ABOUT DIPHTHONGS. AN IMPLEMENTATION INTO VOWEL DISPERSION THEORY

Louis F.M. ten Bosch

1. INTRODUCTION

This study aims at the evaluation of the perceptual effects of diphthongization in vowel systems. Diphthongs are implemented into an extended version of the so-called vowel dispersion theory. The diphthong model obtained in this way copes fairly well with data from phonological databases. Moreover, the results allow diphthongization to be interpreted as a means for improving the perceptual quality of a vowel system. The model attempts to give a phonetically motivated interpretation for the *genesis* or *existence* of diphthongs, rather than a description of diphthongeal paths.

We will relate diphthongs (or rather diphthongeal sounds) to the vowel dispersion theory (Lindblom, 1972, 1975, 1986; Koopmans-van Beinum, 1980; Disner, 1980, 1983; Crothers, 1978; Bonder, 1986; Ten Bosch, Bonder and Pols, 1987). Vowel dispersion theory states that vowel systems generally tend to be optimal, in the sense that all vowels (considered as *phones*) must be evenly spread in the available vowel space. This idea was operationalized for the first time by Liljencrants and Lindblom (1972). They used a dispersion measure that depended on the inter-vowel distances in the two-dimensional formant space. Ten Bosch et al. (1987) combined articulatory and perceptual properties of vowels and introduced aspects of probability into the dispersion theory.
The next section deals with the static theory of vowel dispersion, according to Ten Bosch et al. (1987). In the third section we deal with the dynamic part within the theory, viz. the introduction of diphthongs and long vowels. In the fourth section we attempt to link the model results with linguistic data with respect to diachronical changes of vowels.

2. THE STATIC STRUCTURE OF VOWEL SYSTEMS

The idea of introducing aspects of probability into the theory of vowel systems is not new. In 1975, Lindblom suggested a relation between the acoustical distance of vowels and their mutual confusion probability. However, we implemented it in a slightly different way, using the exponential function and some ideas from probability theory as main tools.

We now briefly recall our monophthong model (Ten Bosch et al., 1987). Consider a vowel system consisting of N monophthongs only. Let $p(v_1, v_2)$ denote the probability of vowel v_1 and vowel v_2 being confused. The model assumes that the following relation holds:

$$p(v_1, v_2) = \exp(-\alpha . d(v_1, v_2)) \qquad (1)$$

$d(v_1, v_2)$ being the acoustic distance between these vowels, α a scaling paramater (here about 0.007), and 'exp' the exponential function (base e). (The acoustic distance d is evaluated by applying a perceptually based log-like transformation of the first two formant frequencies.) Evidently $0 < p \leq 1$. In the case of Dutch, this relation appears to be a satisfactory assumption as it yields theoretical confusion matrices, quite similar to

those which are experimentally obtained (provided the system does not contain long/short vowel pairs). Moreover, it allows a linking between confusion matrices and the internal structure of vowel systems *without* long/short opposition.
After having introduced p, we considered the perceptual quality of a vowel system (denoted D_F), defined by

$$D_F(\text{monophthong system}) = \prod (1-p(v_i, v_j)) \tag{2}$$

in which Π denotes the product over all vowel pairs (v_i, v_j). D_F may be interpreted as the probability that there exists *no confusion* within the system. If D_F would equal 1 (which is impossible), the system would be most optimal. If D_F equals 0, the system is of worst quality. D_F tends to 0 if two vowels get close to each other.
Optimization of D_F is not equivalent to optimization of ASC-like measures (ASC = Acoustic System Contrast, cf. Koopmans-van Beinum, 1980), as high ASC values do not necessarily yield high system dispersion.

With D_F figuring as the perceptual parameter to be optimized, we generated 'optimal' vowel systems for N = 3 up to 9. Figure 1 shows the probability for the generated model solution being one of the monophthong systems in the UPSID database. For more details we refer to Ten Bosch et al. (1987).

