive battery of tone-perception, phoneme-perception, and speech-perception tests are presented. Tests on loudness perception, frequency selectivity, and temporal resolution at the test frequencies of 500, 1000, and 2000 Hz were included. The mean values and the trend across frequencies were also evaluated. Phoneme-perception data were gathered by means of (dis)similarity judgements and phonemic confusions. Speech-reception thresholds were determined in quiet and in noise for unfiltered speech material, and with additional low-pass and high-pass filtering in noise. The results show that hearing loss for speech is related to both the frequency resolving power and temporal properties of the ear. For the noise conditions the 2000-Hz parameters are the most important ones, whereas for the quiet conditions the lower frequencies are more important. Phoneme-perception parameters proved to be more related to the filtered-speech thresholds than to the thresholds for unfiltered speech. This finding may indicate that phoneme-perception parameters play only a role of secondary importance, and for that reason their bridging function between tone perception and speech perception is only limited.

5.1 Introduction

In the preliminary experiment (see Chapter 3) steady-state properties were investigated: the pure-tone audiogram, the frequency-resolving power of the ear, and the perception of isolated steady-state vowels. Especially the relations with speech perception in quiet and in noise were studied. The results were dominated by the audiometric parameters, probably because of the relatively high number of sloping audiograms in the group (Dreschler, 1980). The majority of tests was also included in a battery of tests applied to a second group of subjects for whom a better distribution of flat and sloping, and mild and severe sensorineural hearing losses was obtained.

A steady-state aspect not considered in the preliminary experiments concerns the property of loudness perception. In view of the possibilities for compensation by means of compression in hearing aids it is important to find out the relations between the dynamic range and the difference limens for intensity on the one hand and speech intelligibility on the other.

Additionally to steady-state aspects of speech perception, dynamic aspects should, in our opinion, also be taken into consideration. From the review of the literature on temporal resolution (Section 2.5) it can be concluded that there are only few experimental data on the negative effect of impaired temporal resolution on speech intelligibility. Gap detection as well as forward- and backward-masking experiments were included.

Relations between audiometric data and speech perception show that speech intelligibility in quiet is related to pure-tone thresholds at other frequencies than is intelligibility in noise. It is obvious that there may be a frequency dependence for the other tone-perception measures as well. For that reason all tone-perception experiments were performed at three center frequencies: 500, 1000, and 2000 Hz.

In summary, the following tone-perception parameters were measured:

1. pure-tone thresholds, measured at octaves from 250 to 4000 Hz;

2. uncomfortable loudness levels for pure tones at 500, 1000, and 2000 Hz;

3. just-noticeable differences for intensity at 500, 1000, and 2000 Hz;

4. masked thresholds for a tone in white noise (critical ratio) at 500, 1000, and 2000 Hz;

5. forward- and backward-masking thresholds for octave-filtered clicks around 500, 1000, and 2000 Hz at various temporal distances from a white-noise burst;

6. gap-detection thresholds for octave-filtered band-pass noise signals at 500, 1000, and 2000 Hz.

The white-noise maskers we used in the experiments 4 to 6, were presented at equal SPL values.

It is well-known that the major part of information in speech is carried by the consonants, although they represent only a small part of the speech energy. So results of steady-state vowel experiments may give only a limited explanation of impaired speech perception. The investigation of phoneme perception by hearing-impaired subjects should include measures of consonant perception. The results of Chapter 4 showed that the effects of noise on phoneme perception should be considered as well.

Therefore, the following phoneme-perception parameters were measured:

1. dissimilarity matrices of isolated steady-state vowel segments, determined by means of triadic comparions;

2. confusion matrices of vowels in a CVC-context, both in quiet and in noise;

3. confusion matrices of initial and final consonants for nonsense CVC-syllables in connected discourse, both in quiet and in noise;

4. phoneme-discrimination scores.

As has been said already, high-frequency thresholds for pure tones play an important role in the perception of speech in noise (e.g. Leshowitz, 1977; Smoorenburg and de Laat, 1982). However, this effect is not yet fully understood. It seemed to be of interest to relate also the intelligibility thresholds of low-pass and high-pass filtered speech in noise to the tone- and phoneme-perception parameters listed above.

Therefore, the following speech-perception parameters were measured:

1. speech-reception threshold for sentences in quiet and at two levels of interfering noise, using the test by Plomp and Mimpen (1979);

2. speech-reception thresholds for low-pass and high-pass filtered sentences in noise, using the same test procedure.

This extensive battery of tone-perception, phoneme-perception, and speech-perception tests was applied to 21 sensorineurally hearing-impaired adolescents. All tests were performed twice (test and retest) in separate sessions in order to obtain measures of reliability and precision for each parameter measured.

In further analysis the attention was focussed on the interactions between tests rather than on the results of individual tests. Correlations existing between test parameters are obscured by measurement error according to the equation

$$r_{\infty} = r_{xy} / (r_{xx} . r_{yy})^{0.5}$$

in which r_{∞} represents the true correlation coefficient between parameter X and parameter Y, r_{xy} the correlation coefficient obtained, and r_{xx} and r_{yy} the coefficients of reliability of the parameters X and Y, respectively. Parameters with a coefficient of reliability of less than 0.75 have been excluded from further analysis.

As in the preliminary experiments, data-reduction techiques were used to extract the most relevant parameters. The methods used in further analysis are essentially correlational in nature: correlation analysis, principal-components analysis, and multiple-regression analysis. Since tone-perception data were available for three frequencies, two different approaches were followed:

1. analysis with the tone-perception data at 500, 1000, and 2000 Hz;

2. analysis with tone-perception data compressed into two numbers: a 'mean' and a 'trend' parameter.

The first approach is important for determining the effect of specific frequencies, the latter for determining the overall effect and the effect of a trend across frequencies.

The interactions found should cast some light on the following questions:

1. in what way do possible deteriorations in auditory acuity, frequency-resolving power, loudness perception, and temporal resolution interact;

2. in what way are phoneme perception and speech perception of hearing-impaired subjects affected by interfering noise;

3. do deteriorations in speech intelligibility relate to tone-perception and phoneme-perception results?

5.2 Subjects

The subjects, aged 13 to 20, were pupils of a high school for the hearing impaired. On the basis of the audiometric data available, 25 subjects were selected to compose a heterogeneous group of sensorineurally hearing-impaired subjects. To obtain independent results, subjects who had participated in the preliminary experiments (Chapter 3) had to be excluded. The subjects are labeled by the same numbers in all tables and figures. The subjects were paid.

The measurements were performed in two parts during two summer holidays. The whole test battery was completed with 21 subjects: 4 subjects were not available for the second part and were excluded. Changes in auditory acuity over the period between the tests were minimal, as will be shown in Section 5.3.1. Total measuring time was about 15 hours, distributed over 4 days. Because of the breaks after each 15-20 minutes of testing, each subject spent about 30 hours on the experiment. As has been said earlier, test and retest data were collected on separate days.

All tests were performed monaurally with headphones. The ear with the lower air-conduction thresholds was selected. The apparatus used has been described in Section 3.2.

5.3 Measurements and results

5.3.1 Pure-tone threshold -

On each test day the tone audiogram was measured at standard octave frequencies from 250 to 4000 Hz according to the timing diagram of Fig. 5.1, by means of the adaptive 2AFC-procedure discussed earlier (Section 3.3.1). The results of the first two days were regarded as test and retest of the first experimental part, the results of the last two days as test and retest of the second part. The results of the first and second parts were highly correlated (correlation coefficients higher than 0.92 for all frequencies), with a mean absolute difference of 4.3 dB.

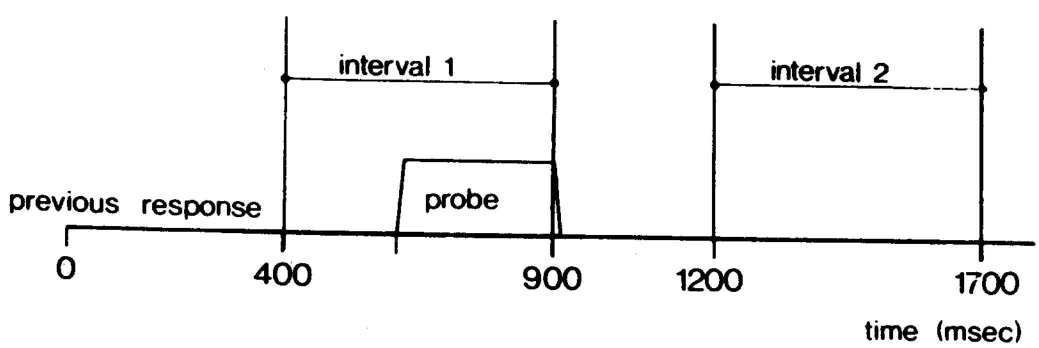


FIG. 5.1. Timing diagram for the measurement of pure-tone thresholds. The order of the two intervals was randomized.

From these data it may be concluded that the audiograms of the subjects were very similar during the two experimental parts. This allows us to combine the results of the two parts.

The sensorineural origin of the hearing loss was established by means of bone-conduction measurements: the mean air-bone gap at 500, 1000, and 2000 Hz was found to be smaller than 10 dB for each subject.

The audiometric results for 21 sensorineurally hearing-impaired subjects are presented in Table 5.1. If necessary, an abbreviation code is introduced. For each parameter the coefficient of reliability (r_{tt}) was estimated from the test-retest correlation coefficient (r_{tr}), applying the Spearman and Brown formula:

$$r_{tt} = 2\, r_{tr} / (1 + r_{tr})$$

(cf. Guilford, 1954; Nunnally, 1967). The standard deviation of the measurement was also computed from the differences between test and retest values, irrespective of the number of measurements underlying these values. So this standard deviation accounts for measurement error, day-to-day variability, and possible learning effects. The range of inter-subject variability is shown by the presentation of lower-quartile, median, and upper-quartile values. As mentioned in Section 5.1, the results for the individual frequencies as well as the trend across frequencies will be used in further analysis. For that reason the mean audiometric loss and the mean audiometric slope were also calculated and are presented in Table 5.1. The mean/trend parameters explain 92.6% of the total audiometric variance.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
audiometric loss							
250 Hz	-	0.97	3.80	6.6	18.4	31.7	dB
500 Hz	L½	0.99	3.25	21.1	29.3	46.0	dB
1000 Hz	L1	0.99	3.21	26.0	47.3	58.5	dB
2000 Hz	L2	0.99	2.83	45.8	53.8	71.4	dB
4000 Hz	-	0.96	4.01	49.8	59.5	68.0	dB
mean	LM	0.99	2.74	30.0	44.4	53.3	dB
trend	LT	1.00	0.93	4.5	11.7	16.3	dB/oct

TABLE 5.1. Results of pure-tone threshold measurements.

In Fig. 5.2 these audiometric parameters are plotted. The slope of an audiogram with a progressive loss towards higher frequencies is defined as positive. From Fig. 5.2 it can be seen that the group was rather heterogeneous with respect to both mean audiometric loss and mean audiometric slope. The group is dominated less by sloping audiograms than the group in the preliminary experiments (Fig. 3.2), and the mean audiometric loss and the mean audiometric slope seem to be uncorrelated.

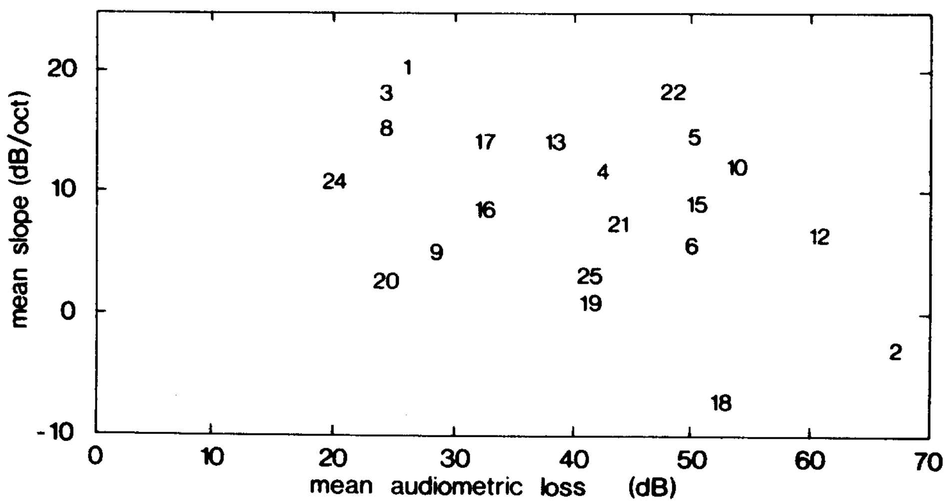


FIG. 5.2. Individual values of mean audiometric loss plotted versus the fitted values of mean audiometric slope.

5.3.2 Uncomfortable loudness level -

Uncomfortable loudness levels (UCL) were measured with pure tones at 500, 1000, and 2000 Hz, using the method of limits: the intensity of a continuous pure tone was increased by 0.5 dB each 100 ms until the subject judged it uncomfortably loud. Both in test and in retest the mean of 4 uncomfortable loudness level judgements was taken. The results are presented in Table 5.2(a).

Our prime interest concerns the dynamic range rather than the uncomfortable loudness level per se. These values represent the distance of the uncomfortable loudness level above hearing threshold. Their reliability, standard deviation, mean, and quartile values are presented in Table 5.2(b). Clearly the dynamic range is largest at low frequencies. The values of the dynamic range averaged over frequency and the trend of the dynamic range over frequency were calculated as well. These two parameters explain 92.3% of the total variance.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
a. UCL							
500 Hz	-	0.92	5.59	105.3	114.3	127.3	dB
1000 Hz	-	0.96	4.16	96.2	106.3	119.6	dB
2000 Hz	-	0.96	4.63	96.0	110.3	116.8	dB
mean	-	0.96	4.43	99.1	112.3	121.1	dB
trend	-	0.88	2.18	-5.9	-2.9	-1.2	dB/oct
b. dynamic range							
500 Hz	R½	0.96	5.73	56.1	62.1	75.1	dB
1000 Hz	R1	0.98	5.20	41.2	49.3	66.3	dB
2000 Hz	R2	0.94	5.63	31.9	45.8	56.8	dB
mean	RM	0.96	5.07	43.3	50.4	64.0	dB
trend	RT	0.97	2.09	-19.2	-12.7	-4.7	dB/oct

TABLE 5.2. Results of the UCL and dynamic-range measurements

5.3.3 Just-noticeable differences for intensity -

Just-noticeable differences (JND) for intensity were determined with pure tones at 500, 1000, and 2000 Hz. They were measured by means of the adaptive 2AFC-procedure, discussed earlier, according to the timing diagram of Fig. 5.3. The intensity of the fixed tone was chosen at the middle of the dynamic range (halfway between threshold and UCL value). Both in test and in retest each condition was measured twice.

