ABSTRACT
Despite of the the remarks concerning the perceptual formant integration and some other factors, it is assumed that an F1/F2-plot based on Bark-scale, in which the vowel points can be plotted according to a continuous scale, is capable to show in the most cases the psycho-acoustical vowel differences concerning the features front/back, close/open, and rounded/unrounded (with some consideration also tense/lax).

About 50 vowel symbols have been used for the description of the vowel systems of the world. About the same number of 1 Bark sized circles have room on the physiologically possible F1/F2-space. This number seems to be near the general F1/F2 vowel resolution.

Different scales of the F1/F2-plot for the psycho-acoustical simulation, exemplified by German vowel material, are compared with each other: full logarithmic (A); linear up to 510 Hz, logarithmic above 510 Hz (B); technical mel-scale (C); F1/F2'-plot (D).

INTRODUCTION
According to the phonological theory, in a specific language maximally only about 10 phonemic vowel qualities can be distinguished using the phonological features front/back, close/open, and rounded/unrounded /1/2/3/.

On the basis of phonetic knowledge there are maximally about 50 phonetic vowel qualities in the languages of the world, if the phonetic features front/back, close/open, and rounded/unrounded are considered, because that amount of vowel symbols are used in literature, e.g. in /3/ (calculated in /4/).

Acoustic phonetics provides the description with the knowledge concerning the formants in the vowel quality perception. In the recent research, well outlined in /5/, it has been pointed that: 1) F1 and F2 are the most important formants; 2) F3 has relevance in some vowels, e.g. in the retroflex ones /6/ and in the perceptual integration of F2 and F3, e.g. in /7/; 3) intensity relationship of F2 and F3 (= t2/t3) might have relevance for phonemic perception /8/; also F1 and F2 might merge perceptually /9/. Because F3 varies in the most vowels very little and because its height is quite well predictable on the basis of F2, its descriptive relevance is not very great.

FORMANT AND VOWEL RESOLUTION
According to the experiments with speech synthesis made in /1/ as well as in /12/ the perceptual resolution (= difference limen, DL) is ca. 3-5 resp. 3-4 % for the formant F2. This means actually that at least about 450 vowel qualities could be distinguished additively from each other, if the same DL is applied for the formant F1, too (calculated in /4/). Nakagawa et al. /13/ doubted that the DL could be that small in natural vowel perception, and actually, they found larger DL's (about 6-13 %) for F2. The DL's for the back vowels were found to be larger than those for the middle and front vowels. The authors concluded that in judgements of vowel quality, the phonemic decoding process that must follow the acoustic analysis of the stimuli may be involved more in the perception of natural than in synthetic vowels. The very rough average vowel formant resolution would be thus ca. 10 %. If the possible F1/F2 vowel space is filled with vowel points which differ from each other by 10 %, we get ca. 60 vowels which seems to correspond very well to the maximal number of phonetic vowel qualities (= 50; cf. above).

General psycho-acoustics defines the limits of auditory perception in general. Here especially the Critical Band (CB) has been considered, a concept created by Fletcher, further developed by Zwicker /14/, and applied in several phonetic studies, e.g. in /15/16/4/10/. Zwicker points out the similarity between the mel and Bark scales, and states that the CB boundaries are not fixed, but relative ones /14/.

If the F1/F2-field is divided in cells by means of the CB boundary lines and every cell is replaced with a circle, it can be seen, that about 45 circles have space within the physiologically possible F1/F2-area (Fig. 1). It can also be seen that the logarithmic scale of F2 is not totally compatible with the CB boundaries: within the low area of F2 there remains empty room...
The assumption that the formants are perceptually integrated, if their distance is less than 3.5 Bark, is studied in Fig. 2. The 8 German long vowels are described by means of the averages of the formants Fl, F2, and F3. When the formant values are presented as 3.5 Bark sized circles, it can be seen where the possible perceptual formant integration (overlap of the circles) might be expected.

The main conclusion is that the full logarithmic scales enlarge the Fl (here vertical) dimension, the other representations enlarge the F2 (here horizontal) dimension. Full logarithmic scales (A) have no experimental evidence (cf. /19:46-47/), and they should be rejected therefore. The linear scale up to 510 Hz (B) compresses the vertical dimension (F2) a little bit, and the technical mel scale (C) compresses it more. Additionally, the formula of the technical mel yields incorrect (too high) formant mel values in higher frequencies (cf. /19:48/). If Fl/F2' (D) is used, the distance between unrounded and rounded
Fig. 3. Different scale transformations used for the psycho-acoustical F1/F2 vowel space simulations. A. Full logarithmic; B. Linear up to 510 Hz, logarithmic above 510 Hz; C. Technical mel-scale; D. F1/F2' plot based on the Carlson, Fant & Granström formula (1975). Scale markings show the original Hz-values. Fixed critical band boundaries /14/ are indicated for A - C. In B and C the size of the vowel circles corresponds roughly to 1 Bark. Standard German short and long vowels produced by five male speakers (N=5x5x15=375) are used. Comparison of the figures shows, how the relative vowel positions are changed in the different simulations.

One Bark sized vowel circles freely moving on an F1/F2-pl0t based on Bark scale

Fig. 4 shows the improved version of the F1/F2-plot (B) based on Bark scale. This plot has been included in the ISA speech processing system developed by R. Toivonen. The original Hz values of the formants are changed into Bark values, and every vowel point can be plotted freely on the F1/F2-chart according to a continuous scale, which corresponds to the theory that the CB boundaries are not fixed but relative /14/. Actually, only "vowel squares" could properly show the Bark distances, but here 1 Bark sized circles are preferred. They can be understood as points looking around themselves: Do they have independent perceptual space enough? In Fig. 4 (about the same as Fig. 3, B) the German vowels are represented by means of averages calculated from five single occurrences uttered by five male native speakers (numerical values in /10/).

A vowel space is a feature space which hardly can be simulated totally by any monolithic formant chart (cf. the problems caused by nasal, laryngealized, breathy, tense/lax, and short/long vowels). We assume, however, that the F1/F2-plot proposed here is a quite good approximation for the psycho-acoustical vowel space considering the prime features front/back, close/open, and rounded/unrounded. Also the tense/lax opposition typical for North German can, with certain reservations, be shown on the plot. On the other hand it is not an easy task to prove by means of the F1/F2-plot only, whether the vowel is rounded or more retracted on the basis of lowered F2.
Fig. 4. An improvement of the simulation B in Fig. 3. True Bark scales are used. The 1 Bark sized vowel circles can be freely placed according to relative Bark distances. Critical band boundaries according to /14/ are indicated.

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