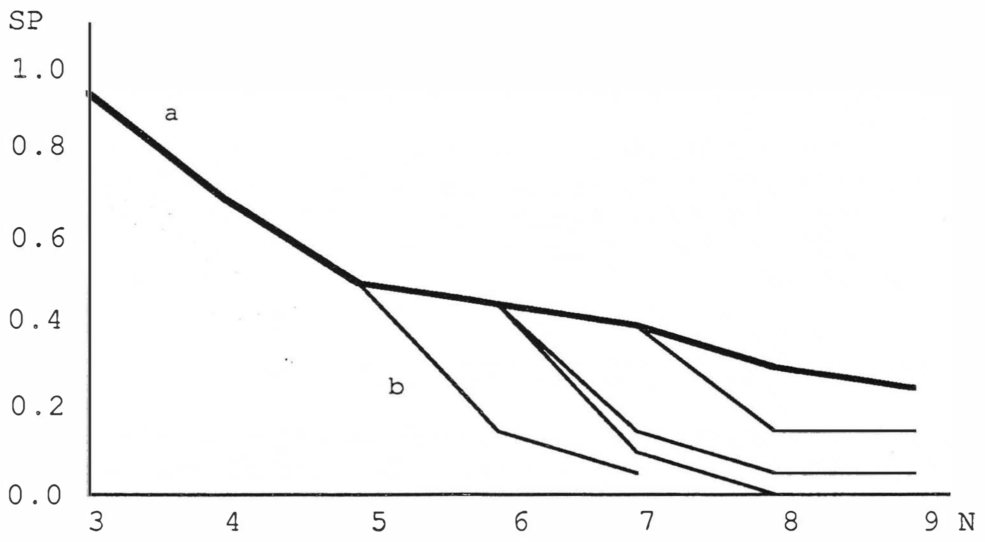

Figure 1. Goodness of fit of the monophthong model. Along the ordinate the probability is shown that the model solution can be found among the monophthong systems in the UPSID database (UPSID, 1981; Maddieson, 1984). This probability is denoted by SP (similarity probability). The heavy line (a) connects all the found maxima, (b) shows some possible ramifications. N denotes the number of vowels in the model system and the phonological reference system. One observes the decreasing SP-value for increasing values of N. Probably this phenomenon can be traced to
- the declining fit of the model itself
- the increasing number of linguistic possibilities for large systems.

3. THE DYNAMIC STRUCTURE OF VOWEL SYSTEMS: DIPHTHONGS

3.1 Linguistic aspects of diphthongs

Catford (1977) distinguishes two main types of diphthongs: a sequential one with long steady parts of the initial and final vowel sound, and a gliding one with a long gliding part between. Diphthongs are 'a sequence of two perceptually different vowel sounds within one and the same syllable' (p. 215). It is a so far unsolved problem what a diphthongeal sound makes a diphthong: the extent of the transition part, merely the existence of the transition part, or the quality of the initial and final vowel only (Pols, 1977; Bladon, 1985; Peeters, 1987).
Maddieson (1984) applies three phonologically inspired definitions for 'diphthong' in the UPSID database: a phonemic unit, a concatenation of two sub-phonemic units (nuclei or morae), or a CV- or VC-sequence, in which C is a semi-vowel. All these interpretations appeared to be useful in the description of linguistic data concerning diphthongs in phonological databases.

We now briefly recall the main properties of diphthongs as appearing in natural languages, using the diphthong studies carried out by Maddieson (UPSID, 1981) and Bladon (1985). (See table 1.)
In general, diphthongs have the following properties:
a. diphthongs reveal preference for the a-i or a-u axis;
b. diphthongs reveal preference for relatively long trajects;
c. /a/, /i/ (/j/) and /u/ (/w/) are often involved as one of the sound parts (Maddieson, 1984; section 8.7);
d. diphthongs tend to lack much contrast between the final segments;
e. except for a., b., c. and d., there is no clear patterning.

Table 1. Linguistic data concerning diphthongs (according to Bladon (1985), based upon UPSID, 1981). One observes less competition for the second element of diphthongs.

	second element								
first element	i,I	e	ɛ	a	ə	ɑ	ɔ	o	ʊ,u
i,I		6	2	8	8	1	1	3	5
e	18			1	2				3
ɛ	5				1				1
a	23	4			1			7	27
ə	5								3
ɑ	4	1			1			1	4
ɔ	2				1				5
o	17	1		1	1				15
ʊ,u	14	2	1	5	7	1	1	2	.