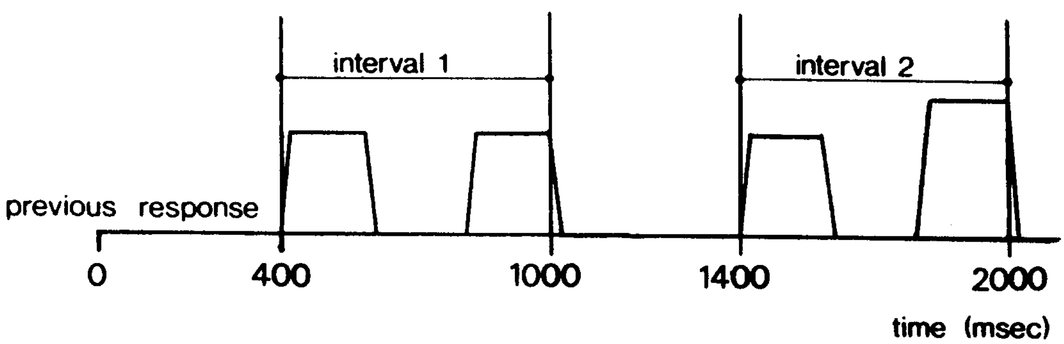


FIG. 5.3. Timing diagram for the measurement of JND's for intensity. The order of the two intervals was randomized.

The results are shown in Table 5.3. The mean and trend parameters explain 96.3% of the total variance.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
JND for intensity							
500 Hz	J½	0.92	0.36	1.2	1.5	2.0	dB
1000 Hz	J1	0.94	0.37	1.5	2.0	2.7	dB
2000 Hz	J2	0.90	0.58	1.5	2.0	2.8	dB
mean	JM	0.95	0.31	1.5	1.8	2.7	dB
trend	JT	0.76	0.32	-0.1	0.2	0.4	dB

TABLE 5.3. Results of the JND measurements.

5.3.4 Critical ratio -

As an indirect estimate of the frequency-resolving power of the ear the masked threshold of a pure tone in white noise relative to masker level, i.e. the critical ratio, was determined at 500, 1000, and 2000 Hz. The measurement was performed by means of the simultaneous-masking procedure shown in Fig. 5.4, using the up-down strategy described earlier. The spectral density of the noise masker was fixed at 60 dB/Hz, and the probe-tone level was varied. Both in test and in retest each condition was measured twice. In further analysis the mean values for test and retest are used.

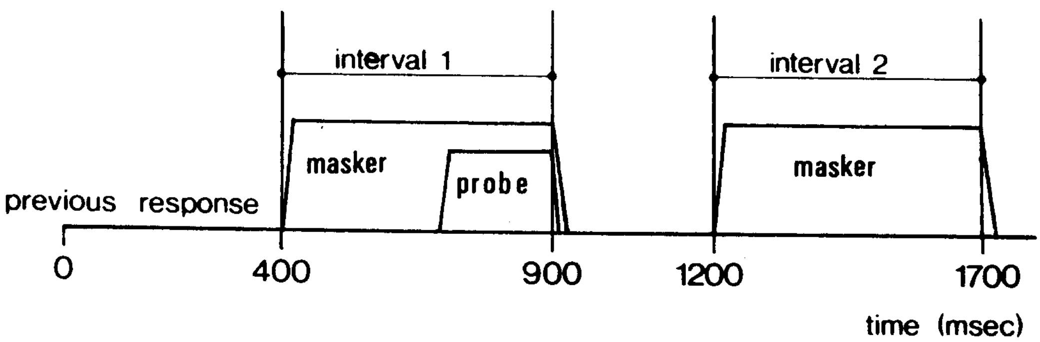


FIG. 5.4. Timing diagram for the measurement of critical ratios. The order of the two intervals was randomized.

The results of the critical-ratio measurement are presented in Table 5.4. The mean and trend parameters explain 92.4% of the total variance, although the results for subjects 11 and 18 are only poorly approximated by a straight line.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimen-sion
critical ratio							
500 Hz	C½	0.93	1.01	17.6	18.7	19.9	dB
1000 Hz	C1	0.87	1.46	20.8	21.6	23.3	dB
2000 Hz	C2	0.92	1.19	24.5	25.5	27.6	dB
mean	CM	0.96	0.66	20.9	21.9	23.8	dB
trend	CT	0.79	0.82	2.8	3.5	4.1	dB/oct

TABLE 5.4. Results of the critical-ratio measurement.

5.3.5 Forward and backward masking -

To characterize the temporal resolution of the ear, backward- and forward-masking thresholds were investigated. This was done by measuring the thresholds of a click, 0.4 ms in duration and octave-filtered around 500, 1000, and 2000 Hz, at various temporal distances from a 60 dB/Hz white-noise burst, 150 ms in duration. The forward-masking thresholds were measured with a click at 5 and 50 after the noise masker had been switched off abruptly, according to the timing diagram of Fig. 5.5(b). The backward-masking thresholds were measured with a click at 3 and 30 ms before the noise masker was switched on abruptly, see Fig. 5.5(a). In addition, the thresholds of the clicks without noise were determined in order to verify that the thresholds found in noise were at least 10 dB above the threshold in quiet. For ease of detectability the clicks were presented twice in each observation interval. These thresholds were determined by varying the level of the clicks by means of the up-down strategy discussed earlier. Both in test and retest each threshold was measured twice.

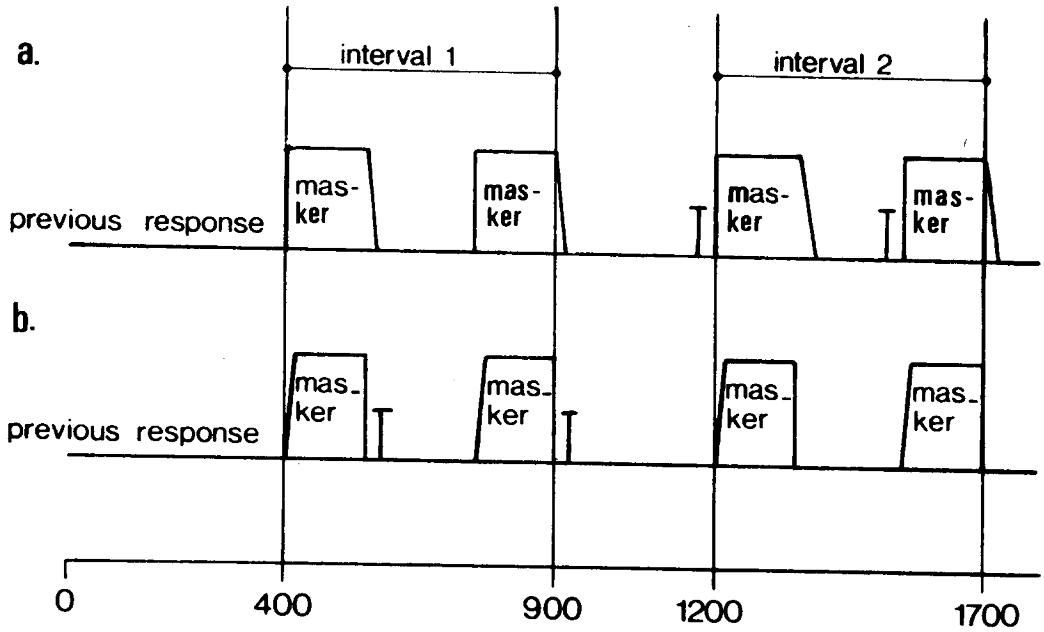


FIG. 5.5. Timing diagram for the measurement of backward- and forward-masking slopes. The order of the two intervals was randomized.

The most relevant information concerns the forward- and backward-masking slopes rather than the raw threshold values. As first approximations of the slopes the differences between the thresholds at 5 and 50 ms after the masker and at 3 and 30 ms before the masker were calculated. This linear approximation seems to be justified in the light of the results of Festen and Plomp (1983), who found nearly linear decay for forward and backward masking in four groups of hearing-impaired subjects. In Table 5.5 only the slope parameters have been included. The mean and trend parameters explain 97.3% and 96.8% of the variance for forward and backward masking, respectively.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
a. forward-masking slope							
500 Hz	F½	0.98	0.06	0.29	0.42	0.69	dB/ms
1000 Hz	F1	0.98	0.06	0.29	0.35	0.64	dB/ms
2000 Hz	F2	0.99	0.03	0.29	0.39	0.58	dB/ms
mean	FM	0.99	0.04	0.29	0.38	0.59	dB/ms
trend	FT	0.93	0.03	-0.11	-0.02	0.03	dB/ms/oct
b. backward-masking slope							
500 Hz	B½	0.98	0.12	0.49	0.80	1.14	dB/ms
1000 Hz	B1	0.99	0.10	0.63	0.92	1.40	dB/ms
2000 Hz	B2	0.99	0.09	0.34	0.91	1.25	dB/ms
mean	BM	1.00	0.06	0.66	0.86	1.18	dB/ms
trend	BT	0.96	0.08	-0.16	-0.07	0.16	dB/ms/oct

TABLE 5.5. Results of the forward- and backward-masking measurements.

5.3.6 Gap detection -

Another measure of the temporal resolution of the ear is obtained by measuring gap-detection thresholds for octave-filtered band-pass noise signals (60 dB/Hz) with center frequencies at 500, 1000, and 2000 Hz. The thresholds were measured by means of the adaptive 2AFC-procedure discussed earlier, according to the timing diagram of Fig. 5.6. Both in test and in retest each condition was measured twice.

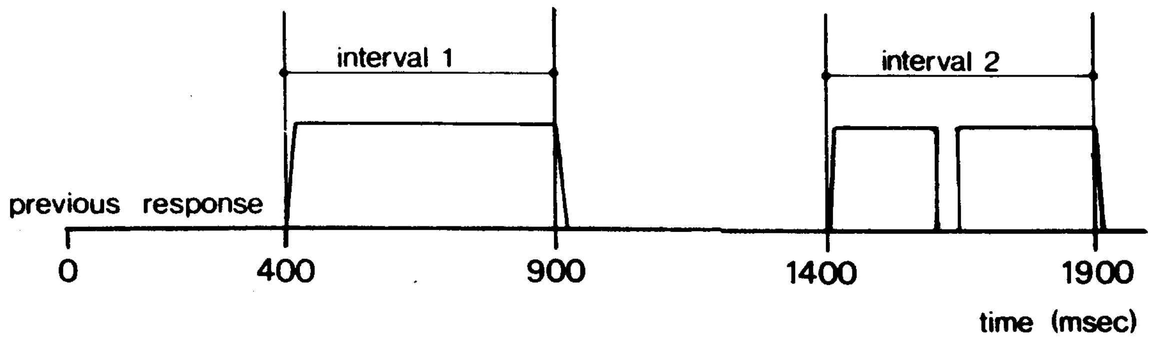


FIG. 5.6. Timing diagram for the measurement of gap-detection thresholds. The order of the two intervals was randomized.

The results are shown in Table 5.6. The mean and trend parameters explain 98.0% of the total variance.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
gap detection							
500 Hz	G½	0.98	1.72	9.3	10.3	13.0	ms
1000 Hz	G1	0.98	1.78	6.6	8.3	10.8	ms
2000 Hz	G2	0.98	2.21	5.9	6.8	9.1	ms
mean	GM	0.99	1.27	7.2	8.4	13.1	ms
trend	GT	0.93	1.54	-2.4	-1.5	-0.9	ms/oct

TABLE 5.6. Results of the gap-detection measurements.

5.3.7 Perception of isolated vowels -

As in our preliminary experiments, the perception of isolated vowels was investigated by means of a non-verbal technique using triadic comparisons. For a triad of vowels, selected from a set of 8 Dutch vowels (Table 3.4), the subject had to decide which pair was the most similar and which pair was the most dissimilar. The vowels were artificially generated steady-state signals, with equal fundamental frequency of 125 Hz and duration of 300 ms, presented at the subject's most comfortable loudness level.

Elimination of small loudness differences between the vowels by means of individual loudness matching was found to be irrelevant in the preliminary experiments. Therefore, all stimuli were presented at the same presentation level. Both in test and in retest all 56 triads were given in a fixed randomized order with a break half-way.

