This paper is an analysis of the Finnish vowel system with special reference to the boundaries between the vowel phonemes. Two basically different methods are followed: One is synthetic, in the sense that sounds are first synthesized mechanically and then phonemically identified by native speakers of Finnish. The other method is analytic: sounds uttered by a native Finn are analyzed by spectrography. First the experiments and results of the synthetic approach are given, and after that the results of the spectrographic analysis. Finally the distinctive features of the Finnish vowel system are described.

The number of synthetic sounds\(^1\) used in the identification tests is 158. The only components that are varied in these sounds are the frequencies of the two lowest formants. \(F_1\) varies from 200 c/s up to 900 c/s in steps of 100 c/s, and \(F_2\) varies from 600 c/s up to 2600 c/s, likewise in steps of 100 c/s. Everything else in the sounds is fixed: \(F_3 = 2800\) c/s, \(F_4 = 3280\) c/s, \(F_5 = 120\) c/s (\(F_0\) rises slightly towards the end of the sounds), duration = 400 milliseconds. The sounds were identified by 150 Finnish university students. They were asked to attach a Finnish letter to each sound they heard.\(^2\) The results are given in Figures 1, 2, and 3. The curves in these charts designate the areas of those sounds that were identified as a particular phoneme by more than 90%, 50%, and 10% of the listeners. Agreement on the part of the listeners (dark areas) indicates that here lies a phoneme center. When we move from this center in any direction the listeners become less and less unanimous, until we reach a certain point beyond which unanimity increases again. This means that we have crossed a phoneme boundary and are approaching the center of another phoneme. We can also make a simpler chart of the phoneme areas. If we draw only the curves which symbolize those sounds that have a fifty fifty probability of being recognized as either of two adjacent phonemes, within each curve, then, will lie all the sounds that are identified as a particular phoneme more often than they are identified as any other phoneme. These curves are the ones that can most properly be considered phoneme boundaries. These boundaries are seen in Fig. 4.

\(^1\) It was very kind of Gunnar Fant to let me have this set of synthetic sounds made by the speech synthesizer OVE 2 in the Speech Transmission Laboratory, Royal Institute of Technology, Stockholm.

\(^2\) A letter in the Finnish writing system corresponds to a phoneme in the Finnish language. Finnish orthography is almost 100 percent phonemic.
The other method of finding the phoneme boundaries is analytic. About 200 vowel sounds (and about 60 lateral sounds) uttered by a native Finn were analyzed. The fundamental pitch in the sounds varies from 110 to 130 c/s. The sounds occurred between various consonants in syllables like tit, tet, tat, lii, lal, lal, mim, mem, mâm, mam etc. The sounds are plotted in a two-dimensional chart according to their
The boundary between /i/ and /y/ and between /e/ and /ö/ is perpendicular to the boundary between /a/ and /ö/. The equation of this line is

\[ F_a + F_1 = 2400 \text{ c/s} \]

There remains only one significant boundary. This is the one between /y/ and /i/.

The equation is

\[ F_a + F_1 = 2100 \text{ c/s} \]

Now all the Finnish vowels can be defined by using the boundaries explained above:

- /a/: \( F_1 > 570 \text{ c/s} \) and \( F_2 - F_1 < 600 \text{ c/s} \)
- /ä/: \( F_1 > 570 \text{ c/s} \) and \( F_2 - F_1 > 600 \text{ c/s} \)
- /ö/: \( 380 \text{ c/s} < F_1 < 570 \text{ c/s} \) and \( F_2 - F_1 > 600 \text{ c/s} \) and \( F_2 + F_1 < 2400 \text{ c/s} \)
- /e/: \( 350 \text{ c/s} < F_1 < 570 \text{ c/s} \) and \( F_2 + F_1 > 2400 \text{ c/s} \)
- /i/: \( F_1 < 380 \text{ c/s} \) and \( F_2 - F_1 < 550 \text{ c/s} \)
- /y/: \( F_1 < 350 \text{ c/s} \) and \( 2100 \text{ c/s} < F_2 + F_1 < 2400 \text{ c/s} \)
- /ö/: \( F_1 < 350 \text{ c/s} \) and \( F_2 + F_1 > 2400 \text{ c/s} \)

There are three kinds of distinctive features in Finnish:

1) In some distinctive features the frequency of \( F_1 \) is the decisive factor. These boundary lines are parallel to \( F_1 \) axis. Examples: boundaries between /i/ and /e/, /ö/ and /ö/, /u/ and /ö/.

2) In the distinctions /u/ vs. /ö/, /ö/ vs. /ü/, and /a/ vs. /ö/ the distance from \( F_1 \) to \( F_2 \), i.e., \( F_2 - F_1 \), is the phonemically relevant feature. Direction: /.

3) In some other distinctions the sum of \( F_2 \) and \( F_1 \) seems to be the relevant factor. Examples: boundaries between /i/ and /y/, /i/ and /ö/, /i/ and /a/, /ö/. Direction: /.

The distinctive features and phoneme boundaries are not absolute: The exact location of the boundaries is dependent on many factors, such as duration, fundamental pitch, environmental factors. So for example, the shorter a sound the closer to the center of the diagram (= neutral vowel) it tends to lie, the higher the fundamental, the higher the formants tend to be. The distinctive line between the [e] in [tel] and the [e] in [taë] is not identical with the distinctive line between the [e] in [tell] and the [e] in [taë]. Therefore, for a linguist trying to investigate the system operating in a language, it is not so important to give exact frequencies of distinctive features in a language, as it is to state 1) the number of contrasting sound units and 2) the directions of the boundaries between them (finding the directions is actually the same thing as finding out which mutual relationships between various formants are relevant in the system).

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1. This boundary is visible only in Fig. 5.
2. A more profound analysis of this distinctive feature needs the consideration of \( F_2 \) too.
3. We cannot say anything definite of the boundary between /i/ and /y/ because of the different results shown in Fig. 4 and Fig. 5.