3.2 Dynamic structure within vowel dispersion theory

Most of the problems that arise in the phonetic-phonological interface are related to the fact that there exists no explicit link between phonological and phonetic units. The linguistically motivated definitions of diphthong do not fully cover their phonetic properties. Therefore we have to choose one specific interpretation in order to be able to relate diphthongs with dispersion theory. In our model, we describe diphthongs by initial and final (formant) position only, degrading the importance of the path in-between. This option is quite questionable, as it may seem rather arbitrary. Moreover, interpretation problems from the phonetic-phonological interface come in. They deal with the search for optimal sets of *phonemes (types)* by looking for optimal sets of *phones (tokens)*, without explicitly disclosing the phonetic-phonological link. However, the falsification procedure is fairly strong. We will present an evaluation of several diphthongized systems and a brief comparison with phonological tendencies.

We confine the discussion to vowel systems containing long vowels and diphthongs only, that means, systems *without* long/short opposition. We do not try to describe the path of a diphthong with given initial and final point, as these paths turn out to be highly dependent on articulatory fine-motions. (For a mathematical description of diphthongeal paths, we refer to Almeida, Drommel and Fiedler, 1977; Yang Shun-an, 1987). We focus on a phonetic explanation for the *genesis* or *existence* of a diphthong and will unfold the model by the following example.

Example 1. Let a 5-vowel system be given by the formant positions (300, 600), (800, 1300), (300, 2200), (500, 1000) and (500, 1800), roughly representing /u/, /a/, /i/, /o/ and /e/ respectively. The corresponding confusion matrix based on formula (1) with $\alpha = 0.007$ is given in table 2.

Table 2. Theoretical confusion matrix belonging to /u, a, i, o, e/. All entries represent fractions and are based upon formula (1).

	/u/	/a/	/i/	/o/	/e/
/u/	0.99	0.00	0.00	0.01	0.00
/a/	0.00	0.96	0.00	0.02	0.02
/i/	0.00	0.00	0.96	0.00	0.04
/o/	0.01	0.02	0.00	0.95	0.02
/e/	0.00	0.02	0.04	0.02	0.94

The perceptual quality of this system /u, a, i, o, e/ is $D_F = 0.8995$, according to monophthong formula (2).

Next, we consider the set of all possible diphthongs and long vowels emerging from this monophthong set. In this way we obtain 20 diphthongs /ai/, /ao/, /oa/, etc. and 5 long vowels /aa/, /oo/, etc. Diphthongs as well as long vowels will henceforth be called transitions.
From this set of transitions, we want to select K of them, such that this K-subset has minimal internal confusion probability (or, equivalently, maximal D_F). This search procedure is similar to the search for optimal vowel systems in case of monophthongs and is based upon the same principles concerning the relation between distance and confusion probability. Firstly, we introduce the confusion probability between transitions p (formula (3)) and the corresponding system quality D_F (formula (4)):

$$p(T_1, T_2) = \exp[-\alpha(d(v_1, w_1) + d(v_2, w_2))] \qquad (3)$$

T_1 and T_2 being the transitions $/v_1v_2/$ and $/w_1w_2/$, respectively

$$D_F(\text{transition system}) = \prod (1 - p(T_i, T_j)) \qquad (4)$$

Π denoting the product over all transition pairs in the subset of K transitions.

The search for optimal subsets of K transitions is implemented in a computer model which calculates the value of D_F (transition formula (4)) for all subsets of K elements out of the set of all transitions within the given N-vowel system. There might be a huge number of those subsets. (In fact, this number equals 25.24....(25-K+1)/1.2....K.2). However, the search for the optimal K-subset is not fascinating itself. Instead of extensively searching an optimal K-set, we attempted to find those K-subsets that are optimal and, simultaneously, can be seen as a simple extension of a subset consisting of K long vowels only. In this case, we are looking for those diphthongs which optimally improve the perceptual quality of a long-vowel system when they are exchanged for long vowels. In practise, we restrict our search procedure to those K-subsets which contain either

- K-1 long vowels and 1 diphthong, or
- K-2 long vowels and 2 diphthongs.