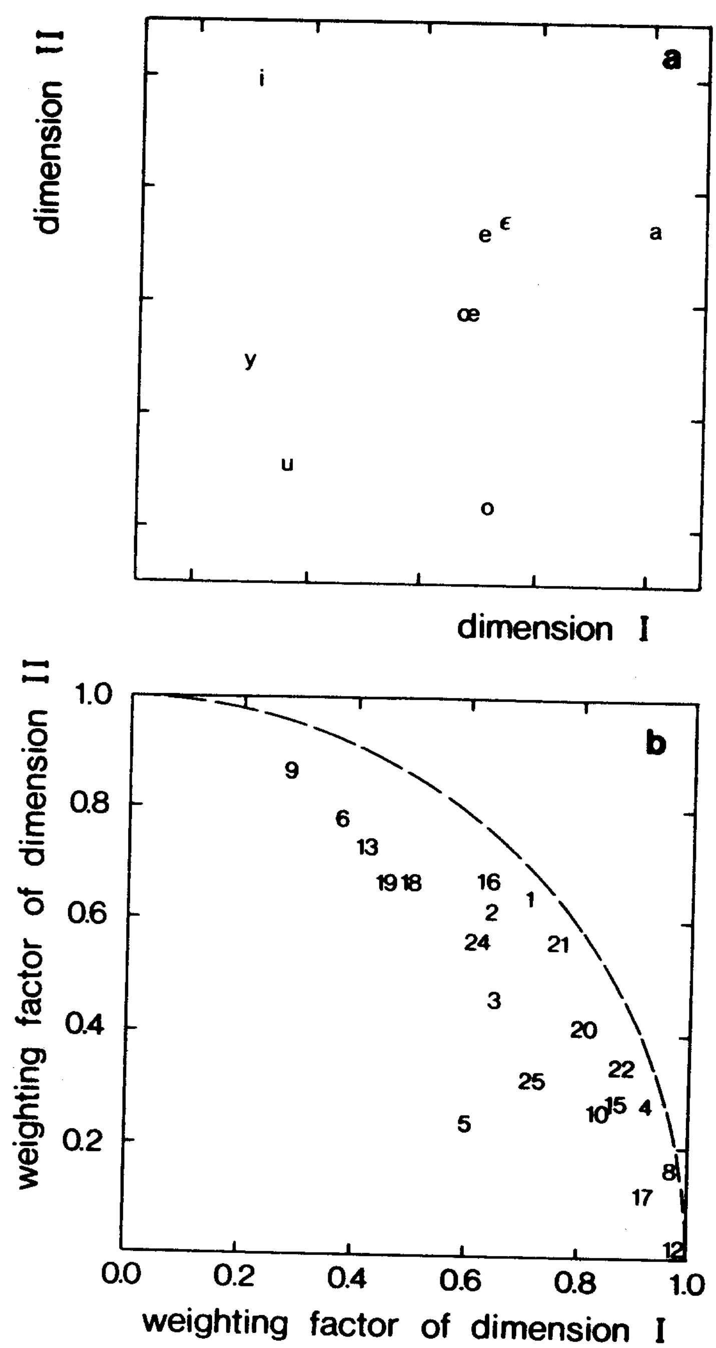


FIG. 5.7. Results of a two-dimensional INDSCAL analysis of the vowel-dissimilarity matrices. Panel a: object space; panel b: subject space.

A two-dimensional INDSCAL analysis (Carroll and Chang, 1970) on the accumulated dissimilarity matrices of test and retest resulted in the object space of Fig. 5.7(a). In this space the stimuli are plotted along the two fundamental dimensions revealed by the analysis. These two dimensions explain 79.0% of the total variance, and are related to the frequency of the first formant and that of the second formant, respectively (rank-correlation coefficients between corresponding formant frequencies and object space coordinates are 0.93 and 0.86, respectively). The reliability of the positions of the stimuli in the object space can be estimated by also performing separate INDSCAL analyses on the test and the retest sets of data; these were found to yield highly similar object spaces (rank-correlation coefficients for corresponding object-space coordinates equal 1.0).

The individual weightings of these fundamental perceptual dimensions are expressed in the subject space, see Fig. 5.7(b). From this plot it can be seen that the results of all subjects are described reasonably well by the two object-space dimensions; the subjects show a wide spread with respect to the use of these dimensions. From the vowel-perception experiments, data comparable with the ones in Tables 5.1 to 5.6 were derived, see Table 5.7(a).

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile
a. isolated vowels						
F1-weighting	f1	0.55	0.159	0.603	0.709	0.873
F2-weighting	f2	0.85	0.120	0.271	0.457	0.667
b. CVC vowels						
F1 (q)	v1	0.75	0.123	0.613	0.764	0.893
F2 (q)	v2	0.80	0.176	0.229	0.343	0.588
F1 (n)	-	0.50	0.126	0.685	0.802	0.849
F2 (n)	-	0.28	0.207	0.361	0.488	0.612
c. initial consonants						
nasality/voicing (q)	q1	0.92	0.108	0.478	0.801	0.890
frication (q)	q2	0.81	0.106	0.103	0.143	0.231
place (q)	-	0.73	0.102	0.107	0.182	0.290
nasality/voicing (n)	n1	0.82	0.126	0.253	0.402	0.540
frication (n)	n2	0.80	0.123	0.317	0.483	0.636
place (n)	-	0.27	0.181	0.195	0.308	0.403
d. final consonants						
nasality (q)	q3	0.90	0.115	0.569	0.825	0.872
voicing (q)	q4	0.88	0.089	0.326	0.397	0.519
frication (q)	q5	0.77	0.135	0.126	0.153	0.257
nasality (n)	-	0.70	0.171	0.444	0.609	0.674
voicing (n)	-	0.07	0.201	0.312	0.353	0.461
frication (n)	-	0.38	0.166	0.270	0.360	0.403

TABLE 5.7. Results of phoneme-perception measurements obtained by means of triadic comparisons (a) and confusions (b, c, d).

5.3.8 Vowel and consonant confusions -

The perception of phonemes was studied by analysis of confusion matrices of vowels and consonants from responses to consonant-vowel-consonant (CVC) words presented in quiet or in noise. Speech material and method are described in Sections 4.2.2. and 4.2.3.

As in Chapter 4, each subject produced 12 confusion matrices for each of the three stimulus categories: initial consonants, vowels, and final consonants. In the experiments of Chapter 4 the clearest effect proved to be the presence or absence of masking noise. Therefore, in the present analysis of the individual results quiet and noise conditions were studied separately, whereas corresponding matrices at different signal levels or signal-to-noise ratios were accumulated. Thus for each subject six confusion matrices resulted: initial consonants, vowels, and final consonants, in quiet and in noise. These six matrices were symmetrized according to the method of Klein, Pols, and Plomp (1970), and analyzed for each phoneme category by two- and three-dimensional INDSCAL anlyses. The combination of quiet and noise conditions into one analysis is permitted, provided that in quiet and in noise the same fundamental dimensions are involved. Because separate analyses of quiet and noise conditions yielded almost the same configurations as those obtained from an analysis of quiet and noise data combined (r-values between corresponding object-space coordinates ranged from 0.95 to 0.98), this was an acceptable assumption.

The INDSCAL analysis of the vowel-confusion matrices explains 83.8% of the variance in two dimensions. In Fig. 5.8 the two-dimensional results are plotted. In the first dimension 58.7% of the variance is explained, in the second dimension 25.1%. The dimensions of the object space in Fig. 5.8(a) are related to the positions of the first two formants (if we ignore the diphthongs /ei/ and /ʌy/, the correlation coefficients are 0.98 and 0.88, respectively). The individual weightings in quiet and noise are plotted in Fig. 5.8(b) and Fig. 5.8(c), respectively. The results are also given in Table 5.7(b).

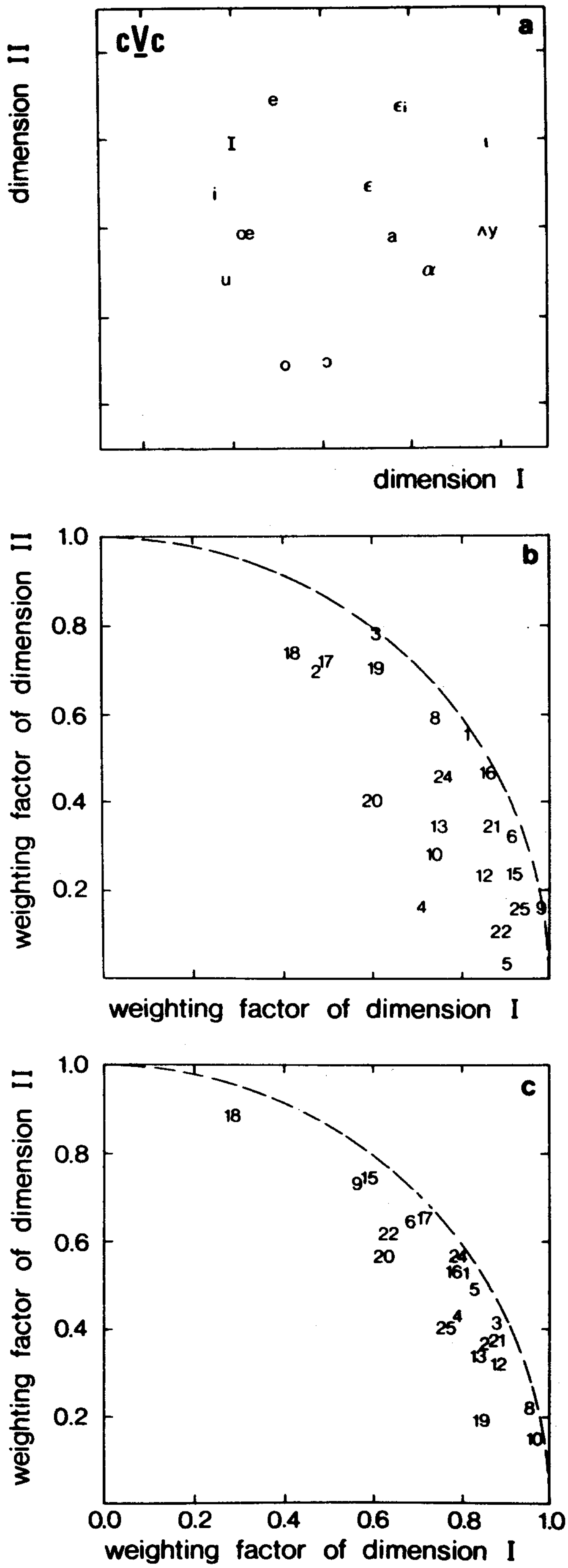


FIG. 5.8. Results of a two-dimensional INDSCAL analysis of confusion matrices of vowels in CVC-words. Panel a: object space; b: subject space in quiet; c: subject space in noise.

The INDSCAL analysis of the confusion matrices for the initial consonants explains 60.2% of the variance in two dimensions and 66.7% in three dimensions. In Fig. 5.9(a) the three-dimensional object space is plotted. The first dimension, which explains 39.5% of the variance, differentiates between nasals on the one hand, and voiced and unvoiced consonants on the other. The second dimension explains 16.6% of the variance and separates the stops /p/, /t/, /b/, /d/, and /k/ from the fricatives /s/, /z/, /v/, /χ/, /f/, /w/, and /h/. The extreme position of /s/ and /z/ reveals the importance of sibilance. The third dimension explains 10.6% of the variance and shows some relation to place of articulation, differentiating between the dentals /s/, /z/, /d/, and /t/, the bilabials /w/, /b/, and /p/, and the labiodentals /v/ and /f/. The individual weightings in quiet are plotted in Fig. 5.9(b), the individual weightings in noise in Fig. 5.9(c). The calculated values on reliability and inter-individual spread are represented in Table 5.7(c).

The INDSCAL analysis of the confusion matrices for the final consonants explains 68.9% of the variance in two dimensions and 75.1% in three dimensions. The three-dimensional object space is presented in Fig. 5.10(a). The first dimension explains 46.2% of the variance and can be regarded as the dimension of nasality. The second dimension explains 18.4% of the variance and separates the voiced and voiceless consonants with the exception of /k/. The third dimension, which explains 10.5% of the variance, separates the stops /p/, /t/, and /k/ from the fricatives /f/, /s/, and /χ/. The individual weightings in quiet and in noise are plotted in Fig. 5.10(b) and Fig. 5.10(c), respectively. Table 5.7(d) summarizes the reliability and quartile values.

We see that the reliability of some of the parameters obtained is only marginal. As was mentioned in Section 5.1. we will ignore the parameters with a reliability coefficient of below 0.75. From Table 5.7 it can be seen that this applies to the vowel and final-consonant parameters in noise and the place parameters for initial consonants.

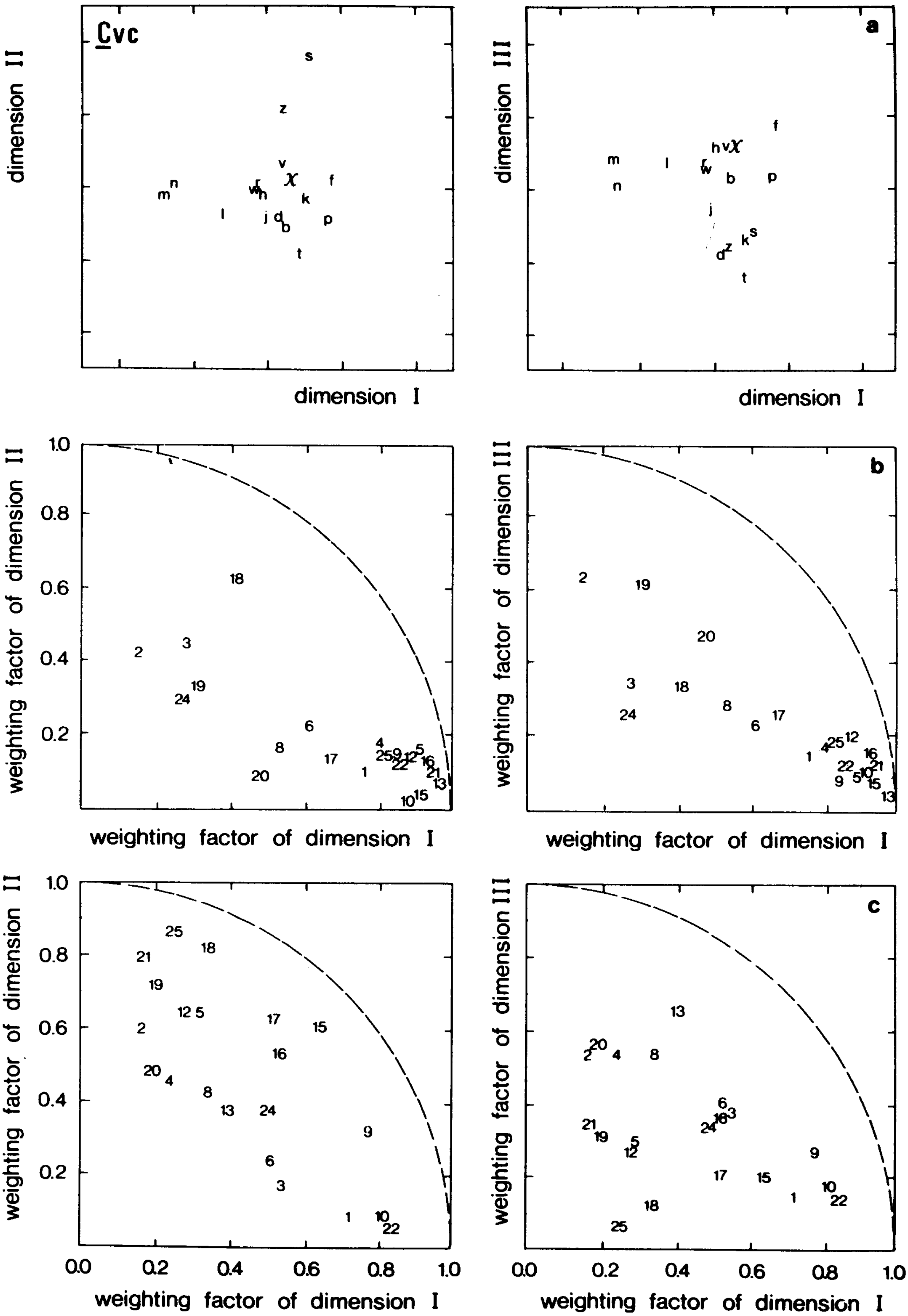


FIG. 5.9. Results of a three-dimensional INDSCAL analysis of confusions of initial consonants in CVC-words. Panel a: object space; b: subject space in quiet; c: subject space in noise.

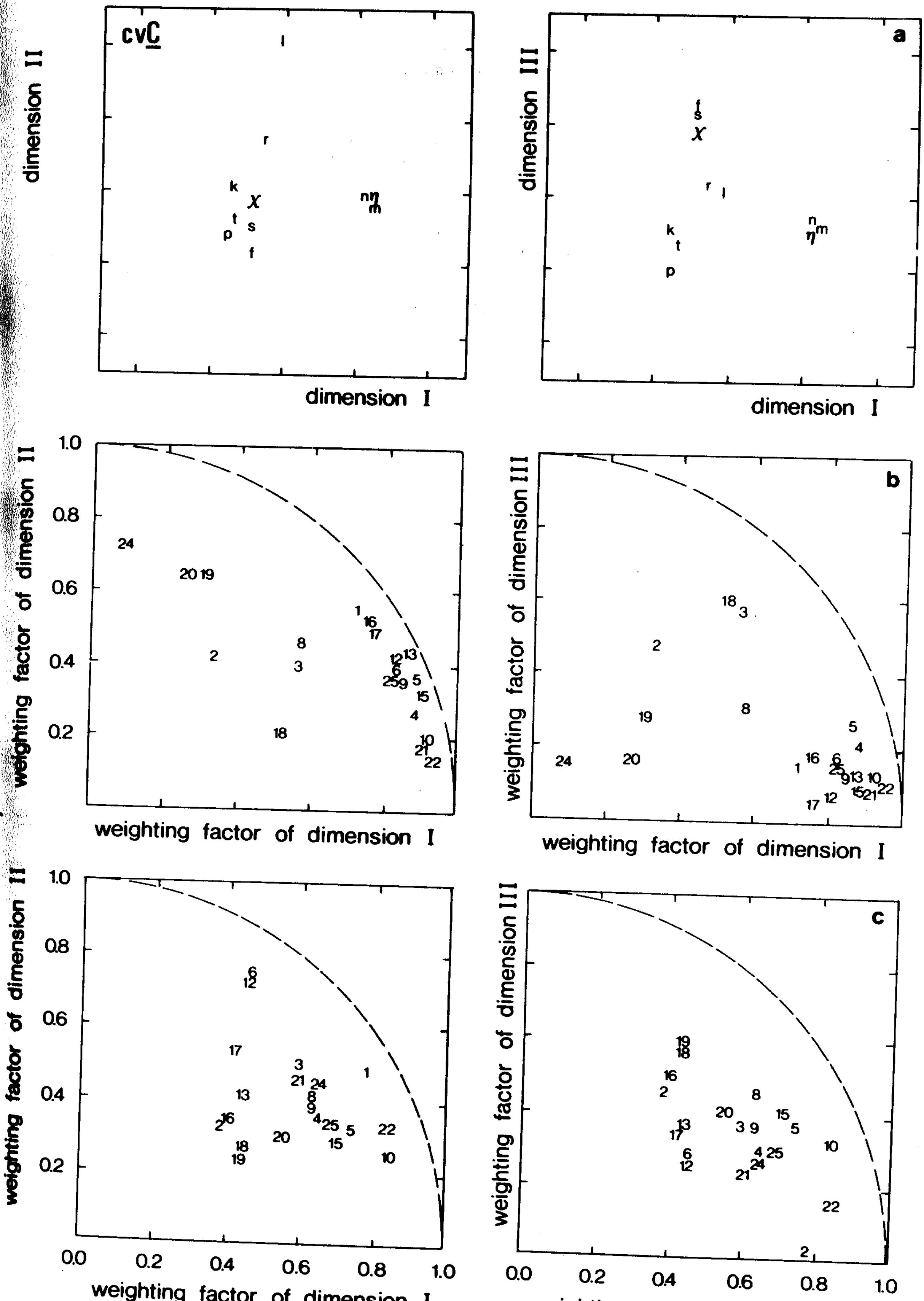


FIG. 5.10. Results of a three-dimensional INDSCAL analysis of confusions of final consonants in CVC-words. Panel a: object space; b: subject space in quiet; c: subject space in

5.3.9 Phoneme-discrimination scores -

Additionally to perceptual information about the nature of confusions, intelligibility scores can be derived from the confusions in CVC-measurements. Both in quiet and in noise, and for each subject, the mean percentages of correct phonemes as a function of sound level (3 conditions) were fitted by cumulative gaussian curves, and the 50%-discrimination levels were calculated.

The reliability and inter-individual spread parameters are presented in Table 5.8(a). The reliability coefficient for the 50%-discrimination threshold in noise is too low for further analysis. This may be caused by the rather shallow slope of the psychometric function, which is 2.9% per dB on the average. So the standard deviation of a single threshold value (8.9%) is equivalent to about 3 dB, which is rather large compared to the small range of inter-individual differences for speech intelligibility thresholds in noise.

parameter	code	reliability coefficient	standard deviation	lower quartile	median	upper quartile	dimension
a. 50%-discrimination threshold							
quiet	-	0.86	8.76	20.7	35.1	43.4	dB
noise	-	0.19	5.97	-1.1	2.1	3.7	dB
b. speech-reception threshold							
SHL in noise	D	0.95	0.76	1.1	2.5	3.3	dB
ΔSHL in quiet	A	0.99	1.71	23.3	31.9	41.2	dB
ΔSHL with lp-filter	ΔDl	0.90	1.61	4.1	5.2	7.7	dB
ΔSHL with hp-filter	ΔDh	0.97	1.54	6.9	9.6	13.8	dB

TABLE 5.8. Results of speech-reception threshold measurements.

5.3.10 Speech-reception thresholds -

Sentence intelligibility in quiet and noise was investigated by means of the test developed by Plomp and Mimpen (1979) and described in Section 3.3.4. Speech-reception thresholds were measured in quiet and at two levels of interfering noise: 60 and 80 dB(A). The noise spectrum equals the long-term average spectrum of the speech signal. The thresholds were fitted by means of Plomp's model (1978) to get the D- and (A+D)-parameters described before. In order to investigate the importance of different frequency regions speech-reception thresholds for low-pass and high-pass filtered speech (cut-off frequency = 1200 Hz, filter slope = 96 dB/oct) were also measured in the presence of background noise at 80 dB(A).

In Table 5.8(b) the resulting values are shown. The hearing loss for speech in noise is regarded as the basic parameter, D. A is the attenuation component, which is equal to the hearing loss for speech in quiet minus the distortion component D. ΔDl and ΔDh are extra elevations of the speech-reception threshold in noise due to low-pass and high-pass filtering, respectively. In view of the small standard deviations obtained, these speech intelligibility parameters appear to be more reliable than the ones obtained in the previous section. The correlation between the speech-in-quiet parameters is high enough ($r=0.94$) to retain A in further analysis.

5.4 Relations

Because our prime interest is in relations between test parameters rather than in results from individual tests, in this section the relations between tests are investigated by means of correlation analysis, principal-components analysis, and multiple-regression analysis.

5.4.1 Correlation coefficients -

In Tables 5.9 and 5.10 the correlation coefficients in the group of tone-perception parameters are presented, both per frequency (Table 5.9) and for the mean/trend parameters (Table 5.10). The results per frequency show:

1. corresponding parameters at different frequencies are clearly interrelated;

2. all tone-perception parameters, except the just-noticeable differences for intensity, are significantly correlated with the amount of hearing loss at the corresponding frequency;

3. dynamic-range parameters are inversely related to pure-tone loss and show rather high correlations with forward- and backward-masking slopes;

4. just-noticeable differences for intensity appear to be completely independent of all other tone-perception parameters;

5. critical-ratio parameters show a weak, but significant, correlation with the following temporal parameters: forward- and backward-masking slopes and gap-detection thresholds;

	L½	L1	L2	R½	R1	R2	J½	J1	J2	C½	C1	C2	F½	F1	F2	B½	B1	B2	G½	G1
audiometric loss																				
500 : L½	-																			
1000 : L1	0.85	-																		
2000 : L2	0.47	0.67	-																	
dynamic range																				
500 : R½	-0.78	-0.67	-0.05	-																
1000 : R1	-0.68	-0.83	-0.28	0.86	-															
2000 : R2	-0.49	-0.69	-0.63	0.50	0.73	-														
JND for intensity																				
500 : J½	-0.17	-0.05	-0.11	0.14	0.03	0.24	-													
1000 : J1	-0.13	-0.15	-0.16	0.06	0.06	0.22	0.84	-												
2000 : J2	-0.19	-0.26	-0.43	-0.01	0.03	0.26	0.74	0.86	-											
critical ratio																				
500 : C½	0.51	0.40	0.44	-0.14	-0.15	-0.29	-0.00	0.08	0.02	-										
1000 : C1	0.70	0.61	0.68	-0.36	-0.35	-0.47	0.09	0.23	0.05	0.71	-									
2000 : C2	0.38	0.47	0.72	-0.09	-0.25	-0.50	0.14	0.24	-0.05	0.52	0.78	-								
forward masking																				
500 : F½	-0.95	-0.86	-0.49	0.79	0.74	0.56	0.19	0.14	0.22	-0.40	-0.61	-0.36	-							
1000 : F1	-0.86	-0.98	-0.59	0.74	0.86	0.69	0.09	0.19	0.23	-0.42	-0.56	-0.40	0.89	-						
2000 : F2	-0.72	-0.93	-0.78	0.53	0.74	0.76	0.07	0.17	0.35	-0.30	-0.58	-0.57	0.78	0.90	-					
backward masking																				
500 : B½	-0.90	-0.87	-0.56	0.65	0.69	0.57	-0.05	-0.02	0.09	-0.50	-0.67	-0.48	0.93	0.88	0.79	-				
1000 : B1	-0.81	-0.97	-0.65	0.58	0.77	0.62	0.01	0.12	0.22	-0.42	-0.60	-0.45	0.82	0.94	0.88	0.87	-			
2000 : B2	-0.56	-0.80	-0.66	0.40	0.62	0.56	-0.05	0.02	0.22	-0.07	-0.43	-0.35	0.57	0.71	0.82	0.58	0.80	-		
gap detection																				
500 : G½	0.61	0.51	0.46	-0.36	-0.31	-0.31	-0.12	0.11	0.01	0.47	0.66	0.60	-0.56	-0.51	-0.46	-0.59	-0.55	-0.40	-	
1000 : G1	0.60	0.57	0.59	-0.31	-0.32	-0.37	-0.10	0.08	-0.13	0.35	0.68	0.70	-0.55	-0.53	-0.59	-0.59	-0.60	-0.57	0.93	-
2000 : G2	0.40	0.59	0.64	-0.14	-0.33	-0.40	0.17	0.16	-0.05	0.28	0.60	0.76	-0.34	-0.52	-0.62	-0.48	-0.61	-0.59	0.68	0.83

TABLE 5.9. Matrix of correlation coefficients in the group of frequency-specific tone-perception parameters (n=21).

		LM	LT	RM	RT	JM	JT	CM	CT	FM	FT	BM	BT	GM
audiometric loss	: LM	*												
iometric trend	: LT	-0.11	*											
dynamic range	: RM	-0.73	0.41	*										
mic range trend	: RT	0.03	-0.90	-0.28	*									
JND	: JM	-0.24	-0.09	0.11	0.16	*								
-trend	: JT	-0.37	-0.39	-0.01	0.30	0.54	*							
critial ratio	: CM	0.70	0.07	-0.35	-0.16	0.10	-0.07	*						
tical ratio trend	: CT	0.09	0.40	-0.10	-0.25	0.07	-0.26	0.05	*					
FM-slope	: FM	-0.96	0.27	0.84	-0.18	0.22	0.29	-0.56	-0.08	*				
lope trend	: FT	0.07	-0.80	-0.18	0.71	0.01	0.40	0.04	-0.45	-0.16	*			
BM-slope	: BM	-0.94	0.17	0.74	-0.09	0.09	0.32	-0.55	-0.12	0.94	-0.05	*		
lope trend	: BT	0.11	-0.46	-0.12	0.29	0.08	0.21	0.31	-0.34	-0.18	0.66	-0.00	*	
gap threshold	: GM	0.67	0.04	-0.37	-0.04	0.02	-0.09	0.69	0.38	-0.58	-0.07	-0.65	0.01	*
trend	: GT	0.27	0.45	-0.08	-0.39	0.10	-0.46	0.22	0.53	-0.18	-0.69	-0.30	-0.36	0.38

TABLE 5.10. Matrix of correlation coefficients in the group of mean/trend tone-perception parameters (n=21).

6. forward- and backward-masking slopes are highly interrelated, but the relation with gap-detection thresholds is less clear.