Moreover, we restrict the searching procedure to those K-subsets in which exactly K of the given N vowels participate. The model searches for the first (and second) optimal diphthong in a long-vowel system, or, equivalently, in a monophthong system without long/short opposition.
The following examples show results of the computer program. Cf. figure 2.

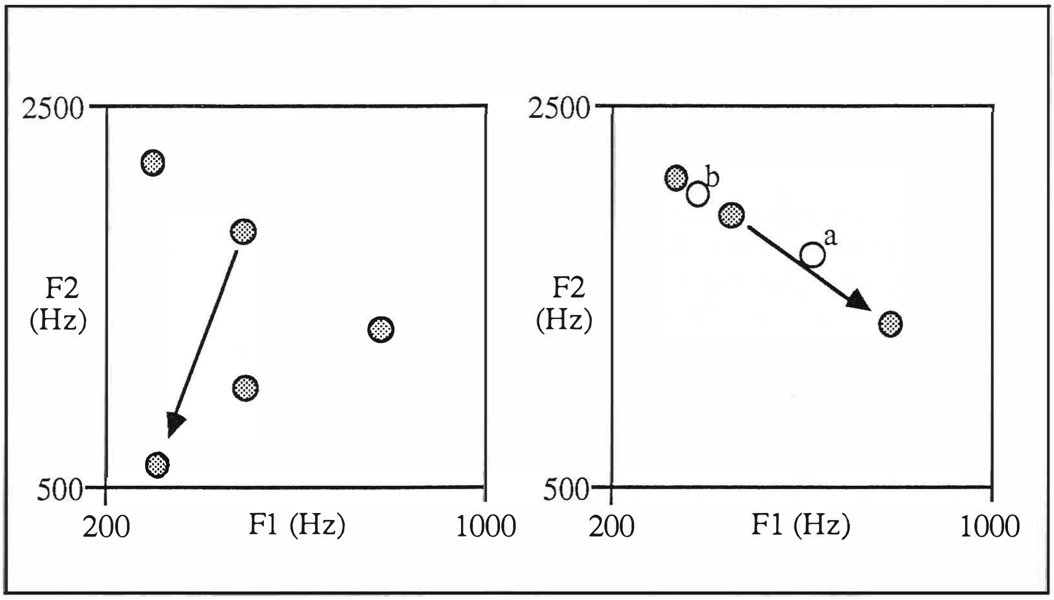

Figure 2. (Left) The vowel system from example 1. Both the F_1 and F_2-axes are linear. The arrow denotes the most preferred diphthong /eu/ in the system /uu, aa, ii, oo, eu/. (Right) The vowel systems from examples 2 (grey points plus point a) and 3 (grey points plus point b). In both examples, the most favourite diphthong is pointing from the /i/-region to /a/.

Example 1. 5-vowel system as above

K = 5

D_F(transition system) is now evaluated according to transition formula (4)

Total number of possible K-subsets: 3125 (= 5^5)

Highest value of D_F: 0.9998

Lowest value of D_F: 0.8895

The long-vowel system /uu, aa, ii, oo, ee/ figures on the *772*th place, $D_F = 0.9968$

Among the 771 improvements, there exist only 4 improved systems with exactly one diphthong, namely

/uu/, /aa/, /ii/, /oo/, /eu/,	$D_F = 0.9989$
/uu/, /aa/, /iu/, /oo/, /ee/,	$D_F = 0.9986$
/uu/, /au/, /ii/, /oo/ /ee/,	$D_F = 0.9972$
/uu/, /aa/, /ia/, /oo/, /ee/,	$D_F = 0.9971$

and 38 improved systems with exactly two diphthongs (the best one being /uu/, /aa/, /iu/, /oo, /ei/, $D_F = 0.9992$). /uu/ and /oo/ are relatively less diphthongized.