Most of these comments hold equally for the results of the mean/trend parameters (Table 5.10). From this table it can also be seen that the mean and trend parameters are reasonably independent of each other, except for just-noticeable differences for intensity and gap-detection thresholds.

The correlation coefficients between tone-perception and phoneme-perception parameters are presented in Tables 5.11(a-c) and 5.12(a-c) for the frequency-specific and the mean/trend parameters, respectively. On the whole, the correlations are quite low. However, some relations should be mentioned:

1. Audiogram parameters appear to play only a moderate role in the perception of consonants: for the perception of initial consonants in noise the trade-off relation between the weightings of nasality and frication information is influenced by the audiometric slope (sloping audiograms tend to have higher nasality weightings and lower frication weightings). For the perception of final consonants in quiet the voicing weighting is inversely related to all audiometric thresholds and consequently to mean audiometric loss.

2. Dynamic-range and JND parameters show rather low correlations with phoneme-perception parameters. The perception of initial consonants in noise is weakly correlated with the dynamic range at lower frequencies. The perception of nasality in quiet is inversely related to

		L½	L1	L2	R½	R1	R2	J½	J1	J2	C½	C1	C2	F½	F1	F2	B½	B1	B2	G½	G1	G2
a. perception of vowels																						
F2 (isolated)	: f2	-.02	-.18	-.36	-.07	.08	.09	-.02	-.09	.09	.07	-.27	-.48	.08	.14	.28	.10	.23	.32	-.38	-.53	-.57
F1 (CVC)	: v1	.02	.15	.05	-.18	-.22	-.19	-.00	-.02	-.01	-.51	-.16	.02	-.08	-.13	-.26	.02	-.05	-.22	.09	.19	.27
F2 (CVC)	: v2	-.24	-.51	-.25	.37	.54	.34	-.12	-.03	.06	.33	-.04	-.17	.31	.45	.53	.26	.42	.51	-.19	-.29	-.46
b. perception of initial consonants																						
nasality/voicing (q)	: q1	.11	.40	.40	-.19	-.40	-.46	-.17	-.28	-.46	-.32	-.02	.24	-.20	-.34	-.59	-.11	-.31	-.52	.10	.27	.36
frication (q)	: q2	.13	-.10	-.21	.06	.17	.30	.04	.07	.24	.58	.17	-.09	-.01	.05	.34	-.07	-.00	.36	.02	-.16	-.24
nasality/voicing (n)	: n1	-.30	-.21	.13	.43	.33	.18	.25	.22	-.01	-.19	-.03	.16	.26	.32	.00	.25	.26	.07	-.23	-.12	-.01
frication (n)	: n2	.46	.36	-.03	-.54	-.43	-.16	-.07	-.15	-.02	.20	.11	-.03	-.48	-.48	-.22	-.46	-.39	-.18	.30	.23	.04
c. perception of final consonants																						
nasality (q)	: q3	.13	.44	.57	-.06	-.31	-.47	-.29	-.40	-.58	-.16	.05	.36	-.22	-.36	-.61	-.12	-.36	-.48	.09	.26	.35
voicing (q)	: q4	-.40	-.58	-.53	.24	.41	.34	.22	.24	.44	-.23	-.33	-.41	.44	.51	.57	.32	.51	.40	-.11	-.21	-.29
frication(q)	: q5	.05	-.13	-.11	.09	.17	.14	-.14	-.08	.05	.58	.16	-.01	.07	.07	.32	.02	.07	.43	-.08	-.20	-.18
d. speech reception thresholds																						
SHL in noise	: D	.47	.52	.62	-.10	-.22	-.27	-.06	-.01	-.20	.53	.74	.71	-.35	-.44	-.52	-.40	-.57	-.44	.55	.67	.76
ΔSHL in quiet	: A	.93	.83	.56	-.70	-.61	-.48	-.27	-.22	-.33	.33	.65	.37	-.91	-.81	-.75	-.81	-.79	-.69	.62	.66	.41
ΔSHL (lp-filtered)	: ΔD1	.52	.21	-.16	-.45	-.20	.07	-.16	-.04	.02	.57	.24	-.05	-.44	-.30	.03	-.43	-.23	.11	.35	.15	-.14
ΔSHL (hp-filtered)	: ΔDh	.18	.34	.49	.02	-.12	-.16	.14	.18	-.07	-.06	.40	.55	-.14	-.25	-.46	-.19	-.35	-.51	.41	.66	.84

TABLE 5.11. Matrix of correlation coefficients between tone-perception parameters (per frequency) and phoneme- and speech-perception parameters (n=21).

		LM	LT	RM	RT	JM	JT	CM	CT	FM	FT	BM	BT	GM	GT
a. perception of vowels															
F2 (isolated)	: f2	-0.21	-0.33	0.03	0.15	0.00	0.16	-0.26	-0.56	0.17	0.27	0.24	0.24	-0.54	-0.41
F1 (CVC)	: v1	0.09	0.03	-0.22	0.04	-0.01	-0.01	-0.24	0.53	-0.16	-0.24	-0.09	-0.27	0.21	0.27
F2 (CVC)	: v2	-0.39	0.00	0.47	-0.11	-0.02	0.20	0.04	-0.50	0.45	0.27	0.44	0.28	-0.36	-0.45
b. perception of initial consonants															
nasality/voicing (q)	: q1	0.35	0.28	-0.38	-0.20	-0.35	-0.52	-0.04	0.57	-0.39	-0.51	-0.34	-0.46	0.27	0.39
frication (q)	: q2	-0.07	-0.33	0.19	0.20	0.14	0.32	0.24	-0.68	0.13	0.49	0.11	0.48	-0.15	-0.34
nasality/voicing (n)	: n1	-0.15	0.43	0.36	-0.32	0.14	-0.26	-0.02	0.36	0.22	-0.41	0.21	-0.19	-0.11	0.21
frication (n)	: n2	0.31	-0.48	-0.44	0.45	-0.08	0.04	0.11	-0.24	-0.42	0.44	-0.37	0.30	0.18	-0.24
c. perception of final consonants															
nasality (q)	: q3	0.43	0.41	-0.30	-0.35	-0.48	-0.58	0.10	0.54	-0.41	-0.51	-0.35	-0.40	0.27	0.39
voicing (q)	: q4	-0.57	-0.11	0.37	0.04	0.34	0.43	-0.37	-0.19	0.53	0.14	0.45	0.09	-0.23	-0.29
frication (q)	: q5	-0.07	-0.15	0.15	0.02	-0.05	0.21	0.27	-0.59	0.15	0.34	0.19	0.45	-0.17	-0.16
d. speech reception thresholds															
SHL in noise	: D	0.60	0.13	-0.21	-0.13	-0.11	-0.24	0.75	0.20	-0.46	-0.17	-0.51	-0.06	0.72	0.51
ΔSHL in quiet	: A	0.88	-0.38	-0.67	0.35	-0.30	-0.23	0.52	0.06	-0.87	0.37	-0.83	0.11	0.58	-0.04
ΔSHL (lp-filtered)	: ΔD1	0.22	-0.67	-0.23	0.56	-0.05	0.19	0.29	-0.63	-0.26	0.73	-0.20	0.58	0.09	-0.52
ΔSHL (hp-filtered)	: ΔDh	0.38	0.29	-0.10	-0.17	0.07	-0.24	0.34	0.63	-0.29	-0.43	-0.39	-0.36	0.71	0.75

TABLE 5.12. Matrix of correlation coefficients between tone perception parameters (mean/trend) and phoneme- and speech-perception parameters (n=21).

both the dynamic range and the JND for intensity at 2000 Hz.

3. With respect to the critical-ratio parameters, the trend over frequency is more related to phoneme-perception parameters than the CR's at individual frequencies are. A relatively fast increasing CR as a function of frequency tends to favour the weightings of low-frequency characteristics (F1-position for vowels, nasality for consonants).

4. Forward- and backward-masking slopes at higher frequencies tend to be related to the weighting of second-formant information in CVC-vowels and inversely related to the nasality-weightings for consonants in quiet. In noise the lower-frequency masking slopes seem to be more important, whereas all masking slopes are positively correlated with the weighting of voicing information in the perception of final consonants.

5. Gap-detection thresholds at higher frequencies are inversely correlated with second-formant weightings of isolated vowels and of vowels in CVC-words in quiet.

The correlations between tone-perception and speech-perception parameters are given in Tables 5.11(d) and 5.12(d). The following conclusions may be drawn:

1. For speech intelligibility in noise the high-frequency values of hearing loss and critical ratio are the most

important ones, as are the gap-detection parameters.

2. In speech intelligibility in quiet the following parameters are especially involved: hearing loss and dynamic range at 500 and 1000 Hz, the critical ratio at 1000 Hz, and the forward- and backward-masking slopes.

3. The speech-reception thresholds for low-pass and high-pass filtered speech in noise are related to audiometric loss, critical ratio, and temporal parameters of the frequencies in the corresponding range. This frequency dependence results in high correlations with the trend parameters for these auditory properties.

4. With unfiltered speech the mean parameters are most important: the mean CR and gap-detection threshold for speech intelligibility in noise, mean loss, dynamic range, and forward- and backward-masking slopes for speech intelligibility in quiet.

Correlation coefficients in the group of phoneme-perception parameters are presented in Table 5.13. The following comments can be made:

1. the perception of isolated vowels is relatively independent from other phoneme-perception parameters;

2. the weighting of F1-information in CVC-vowels is related to the weighting of nasality and voicing in initial and final consonants in quiet;

3. the weighting of F2-information in CVC-vowels is related to the weighting of frication in consonant perception in quiet;

4. the parameters for consonant perception in noise appear to be rather independent.

		f2	v1	v2	q1	q2	n1	n2	q3	q4
perception of vowels										
F2 (isolated)	: f2	*								
F1 (CVC)	: v1	0.00	*							
F2 (CVC)	: v2	0.22	-0.80	*						
perception of initial consonants										
nasality/voicing (q)	: q1	-0.22	0.68	-0.73	*					
frication (q)	: q2	0.32	-0.65	0.66	-0.79	*				
nasality/voicing (n)	: n1	0.09	0.34	-0.19	0.33	-0.28	*			
frication (n)	: n2	-0.13	-0.18	0.10	-0.05	0.22	-0.74	*		
perception of final consonants										
nasality (q)	: q3	-0.22	0.57	-0.62	0.88	-0.57	0.36	-0.13	*	
voicing (q)	: q4	0.15	-0.19	0.42	-0.45	0.02	-0.25	0.09	-0.70	*
frication (q)	: q5	0.23	-0.62	0.63	-0.69	0.89	-0.28	0.11	-0.46	-0.09

TABLE 5.13. Matrix of correlation coefficients in the group of phoneme-perception parameters (n=21).

Table 5.14 presents the correlation coefficients between phoneme-perception and speech-perception parameters. The speech-reception threshold in noise is inversely related to the F2-weighting in the perception of isolated vowels and to the weighting of voicing in the perception of final consonants in quiet. Most phoneme-perception parameters correlate only poorly with the non-filtered speech-reception thresholds. However, in the case of low-pass filtering the correlation coefficients are higher.

		f2	v1	v2	q1	q2	n1	n2	q3	q4	q5
SHL in noise	: *D*	-0.52	-0.11	-0.14	0.15	0.11	0.01	-0.02	0.27	-0.52	0.19
ΔSHL in quite	: *A*	-0.15	0.09	-0.28	0.24	-0.03	-0.24	0.42	0.30	-0.44	-0.13
ΔSHL (lp-filtered)	: *ΔDl*	0.26	-0.58	0.43	-0.52	0.63	-0.53	0.53	-0.51	0.10	0.51
ΔSHL (hp-filtered)	: *ΔDh*	-0.64	0.40	-0.49	0.39	-0.41	0.28	-0.28	0.36	-0.29	-0.30

TABLE 5.14. Matrix of correlation coefficients between phoneme perception parameters and speech-perception parameters (n=21).

Finally, Table 5.15 shows the correlations between the filtered and unfiltered speech-reception thresholds. From this table it can be seen that the extra threshold elevation due to high-pass filtering in noise is related to the hearing loss for speech in noise.

		A	D	ΔD1
SHL in noise	: *D*	*		
ΔSHL in quiet	: *A*	0.45	*	
ΔSHL (lp-filtered)	: *ΔDl*	0.02	0.37	*
ΔSHL (hp-filtered)	: *ΔDh*	0.68	0.26	-0.42

TABLE 5.15. Matrix of correlation coefficients in the group of the speech-perception parameters (n=21).

5.4.2 Principal-components analysis -

In order to visualize the complex structure of the interactions between the parameters, principal-components analyses were carried out. In such analyses, directions or factors are computed which represent as much as possible of the total variance.

Fig. 5.11 presents the results for the correlation matrix of frequency-specific parameters (see Tables 5.9, 5.11, 5.13, 5.14, and 5.15). Fig. 5.11(a) shows the percentage of variance explained by successive factors. In two dimensions 57.5% of the variance could be explained.