One may observe the very small differences in D_F. However, improvement of high values of D_F is difficult. The D_F-scale is highly non-linear on which 1.0000 cannot be reached.

Example 2.

4-vowel system (vowels will be represented by points)

point 1: (800, 1300) (a-like)

point 2: (600, 1700) (ε-like)

point 3: (450, 1900) (e-like)

point 4: (300, 2200) (i-like)

D_F(monophthong system) = 0.7294 (formula (2))

K = 4

Number of combinations: 256 (= 4^4)

Long-vowel system on 86th place, D_F(transition system) = 0.9724 (formula (4))

3 improved systems with one diphthong, of which the best is

/11/, /22, /31/, /44/ ($D_F = 0.9799$)

16 improved systems with two diphthongs, of which the best is

/11/, /22/, /34/, /41/ ($D_F = 0.9929$)

Example 3. (Compare with example 2.)

4-vowel system

point 1: (800, 1300) (the same)

point 2: (450, 1900) (the same)

point 3: (350, 2000)

point 4: (300, 2200) (the same)

$D_F = 0.4231$ (monophthong formula (2))

K = 4

Number of combinations: 256

Long-vowel system on 125th place, $D_F = 0.8003$ (transition formula (4))

3 improved systems with one diphthong, of which the best is

/11/, /22, /31/, /44/ ($D_F = 0.9863$)

23 improved systems with two diphthongs, of which the best is

/14/, /22/, /31/, /44/ ($D_F = 0.9868$)

These examples and other, similar ones show that the long-vowel system looses its large D_F-value in case of a badly dispersed position of the vowels. In case of vowel clustering (example 3, figure 2 right), diphthongization towards an isolated vowel outside the cluster (here point 1, /a/-like) becomes more and more favourable. In section 4 we will demonstrate this phenomenon in case of a five-vowel system with K = 5.

The results have to be extracted from numerically ordered linked lists in which relevant information is encoded about the transition configuration (obligatory lengtening or diphthongization, etc). Trees are constructed above the long-vowel system of all possible diphthongeal improvements together with their 'ramification degree'. For instance, a system with three long vowels and one diphthong /L_1, L_2, L_3, D_4/ has ramification degree 1 over the system with four long vowels /L_1, L_2, L_3, L_4/ if D_4 is a diphthongization of L_4. /D_1, L_2, L_3, D_4/ has ramification degree 2, provided D_1 and D_4 are diphthongizations of L_1 and L_4 respectively. Our search was limited to all systems containing K transitions with ramification degree less than 3.

We studied the diphthongization within about fifty vowel systems. From this evaluation we draw the following conclusions:

- *in general*, introduction of diphthongs in a monophthong system is favourable from the acoustic/perceptual point of view;
- introduction of diphthongs in a 3- or 4-vowel system is less useful (in the sense of optimalization of D_F) than in a vowel system containing more elements;
- diphthongs show preference for either long paths or very short paths. In the latter case, they may be interpreted as allophones of monophthongs;
- /a/, /i/ and /u/ are often involved in diphthongeal paths;
- in case of high local vowel density near the boundary of the vowel space, diphthongization of the vowels near the boundary is favourable.

4. RELATION TO DIACHRONICAL CHANGES OF VOWELS

We will give an example how the model may be valuable in explaining diachronical vowel shifts. We found this parallel while examining some of the model results but did not study it extensively until now. Further research will possibly disclose more of the involved peculiarities.

The model predicts relationships between long vowels and diphthongs with respect to the probability of their mutual exchange. It is well known that diphthongs may interchange their lexical position by long vowels and reverse. The Great Vowel Shift (15th century) deals with one of the many examples of this phenomenon, recognized by Lass as a push chain (Lass, 1984). Table 3 gives a survey of the main shifts involved. All transformations as found in the GVS and proposed in Dutch (table 4) can be decomposed into a small set of basic transformations:

- concerning monophthongs:
  - **T** (translation): $v_1 > v_2$ (in which the symbol '>' means 'becomes'),
  - **C** (curtailing) assimilation, i.e. curtailing the final part of the diphthong,
- concerning diphthongeal sounds:
  - **S** (splicing) dissimilation, i.e. splicing into two monophthongeal parts,
  - **G** (gliding) dissimilation, i.e. adding semi-vowel as final segment.

The vowel rotation **R** (cyclic rotation), determined by $v_1 > v_2 > ... > v_j > v_1$, as for instance applied by Disner (1980, 1983) in her descriptions of regularities and anomalies within vowel systems, can be decomposed into subsequent translations.

Table 3. Scheme of the Great Vowel Shift, according to Lass (1984). ME denotes Middle English. For explanation of the last column see the text.

ME 16th c. 20th c.	example	composition
i: $\xrightarrow{S}$ ei $\xrightarrow{S}$ ai	bite	S
e: $\xrightarrow{T}$ i: $\xrightarrow{0}$ i:	beet	T
ɛ: $\xrightarrow{T}$ e: $\xrightarrow{T}$ i:	beat	T
a: $\xrightarrow{0}$ a: $\xrightarrow{T}$ ɛ: $\xrightarrow{T}$ e: $\xrightarrow{G}$ ei	mate	GT
u: $\xrightarrow{S}$ ou $\xrightarrow{S}$ au	mouth	S
o: $\xrightarrow{T}$ u: $\xrightarrow{0}$ u:	boot	T
ɔ: $\xrightarrow{T}$ o: $\xrightarrow{S?}$ əu	boat	ST

Table 4. Some of the Dutch vowel dia- (and syn)chronisms. The proposed compositions given here have a tentative character.

sound development	example	composition
e: $\xrightarrow{G}$ ei ($\xrightarrow{C}$ e)	zee	(C) G
u: $\xrightarrow{T}$ y: $\xrightarrow{S}$ ʌy ($\xrightarrow{C}$ ʌ)	ui	(C) ST
e: $\xrightarrow{T}$ ɛ? $\xrightarrow{G}$ ɛi ($\xrightarrow{C}$ ɛ)	ei	(C) GT ?
i: $\xrightarrow{S}$ ɛi ($\xrightarrow{C}$ ɛ)	ijs	(C) S

In the right columns of tables 3 and 4 we denoted the decomposition code of the respective shifts, to be read from right to left. For instance, in the code '**GT**' '**T**' precedes '**G**'. All these codes are represented in figure 3.

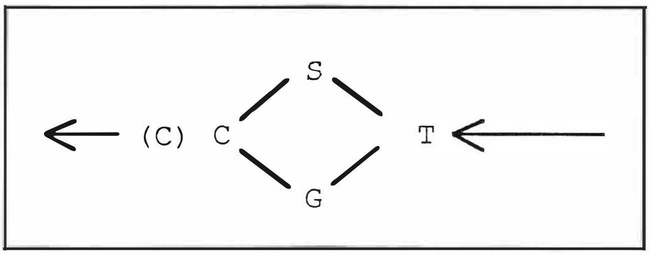

Figure 3. (De)composition scheme of diphthongeal codes.

In the evaluated examples, shifts of type **S** and **G** were frequently present in the development of a long-vowel system towards a diphthongized system. **S** and **G** may be seen as primary tools for introducing diphthongs diachronically. Both the transformations **S** and **G** can be traced in the improved systems with ramification degree 1 or 2. The following examples 4, 5 and 6 show both effects in a five-vowel system which gets worse and worse from the perceptual point of view. Figures 4 and 5 show the main results in case of ramification degree 1 and 2, respectively.

Example 4.

5-vowel system
point 1: (300, 600) (u-like)
point 2: (800, 1300) (a-like)
point 3: (300, 2200) (i-like)
point 4: (600, 1000) (o-like)
point 5: (500, 2000) (e-like)
short-vowel system: $D_F = 0.8601$ (monophthong formula (2))
K = 5
Number of combinations: 3125
Long-vowel system on 1246th place, $D_F = 0.99236$ (transition formula (4))
7 improved systems with one diphthong, of which the best is
/11, 12, 33, 44, 55/ ($D_F = 0.99563$)
63 improved systems with two diphthongs, of which the best is
/11, 25, 33, 44, 51/ ($D_F = 0.99932$)

Example 5.