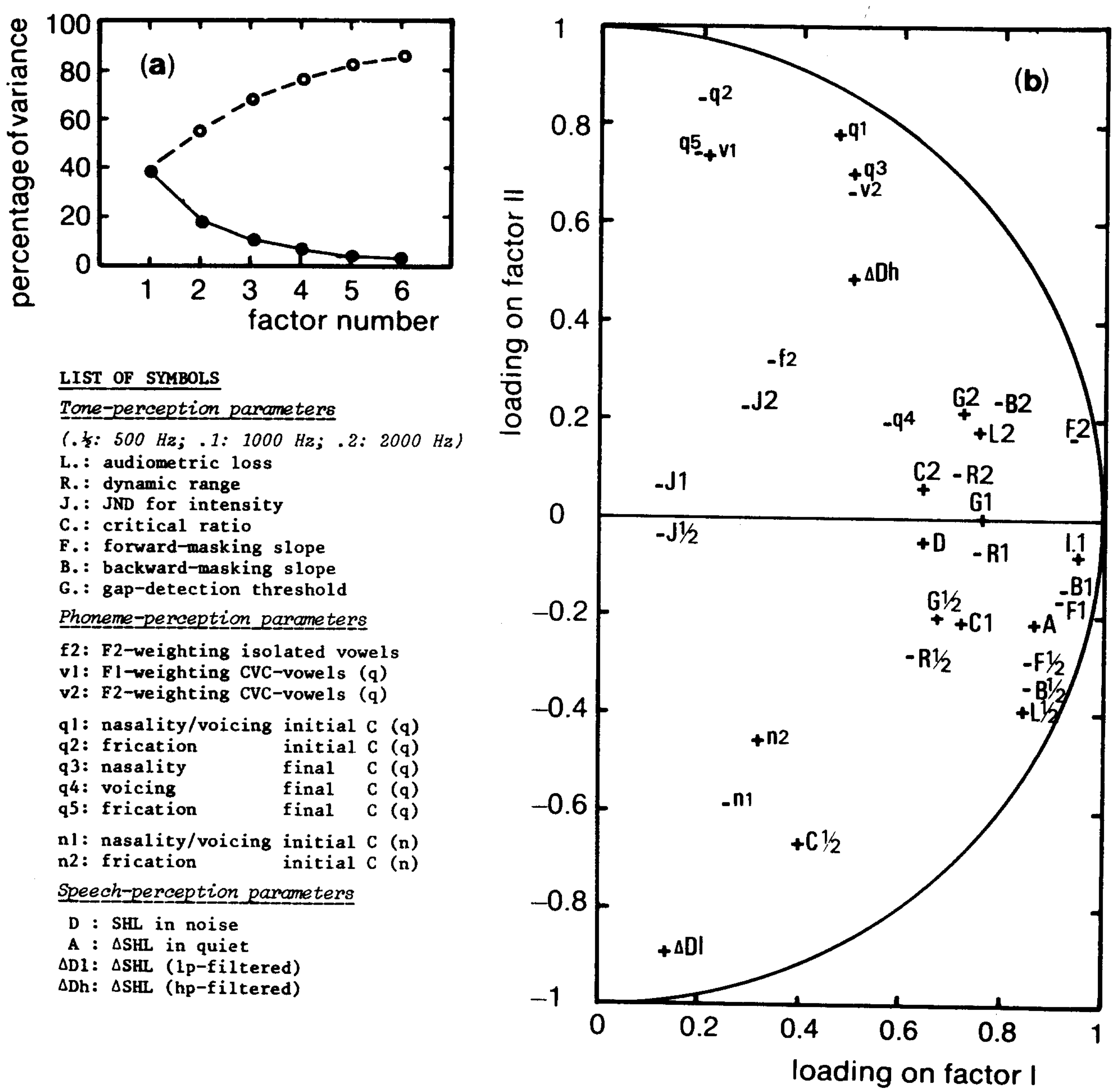
The correspondence of each test with each of the factors is expressed in the so-called factor loadings. A plot of the parameters according to their factor loadings provides a picture of relations between parameters: closely related parameters manifest themselves as clusters. In Fig. 5.11(b) this plot is reproduced. In order to situate all parameters in the right half-plane, the polarity of some parameters was changed from plus to minus; in both cases the exact position of the factor loading is indicated by the sign symbol. The circle is reached if all variance of a certain parameter is explained by the first two factors. Most parameters are positioned reasonably well near the circle. This indicates that the variance is rather well represented by the two factors, except in the case of the JND parameters (J½ , J1, J2) and the isolated-vowel perception parameter (f2). With regard to the clustering of the other parameters the following comments can be made:

1. There is a clear dichotomy between tone-perception parameters (L½-2, R½-2, C½-2, F½-2, B½-2, and G½-2) and phoneme-perception parameters (v1-2, q1-5, and n1-2). This indicates that the tone-perception parameters investigated are not the determinants of the perception of phonemes.

2. For the tone-perception parameters there is a clustering per frequency rather than per test: dynamic range (R), critical ratio (C), and forward- and backward-masking slopes (F, B) seem to be closely related to the audiometric losses (L) at the corresponding frequencies.

3. The hearing loss for speech in noise (D) is positioned near the clusters for the 1000-Hz and 2000-Hz tests. This means that the high-frequency parameters are very important for speech perception in noise.

4. The extra elevation of hearing loss for speech in quiet (A) is positioned between the 500-Hz and 1000-Hz clusters: in quiet, the low-frequency characteristics are important.



LIST OF SYMBOLS

Tone-perception parameters

(.½: 500 Hz; .1: 1000 Hz; .2: 2000 Hz)
L.: audiometric loss
R.: dynamic range
J.: JND for intensity
C.: critical ratio
F.: forward-masking slope
B.: backward-masking slope
G.: gap-detection threshold

Phoneme-perception parameters

f2: F2-weighting isolated vowels
v1: F1-weighting CVC-vowels (q)
v2: F2-weighting CVC-vowels (q)

q1: nasality/voicing initial C (q)
q2: frication initial C (q)
q3: nasality final C (q)
q4: voicing final C (q)
q5: frication final C (q)

n1: nasality/voicing initial C (n)
n2: frication initial C (n)

Speech-perception parameters

D : SHL in noise
A : ΔSHL in quiet
ΔDl: ΔSHL (lp-filtered)
ΔDh: ΔSHL (hp-filtered)

FIG. 5.11. Results of the principal-components analysis of the frequency-specific parameters. Panel a: percentage of variance explained by successive factors per dimension (filled symbols) and cumulatively (open symbols); panel b: factor loadings of the tests on the first two dimensions.

5. The phoneme-perception parameters are divided into two groups according to the presence (nl-2) or absence (vl-2, ql-5) of background noise (the separation of the phoneme-perception parameters is smaller than it may seem in the diagram due to the polarity inversions applied). Taking also the polarity of these parameters into account, the top of the half-plane can be associated with lack of high-frequency cues in quiet, the bottom with lack of low-frequency cues in noise. This is in agreement with the orientation of the tone-perception parameters.

6. The effects of high-pass filtering (ΔDh) are determined by subjects' inability to use high-frequency cues; similarly, the effects of low-pass filtering (ΔDl) are determined by subjects' inability to use low-frequency cues.

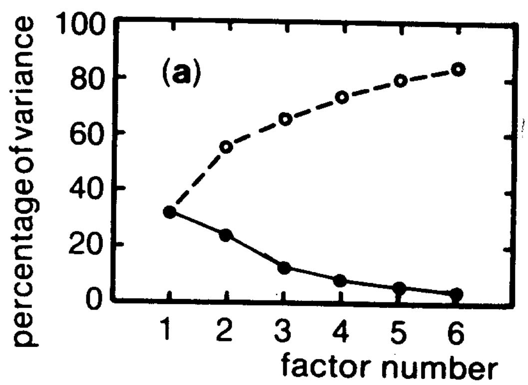
In summary, the unfiltered speech-perception data are related mainly to tone-perception data: in quiet to low-frequency parameters and in noise to high-frequency ones. The phoneme-perception data seem to play a role of only secondary importance, and only become important in cases of filtering.

Fig. 5.12 presents, in a similar way, the results from the correlation matrix with mean and trend parameters (see Tables 5.10, 5.12, 5.13, 5.14, and 5.15). In two dimensions 54.7% of the variance was explained. A rotation was carried out in order to get a comparable orientation as in Fig. 5.11(b). Fig. 5.12(b) shows a high degree of agreement with Fig. 5.11(b) with respect to the common parameters. Therefore, we will discuss only the positions of the mean and trend parameters:

1. The mean parameters (LM, RM, JM, CM, FM, BM, and GM) are clustered near the unfiltered speech conditions, A and D, except for the mean JND for intensity (JM). D is closer to the mean gap detection threshold (GM), A to the other mean parameters;

2. The trend parameters (LT, RT, JT, CT, FT, BT, and GT) show a closer relationship with the phoneme-perception parameters (vl-2, ql-5, nl-2) and the filtered-speech characteristics (ΔDl and ΔDh).

In summary, the phoneme-perception parameters are related rather to trend parameters than to mean parameters or frequency-specific parameters.



LIST OF SYMBOLS

Tone-perception parameters

(*.M: mean; .T: trend)*

L.: audiometric loss
R.: dynamic range
J.: JND for intensity
C.: critical ratio
F.: forward-masking slope
B.: backward-masking slope
G.: gap-detection threshold

Phoneme-perception parameters

f2: F2-weighting isolated vowels
v1: F1-weighting CVC-vowels (q)
v2: F2-weighting CVC-vowels (q)

q1:	nasality/voicing	initial	C (q)
q2:	frication	initial	C (q)
q3:	nasality	final	C (q)
q4:	voicing	final	C (q)
q5:	frication	final	C (q)
n1:	nasality/voicing	initial	C (n)
n2:	frication	initial	C (n)

Speech-perception parameters

D : SHL in noise
A : ΔSHL in quiet
ΔD1: ΔSHL (lp-filtered)
ΔDh: ΔSHL (hp-filtered)

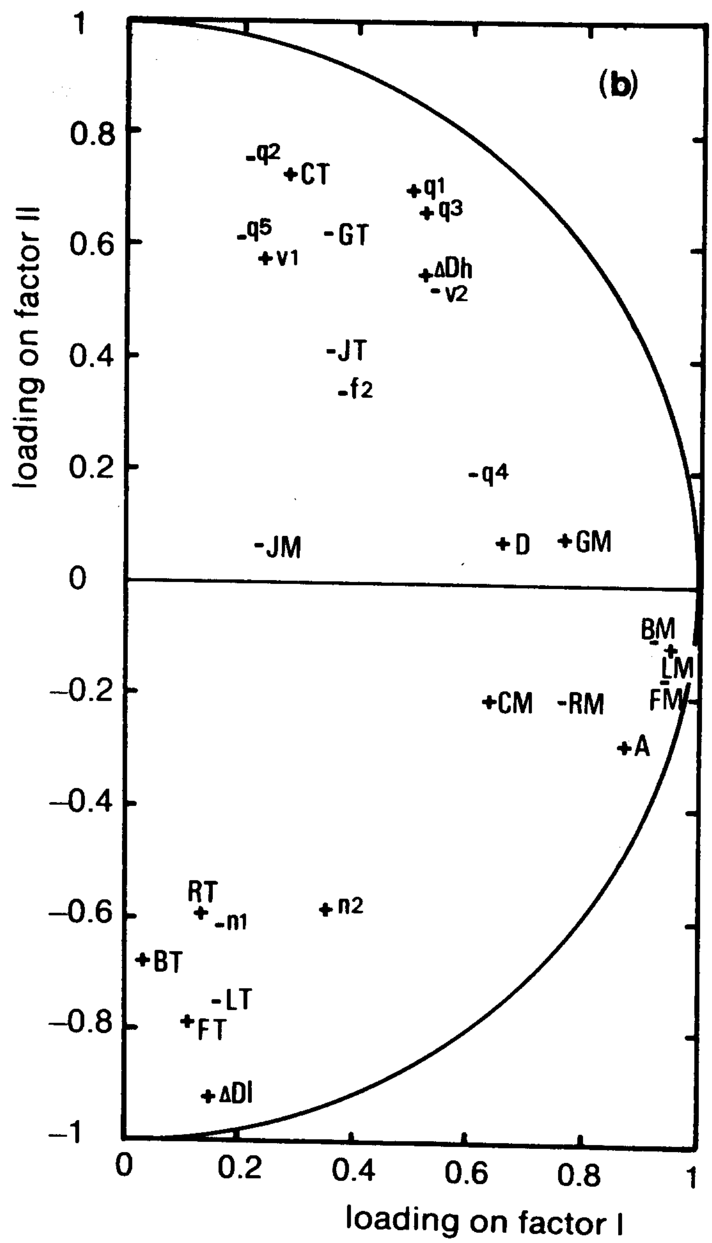


FIG. 5.12. Results of the principal-components analysis of the mean and trend parameters. Panel a: percentages of variance explained by successive factors per dimension (filled symbols) and cumulatively (open symbols); panel b: factor loadings of the tests on the first two dimensions.

5.4.3 Multiple-regression analysis -

From the foregoing analyses a complete picture of the relations between the test parameters was obtained. However, it remains unclear which parameters are the most decisive ones for the perception of speech in quiet and in noise. On the one hand, simple correlations between parameters do not account for possible interactions with other test parameters. On the other hand, the clustering of parameters in the results of the principal-components analysis does not reveal the most important relations within that cluster. For these reasons, a multiple-regression analysis was used in order to find the parameters which are the best predictors of the speech-reception results.

To each of the four speech-perception parameters and to both the frequency-specific and the mean/trend parameter sets a stepwise analysis including five predicting variables was applied. The results are presented in Table 5.16. For each analysis the order of inclusion and the resulting multiple-R^2 values are indicated. For example, in the prediction of the hearing loss for speech in noise (D) the gap-detection threshold at 2000 Hz proved to be the most important predictor, resulting in a multiple-R^2 value of 0.577. After partialing out the interactions for this parameter with the other parameters, the critical ratio at 1000 Hz proved to be the second most important predictor, increasing the multiple-R^2 value from 0.577 to 0.705. Similarly, the backward-masking slope parameters at 500, 1000, and 2000 Hz were included in three successive steps, increasing the multiple-R^2 value to 0.844.

According to this analysis the speech-reception threshold in noise (D) can be estimated with a standard error of 1.0 dB by means of five parameters (Table 5.16(a)). It is striking that the predictive parameter sets are dominated by frequency-resolution parameters (C1, CM, and CT) and time-resolution parameters (G2, B½ , B1, B2, GT, and BT), rather than by audiometric-loss parameters. The role of the perception of F2-information from isolated vowels is in agreement with the results of the preliminary study (Chapter 3).

By means of the sets indicated in Table 5.16(b), the attenuation component of the hearing loss for speech in quiet (A) can be estimated with a standard error of 3.3 dB. All parameters in the predicting sets are tone-perception parameters. The audiometric-loss parameters (L½, L2, and LM) appear to be the most important ones, but time-resolution parameters (B2, F1, GT, and FM) and the trend of the dynamic range (RT) also play a part.

For the perception of low-pass filtered speech (ΔDl) the dynamic range and the critical ratio at 500 and 1000 Hz seem to be important (Table 5.16(c)). Some high-frequency phoneme-perception parameters are also included (q2, n2). The latter is involved in the prediction of high-pass filtered speech (ΔDh) as well

(Table 5.16(c)). However, the perception of high-pass filtered speech is determined mainly by gap-detection parameters (G2, GT, and GM). The presence of low-frequency tone-perception parameters in the predicting sets for ΔDh may indicate the influence of upward spread of masking.

Frequency-specific parameters		multiple R^2	Mean/trend parameters		multiple R^2
a. prediction of SHL in noise (D)					
1. gap threshold 2000 Hz	: G2	.577	1. mean critical ratio	: CM	.562
2. critical ratio 1000 Hz	: C1	.705	2. gap trend	: GT	.686
3. BM-slope 500 Hz	: B½	.740	3. F2 (isolated vowels)	: f2	.738
4. BM-slope 1000 Hz	: B1	.807	4. critical ratio trend	: CT	.764
5. BM-slope 2000 Hz	: B2	.844	5. BM-slope trend	: BT	.780
b. prediction of ΔSHL in quiet (A)					
1. loss 500 Hz	: L½	.874	1. mean loss	: LM	.774
2. BM-slope 2000 Hz	: B2	.912	2. dynamic range trend	: RT	.878
3. FM-slope 1000 Hz	: F1	.925	3. gap trend	: GT	.906
4. critical ratio 500 Hz	: C½	.933	4. critical ratio trend	: CT	.928
5. loss 2000 Hz	: L2	.949	5. mean FM-slope	: FM	.943
c. prediction of ΔSHL lp-filtered (ΔDl)					
1. Cvc-frication (quiet)	: q2	.400	1. FM-slope trend	: FT	.527
2. dynamic range 500 Hz	: R½	.641	2. critical ratio trend	: CT	.641
3. dynamic range 1000 Hz	: R1	.693	3. mean gap threshold	: GM	.733
4. critical ratio 500 Hz	: C½	.741	4. Cvc-frication (noise)	: n2	.752
5. critical ratio 1000 Hz	: C1	.812	5. Cvc-frication (quiet)	: q2	.767
d. prediction of ΔSHL hp-filtered (ΔDh)					
1. gap threshold 2000 Hz	: G2	.706	1. gap trend	: GT	.559
2. critical ratio 500 Hz	: C½	.803	2. mean gap threshold	: GM	.769
3. Cvc-frication (noise)	: n2	.867	3. Cvc-frication (noise)	: n2	.834
4. F2 (isolated vowels)	: f2	.893	4. F2 (isolated vowels)	: f2	.879
5. loss 500 Hz	: L½	.913	5. dynamic range trend	: RT	.925

TABLE 5.16. Prediction of speech-perception data from a stepwise multiple-regression analysis. The numbers of the first column represent the order of inclusion of the parameters. The resulting multiple-R^2 values are indicated.

5.5 Discussion

The results of this study have shown that a large number of parameters can rather reliably be obtained from hearing-impaired subjects. The analysis of data from mean and trend parameters provides a useful complement to the information from frequency-specific parameters.

Some comments can be made on the individual tests:

1. Information from dynamic-range data was limited because of the strong correlations with audiometric thresholds. On the other hand, uncomfortable loudness levels proved to be unrelated to nearly all other parameters.

2. The independent role of difference limens for intensity in our results is in agreement with Ross et al. (1965).

3. In this experiment the critical ratio was used as an indirect estimate of frequency selectivity. Patterson and Moore (1983) recently showed that CR is not the optimal parameter because of confounding effects of detection efficiency. However, the critical ratio is still related to frequency selectivity, as was shown in Section 3.3.2.2 and was found also by Pick et al. (1977) and Festen and Plomp (1983). The influence of detection efficiency may explain the position the mean CR (CM) in between of the positions for hearing loss for speech in quiet (A) and in noise (D) rather than near the hearing loss for speech in noise (Fig. 5.12(b)). Festen and Plomp (1983) suggested the same on the basis of their results at 1000 Hz.

4. Forward- and backward-masking slopes are strongly correlated. This correlation is presumably induced by the common dependence on pure-tone thresholds. As Plomp (1964) demonstrated, for normal-hearing subjects forward-masking slopes strongly depend on the sensation level of the masker. As we measured at a fixed SPL value, the sensation level of the masker is determined by the pure-tone loss. Our hypothesis is supported by the fact that the correlation coefficients are significantly reduced after partialing out the audiometric loss.

5. The analysis of dissimilarity matrices of isolated vowels and confusion matrices of CVC-vowels shows clear differences, which may be caused by differences between discrimination and identification (see also Walden et al., 1980).

6. In the results of consonant perception the dominance of voicing and nasality is consistent with recognition

data for normal-hearing subjects with filtering and background noise (Miller and Nicely, 1955; Wang and Bilger, 1973), and for hearing-impaired subjects (Danhauer and Singh, 1975).

With respect to the analysis of correlation matrices, it should be noted that the correlations found are influenced by interactions between tests. Sometimes correlational clusters were found in which all tests show strong mutual correlations. Not seldom were the audiometric parameters involved in these clusters. This does not imply that the other tests in the cluster are not related, but correlations with the audiogram make it impossible to reveal a clear relationship.

The principal-components analysis accounts for these interactions. A clearly interpretable two-dimensional space is obtained, in which the relations found are summarized (Fig. 5.11). The horizontal factor of Fig. 5.11(b) distinguishes phoneme perception from tone perception and the vertical factor distinguishes low and high frequencies. The separation of phoneme-perception and tone-perception parameters may be a consequence of the involvement of totally different mechanisms in both tasks, but may also be due to the limited influence of each frequency band upon the perception of broadband stimuli. The latter suggestion finds support in the analysis of the mean and trend results (Fig. 5.12): phoneme-perception parameters show a clear correspondence with trend parameters. The dichotomy between various phoneme-perception parameters in relation to the presence or absence of background noise may indicate perceptual differences in quiet and noise conditions. The place of the filtered-speech conditions in Fig. 5.11 suggests that the influence of noise on the perception of phonemes is caused by the lower-frequency parts of the spectrum. This is in agreement with the findings in Chapter 4 and it provides a possible explanation of the importance of high-frequency parameters for speech intelligibility in noise.

Finally, in the multiple-regression analysis, sets of tone-perception and phoneme-perception parameters for the prediction of speech-perception results were obtained. The presence of loudness-perception, frequency-resolution, and time-resolution parameters in the sets was not induced by relations with, for example, the audiometric loss, but shows the independent role of these auditory properties in the perception of speech. A clear illustration of this independent role is given by the predictive sets for the hearing loss for speech in noise (Table 5.16(a)): in these sets audiometric-loss parameters are not even included at all.

5.6 Conclusions

On the basis of this study the following conclusions may be drawn:

1. contrary to speculations about a trade-off relation between frequency resolution and temporal resolution, we found a co-occurrence of poor frequency resolution and poor temporal resolution;

2. impaired speech intelligibility is related to both frequency resolution and temporal resolution;

3. for speech intelligibility in noise especially the 2000-Hz parameters are important, and for speech intelligibility in quiet the lower-frequency parameters are important;

4. phoneme-perception parameters are related to trend parameters (e.g. slope of the audiogram) rather than to frequency-specific parameters;

5. phoneme-perception parameters play only a role of secondary importance in speech intelligibility.

CHAPTER 6

FINAL DISCUSSION

6.1 Evaluation of the experimental approach

The review of the literature presented in Chapter 2 supported the need for relational studies on speech perception in hearing-impaired subjects. Several basic auditory properties seem to influence speech intelligibility, but possible interactions cannot be investigated by means of separate studies. In our opinion the battery approach has proved to be a valid tool for investigating complex relational structures. Although the causality of the relations found is subject to interpretation criteria, the battery approach provides direct comparisons with speech intelligibility measures. In the results of the principal-components analyses and multiple-regression analyses interactions between different test are taken into account.

The experiments described in Chapter 3 were limited to static auditory properties. Vowel-perception experiments yielded useful information about an intermediate stage between tone perception and speech perception. For the extension of this approach to dynamic properties in consonant-perception experiments as an intermediate stage, first of all a better knowledge of the effects of presentation level and signal-to-noise ratio on phoneme perception was necessary (see Chapter 4). In the final experiments descibed in Chapter 5 the three-frequency set-up of the tone-perception experiments yielded useful information about the influence of specific frequency regions and the importance of a trend across frequencies. Differences in perceptual strategy between individuals or between situations involving the same individual could be traced by means of INDSCAL analyses of phoneme-perception data. The differences between speech intelligibility in quiet and in noise show the indispensability of both aspects of speech perception. The results show that the phoneme-perception parameters play a rather independent role. Interindependence of tone-perception and phoneme-perception parameters may reflect differences between psycho-acoustic and phonetic processing modes as described by Tyler et al. (1982b). Interindependence of phoneme-perception and speech-perception parameters may reflect the fact that speech intelligibility is not only determined by the perception of individual phonemes.

However, the finding that phoneme-perception parameters are related primarily to filtered-speech parameters is somewhat surprising and may be caused by a second-order importance of phoneme-perception parameters. This implies that the bridging function of phoneme-perception parameters between tone perception and speech perception is not fulfilled. But the phoneme-perception experiments yielded other important information. The results of the multiple-regression analysis showed that loudness perception, frequency selectivity, and temporal resolution have their own contribution to the perception of speech by hearing-impaired subjects.

6.2 Speech intelligibility in the hearing impaired

In the light of our experimental results, we will review the suggestions concerning possible impairment of speech intelligibility mentioned in Chapter 1. With respect to the auditory properties of loudness perception, there seem to be effects of a reduced dynamic range on speech intelligibility in quiet, but these can hardly be distinguished from the effects of elevated pure-tone thresholds with which they are confounded. There seems to be no influence of JND's for intensity on speech perception in our results. This may be due to the fact that the majority in our group of subjects showed cochlear losses. In cases of retrocochlear impairment JND's for intensity are presumably larger and may become a limiting factor in the perception of speech sounds. With respect to auditory frequency selectivity, frequency-discrimination ability was not focussed upon in our study. The correlations between the critical-ratio parameters and the perception of vowels reflect the difficulty of extracting formants in speech due to reduced frequency resolution. An increased susceptibility to masking noise due to broader critical bands is reflected in the high correlation between the mean critical ratio and the speech-reception threshold in noise. From the results with high-pass filtered speech some indications for the detrimental effect of upward spread of masking upon the perception of speech were obtained. With respect to auditory temporal resolution this study provides several indications that both forward- and backward-masking slopes and gap-detection thresholds are important for speech perception. Forward- and backward-masking slopes show relations with phoneme-perception parameters and speech-reception thresholds in quiet; gap-detection parameters seem above all to be involved in speech intelligibility in noise.

In this study the number of auditory properties investigated had to be limited. Speech intelligibility may also be impaired by excessive production of aural harmonics (de Boer and Bouwmeester, 1974 and 1975). There are also indications of the absence of lateral suppression in hearing-impaired subjects (Wightman, 1977; Festen and Plomp, 1983). This fact is assumed to cause a deterioration of non-simultaneous frequency selectivity, but any direct relations with speech intelligibily are unknown. For communication situations the effects of binaural phenomena such as the cocktail-party effect and binaural dereverberation are important. In view of the difficulties experienced from background noise and reverberation these aspects may also be crucial to speech intelligibility in daily life. For severely hearing-impaired subjects lipreading provides a useful complement to auditory information. For these subjects directional hearing is of great importance. Therefore, binaural interaction should also be considered by choosing the method of auditory rehabilitation (for a review see Markides, 1977).

6.3 Comparisons with other relational studies

Comparing our results with the relational studies mentioned in Section 2.6, there is a good deal of agreement about the following points:

1. there is no trade-off relation between frequency selectivity and temporal resolution in hearing-impaired subjects;

2. both frequency selectivity and temporal resolution are related to speech intelligibility, although these relations are also influenced by the common dependence on audiometric thresholds;

3. the higher-frequency parameters are important for speech intelligibility in noise;

4. speech intelligibility shows low correlations with phoneme-perception parameters (see also Tyler et al., 1982a, who used voice-onset-time experiments);

5. there are high inter-individual differences in hearing-impaired populations.

In greater detail, our study is most directly comparable with the work of Festen and Plomp (1983), who concentrated on tone-perception parameters at 1000 Hz and their relations to speech intelligibility in quiet and noise for a rather homogeneous population of sensorineurally hearing-impaired subjects. The matrix of correlation coefficients of the parameters common to both studies has been calculated and is presented in Table 6.1. In spite of the different populations used, the correspondence is striking. Festen and Plomp's results show that more direct estimates of the frequency-resolving power obtained from rippled-noise measurements and psychophysical tuning curves are more closely related to speech intelligibility in noise than the CR measure we used. Because they did not measure gap-detection thresholds, a possible relation between speech intelligibility in noise and temporal-resolution parameters could not be revealed.

		1	2	3	4	5	6	7
1. mean audiometric loss		*						
2. click threshold	(1 kHz)	.99 *.95*	*					
3. click in noise	(1 kHz)	.21 *.34*	.20 *.23*	*				
4. critical ratio	(1 kHz)	.61 *.59*	.61 *.52*	.30 *.29*	*			
5. backward-masking slope	(1 kHz)	-.97 *-.80*	-.96 *-.79*	-.16 *-.23*	-.60 *-.49*	*		
6. forward-masking slope	(1 kHz)	-.98 *-.78*	-.97 *-.75*	-.31 *-.16*	-.56 *-.49*	.94 *.91*	*	
7. SHL in quiet		.84 *.83*	.86 *.80*	.12 *.26*	.71 *.53*	-.82 *-.81*	-.82 *-.85*	*
8. SHL in noise		.52 *.38*	.54 *.22*	.08 *-.14*	.74 *.63*	-.57 *-.24*	-.44 *-.32*	.57 *.31*

r: this study (n=21)
r: Festen and Plomp, 1983 (n=22)

TABLE 6.1. Matrix of correlation coefficients between parameters common with the study by Festen and Plomp (1983).