5-vowel system
point 1: (300, 600) (u-like)
point 2: (650, 1050) (o-like)
point 3: (300, 2200) (i-like)
point 4: (550, 950) (ɔ, o-like)
point 5: (500, 2000) (e-like)
short-vowel system: $D_F = 0.6840$ (monophthong formula (2))
K = 5
Number of combinations: 3125
Long-vowel system on 2226th place, $D_F = 0.93143$ (transition formula (4))
10 improved systems with one diphthong, of which the best is
/11, 22, 33, 43, 55 ($D_F = 0.99515$)
100 improved systems with two diphthongs, of which the best is
/11, 22, 31, 43, 55/ ($D_F = 0.99927$)

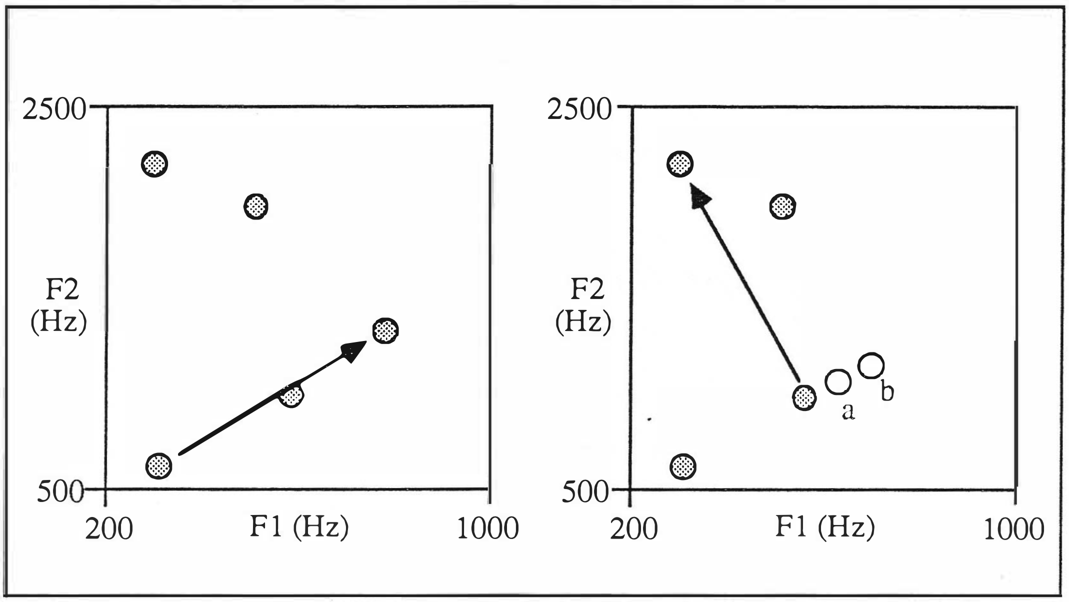

Figure 4. Best diphthongs in case of examples 4 (left), and 5 and 6 (right). In the right figure, examples 5 and 6 correspond to the four grey points plus point a and b, respectively.