In addition, some comparisons with the work of Tyler et al. (1982a,b) can be made, although their results originate from mixed groups including both normal-hearing and hearing-impaired subjects. With that restriction in mind the correlation coefficients at 500 Hz in Table 6.2(a) can be compared. There is reasonably good agreement, with the exception of the correlation between CR and speech thresholds and the correlation between temporal integration and audiometric loss. The latter discrepancy may be due to the rather rough estimate of temporal integration we obtained.

a. 500-Hz parameters

	1	2	3	4
1. audiometric loss (500 Hz)	*			
2. critical ratio (500 Hz)	.51 *-/.51*	*		
3. temporal integration (500 Hz)	-.62 *-.35/-.29*	-.37 *-/-.30*	*	
4. gap detection (500 Hz)	.61 *.52/-*	.47 *-/-*	-.18 *-.17/-*	*
5. speech-in-noise thresholds	-.47 *-.70/-.39*	-.53 *-/-.17*	.15 *.03/.11*	-.55 *-.62/-*

b. 4000-Hz parameters

	1	2	3	4
1. audiometric loss (4000 Hz)	*			
2. critical ratio (4000 Hz)	.72 *-/.27*	*		
3. temporal integration (4000 Hz)	-.38 *-.67/-.56*	-.22 *-/-.26*	*	
4. gap detection (4000 Hz)	.64 *.67/-*	.76 *-/-*	.08 *-.47/-*	*
5. speech-in-noise thresholds	-.62 *-.73/-.64*	-.71 *-/-.25*	.10 *.67/.32*	-.76 *-.73/-*

r: this study, 1983 (n=21)
r_1/r_2: Tyler et al., 1982 a,b
r_1: 1982a (n=32)
r_2: 1982b (n=41)

TABLE 6.2. Matrix of correlation coefficients between parameters common with or comparable with the work of Tyler et al. (1982a,b).

For the higher frequencies we compared our results at 2000 Hz with their results at 4000 Hz (see Table 6.2 (b)). The correspondence for the higher frequencies is much smaller with some positive exceptions for the relations between audiometric loss, gap detection, and speech intelligibility in noise. Discrepancies may be caused by the differences in test frequency. In summary, within different populations of sensorineurally hearing-impaired individuals there is agreement to a certain extent about the effects of frequency resolution and temporal resolution upon speech intelligibility. On the other hand, high correlations are scarce and all authors report considerable inter-individual differences.

6.4 Implications for clinical audiometry

How can the hearing-impaired individual benefit from these results? In our opinion the results of this kind of research should have implications for routine clinical audiometry. Although the pure-tone audiogram is definitely the most important test of hearing impairment, it provides only a limited insight into the residual auditory abilities. Particularly in audiometric investigations directed towards auditory rehabilitation, it would be advisable to compose a small test battery in order to screen some of the basic auditory properties described in this study. Possible components of such a battery are:

1. Screening on frequency resolution, for instance at 500 and 2000 Hz. Although not included in the present study, Patterson's (1982) technique with stopband noise maskers seems to provide the most reliable estimates and can easily be transformed into a fast screening method.

2. Screening on temporal resolution. In view of our results gap-detection thresholds are strong candidates. They are easier to measure than forward- or backward-masking slopes and a single measure will suffice, because in our experiments the frequency-dependence proved to be small. If one is interested in masking slopes, the method of Zwicker and Schorn (1982) can be taken into consideration.

3. Screening on binaural interaction. The most appropriate test should be looked for in the research on binaural phenomena in hearing-impaired subjects.

4. Of course, the measurement of speech hearing loss in noise is obligatory.

Some tests will need a higher reliability than is possible with the use of routine clinical methods. The results of this study show that a high reliability can be realized in hearing-impaired subjects, but a great deal of attention must be devoted to the experimental procedure. A consistent protocol will facilitate cooperation on the part of untrained subjects. A 3-AFC procedure may be more appropriate than one with two alternatives.

It would be encouraging to use a test battery such as the one described above if hearing aids were able to eliminate or circumvent the problems due to distortion of impaired loudness perception, frequency selectivity, or temporal resolution. Unfortunately, the prospects of a complete compensation for decreased frequency selectivity are not promising. Earlier attempts using frequency-lowering or spectral sharpening have failed (e.g. Braida et al., 1979). The prospects of dichotic presentation have been meager thus far. Likewise, a complete compensation for impaired temporal resolution is hard to imagine, although no research has been devoted to this area. However, although complete compensation may be a utopia, alleviation of the complaints is within reach and can be improved by proper signal processing. A set of data such as the present one should, in relation to the results of auditory rehabilitation of individual hearing-impaired subjects, provide guidelines for future developments in hearing-aid design.

In the meantime, the selection from currently available hearing aids may be improved by the results of such a test battery:

1. A reduced dynamic range may profit from the application of compression. Although data on single-channel compression (Dreschler, 1983c) or multi-channel compression (Lippman et al., 1982) have failed to establish improved speech intelligibility in groups, it may work for some individuals. According to experiments by Laurence, Moore, and Glasberg (1983), two-channel compression seems to be able to improve speech intelligibility.

2. An increased upward spread of masking due to reduced frequency resolution should caution against amplification of the low-frequency components (e.g. Gutnick, 1982).

3. Impaired temporal resolution may be a contra-indication against unnecessary temporal distortions as introduced by compression.

4. A relatively high hearing loss for speech in noise should lead to special attention being given to the amplification of the higher frequencies (e.g. Skinner, 1980, 1983).

5. Difficulties in binaural interaction will have consequences for the use of two aids: their similarity may be critical, and the use of two compression aids may introduce extra uncertainties.

When all these measurements are combined with the knowledge that the subject's own experience remains a decisive factor, this test battery may enhance the quality of auditory rehabilitation.

6.5 Concluding remarks

In summary, this study provides strong indications for the involvement of various basic auditory properties other than the pure-tone thresholds in the perception of speech by hearing-impaired subjects. It suggests some possible extensions of the routine clinical test battery in order to find the limiting factors to good speech intelligibility for each individual. The choice of auditory rehabilitation by means of hearing aids should be directed towards alleviation of these limiting factors. Future developments in hearing aids may increase the possibilities of compensation for reduced frequency selectivity or temporal resolution.

SUMMARY

1. The aim of this study

Hearing impairment is characterized not only by attenuation of sounds, but usually also by different kinds of distortion due to changes in auditory functions in the pathological auditory system. In the present study a number of distortions is investigated and relations with reduced speech intelligibility are established.

2. Experimental approach

In Chapter 1 possible effects of changes in loudness perception, frequency selectivity, and temporal resolution upon the perception of speech are discussed. In the second chapter the psychophysical literature on hearing impairment is reviewed in order to find support for these suggestions. Many studies are concerned with a single property of the auditory system, and this prevents the interpretation of the results in relation to speech intelligibility. For this reason, in the present study an integral psychophysical approach was applied, aimed at more than one auditory property. Relations were investigated by means of inter-individual differences in test results. In this way underlying interactions between auditory properties could be revealed and possible changes in perceptual strategy could be determined.

3. Experimental results

In Chapter 3 the results of a preliminary experiment on a heterogeneous group of 10 hearing-impaired subjects are presented. In this study the effects of the pure-tone audiogram and of frequency selectivity upon speech intelligibility in quiet and in noise were investigated. As an intermediate stage between tone perception and speech perception, the perception of isolated vowels was mapped by means of a non-verbal discrimination test. The relations between the test parameters show that speech intelligibility in noise depends mainly on distortion factors like the slope of the pure-tone audiogram and the width of the 'critical band' as a measure of frequency selectivity. There is also a significant correlation with the perceptual pattern of vowel discrimination. The composition of the group of subjects appears to interfere with the determination of the separate effects of pure-tone acuity and frequency selectivity.

In speech perception not only static properties are at work. Especially in the perception of consonants - which are supposed to be more important for speech intelligibility than vowels - dynamic properties play an important part. Before extending the

preliminary study in this direction, Chapter 4 is concerned with the influence of signal-to-noise ratio upon the perception of phonemes by hearing-impaired subjects. From confusion matrices of initial consonants, vowels, and final consonants, it is concluded that the pattern of confusions is determined particularly by the presence or absence of interfering noise. The effects of presentation level are of secondary importance. In conditions with interfering noise an increased use of high-frequency information is shown.

Finally, Chapter 5 is devoted to the results of a large battery of tests, including tests on tone perception, phoneme perception and speech perception on 21 sensorineurally hearing-impaired listeners. The tone-perception tests were directed to the pure-tone audiogram, loudness perception, frequency selectivity, and temporal resolution at 500, 1000, and 2000 Hz. The results were analyzed according to both the individual frequencies and the mean and trend over the three frequencies. Tone-perception parameters show a close relationship per frequency. For speech intelligibility in quiet the parameters at 500 and 1000 Hz appear to be important, in noise the parameters at 2000 Hz play an important part. Phoneme-perception parameters are related mainly to the trend over frequencies of tone-perception parameters. They only show an important relation with speech perception in cases of speech filtering.

4. Final discussion

In Chapter 6 the experimental results are compared with the results from other studies. The merits of our approach using analysis of inter-individual differences in a large battery of tests are evaluated. Finally, the implications for the rehabilitation of hearing-impaired subjects by means of hearing aids are discussed.

SAMENVATTING

1. Probleemstelling

Bij slechthorendheid treedt niet alleen een verzwakking van het aangeboden geluid op, maar meestal gaat deze gepaard met verschillende soorten van vervorming ten gevolge van veranderingen in auditieve functies van het pathologisch gehoor. In dit onderzoek worden enkele soorten van vervorming in kaart gebracht en gerelateerd aan verminderd spraakverstaan.

2. Werkwijze

In hoofdstuk 1 wordt besproken welke effecten veranderingen in de luidheidsopbouw, het frequentie-oplossend vermogen en het tijd-oplossend vermogen kunnen hebben op het verstaan van spraak. In het tweede hoofdstuk wordt nagegaan in welke mate deze veronderstellingen steun vinden in de psychofysische literatuur over het spraakverstaan van slechthorenden. Bij veel studies blijkt de concentratie van aandacht op slechts een aspect van het auditief systeem een handicap te zijn bij de interpretatie van de experimentele resultaten. Daarom is in dit onderzoek gekozen voor een geintegreerde psychofysische benadering van meer dan een eigenschap van het auditief systeem. Hierbij wordt gebruik gemaakt van de samenhang van inter-individuele verschillen in testresultaten. Op deze manier kan inzicht verkregen worden in de onderlinge interaktie van deze eigenschappen en kunnen mogelijke veranderingen in luisterstrategie bij slechthorenden worden vastgesteld.

3. Experimentele resultaten

In hoofdstuk 3 worden de resultaten beschreven van het eerste onderzoek bij een heterogene groep van 10 slechthorende proefpersonen. Bij dit experiment werd de invloed van het toondrempel-audiogram en het frequentie-oplossend vermogen op het verstaan van spraak in stilte en bij achtergrondlwawaai onderzocht. Als tussenliggende stap tussen toonperceptie en spraakperceptie werd de perceptie van klinkersegmenten in kaart gebracht m.b.v. een non-verbale beoordelingstest. Uit de samenhang van de resultaten blijkt dat met name het spraakverstaan bij achtergrondlawaai afhankelijk is van vervorming introducerende factoren als de helling van het toondrempel-audiogram en de breedte van de 'kritieke band' als maat voor het frequentie-oplossend vermogen van het gehoor. Het spraakverstaan bij achtergrondlawaai blijkt ook redelijk te correleren met de patroon-wijzigingen in de perceptie van klinkers. De samenstelling van de groep proefpersonen blijkt het afzonderlijk vaststellen van de effecten van toondrempel-audiogram en frequentie-resolutie te bemoeilijken.

Voor het verstaan van spraak zullen echter niet alleen de bovengenoemde statische eigenschappen van belang zijn. Met name in de perceptie van medeklinkers - die geacht worden belangrijker voor het spraakverstaan te zijn dan klinkers - spelen dynamische eigenschappen een belangrijke rol. Alvorens het eerste experiment hiertoe uit te breiden, is in hoofdstuk 4 onderzocht in hoeverre de perceptie van fonemen door slechthorenden beinvloed wordt door de signaal-ruisverhouding. Uit de meting van verwarringsmatrices voor begin-medeklinkers, klinkers en eind-medeklinkers bij een groep van 25 perceptief slechthorenden kan worden afgeleid, dat met name de aan- of afwezigheid van achtergrondruis bepalend is voor de soort van verwarringen. Het effect van het spraaknivo is hieraan ondergeschikt. Bij achtergrondruis blijkt meer gebruik gemaakt te worden van de hoog-frequente informatie in de spraak.

Tenslotte worden in hoofdstuk 5 de resultaten beschreven van een breed opgezette testbatterij op het terrein van toonperceptie, foneemperceptie en spraakperceptie, gemeten bij 21 slechthorenden met een perceptief verlies. Bij de toonperceptietests werden parameters afgeleid voor het toondrempel-audiogram, de luidheids-opbouw, het frequentie-oplossend vermogen en het tijd-oplossend vermogen bij 500, 1000 en 2000 Hz. Bij de analyse werden zowel de resultaten per frequentie als het gemiddelde en de trend over de drie frequenties in de beschouwing betrokken. In de resultaten vertonen de toonperceptie-parameters een nauwe samenhang per frequentie. Voor het spraakverstaan zijn de toonperceptie-parameters bij 500 en 1000 Hz van belang in stilte, de parameters bij 2000 Hz van belang bij achtergrondlawaai. De foneemperceptie-parameters hangen vooral samen met de trend van toonperceptie-parameters over de drie frequenties en lijken pas bepalend voor het spraakverstaan bij filtering van de spraak.

4. Slotdiscussie

In hoofdstuk 6 worden de experimentele resultaten van dit onderzoek vergeleken met de resultaten van andere studies. De verdienste van de gevolgde aanpak via analyse van inter-individuele verschillen in een breed opgezette batterij auditieve tests wordt geevalueerd. Tenslotte worden de implicaties van de verkregen resultaten voor de revalidatie van slechthorenden m.b.v. hoortoestellen belicht.

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