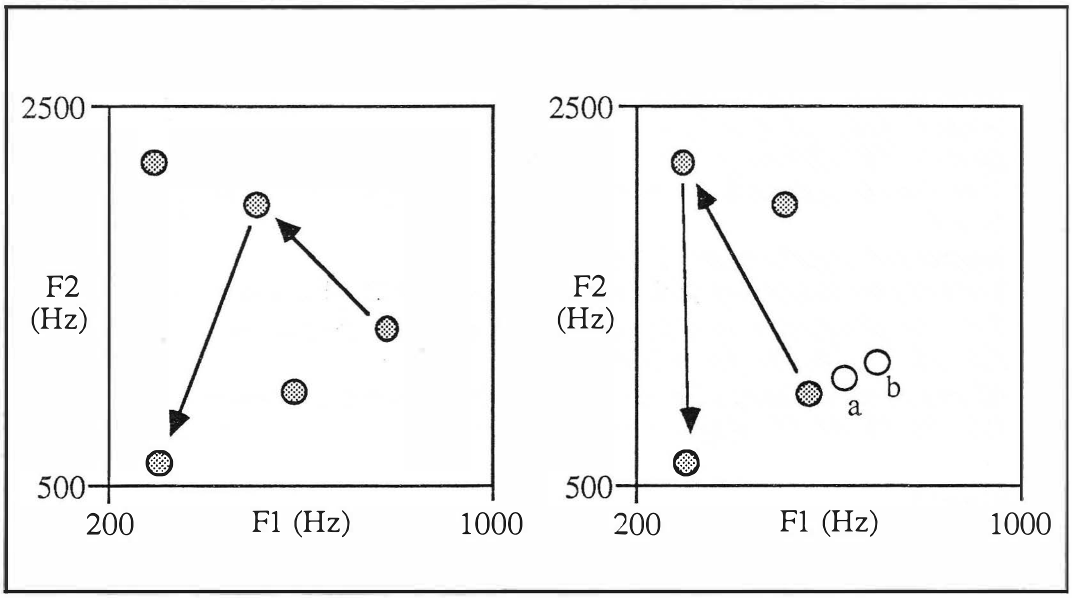

Figure 5. Most optimally improved systems containing two diphthongs in case of examples 4 (left), and 5 and 6 (right). In the right figure, examples 5 and 6 correspond to the four grey points plus point a and b, respectively.

One observes the system quality in example 5, which is substantially lowered due to the vicinity of the second and fourth vowel. Of the 100 systems with 2 diphthongs, the systems with large D_F always diphthongized the second or the fourth vowel, or both (splicing). In most of these diphthongs, the /i/ was involved (gliding).

Example 6.
5-vowel system, cf. example 5. Only second vowel (nr. 2) shifted.
point 1: (300, 600) (u-like)
point 2: (700, 1150) (α-like)
point 3: (300, 2200) (i-like)
point 4: (550, 950) (o-like)
point 5: (500, 2000) (e-like)
short-vowel system: $D_F = 0.8110$ (monophthong formula (2))
K = 5
Number of combinations: 3125
Long-vowel system on 1706th place, $D_F = 0.98319$ (transition formula (4))
10 improved systems with one diphthong, of which the best is
/11, 22, 33, 43, 55/ ($D_F = 0.99522$)
85 improved systems with two diphthongs, of which the best is
/11, 22, 31, 43, 55/ ($D_F = 0.99935$)

The lists corresponding to the two previous examples turn out to be very similar. Of all diphtongs figuring in the head of the list, about 75% diphthongized /i/ to /oi/ or /αi/ (or reverse) (gliding).
In the following three examples 7, 8 and 9, we show the effects of increasing vowel density near the space boundary in the neighbourhood of /i/. Figures 6 and 7 show the results in case of ramification degree 1 and 2, respectively.

Example 7.
5-vowel system
point 1: (300, 600) (u-like)
point 2: (800, 1300) (a-like)
point 3: (300, 2200) (i-like)
point 4: (650, 1650) (ε-like)
point 5: (500, 2000) (e-like)
short-vowel system: $D_F = 0.7397$ (monophthong formula (2))
K = 5
Number of combinations: 3125
Long-vowel system on 1476th place, $D_F = 0.97439$ (transition formula (4))
7 improved systems with one diphthong, of which the best is
/11, 22, 33, 41, 55/ ($D_F = 0.99651$)
71 improved systems with two diphthongs, of which the best is
/11, 23, 33, 44, 51/ ($D_F = 0.99828$)

Example 8.
5-vowel system
point 1: (300, 600) (u-like)
point 2: (800, 1300) (a-like)
point 3: (300, 2200) (i-like)
point 4: (400, 2100) (I-like) (changed)
point 5: (500, 2000) (e-like)
short-vowel system: $D_F = 0.5404$ (monophthong formula (2))
K = 5
Number of combinations: 3125

Long-vowel system on 1854th place, $D_F = 0.88777$ (transition formula (4))
6 improved systems with one diphthong, of which the best is
/11, 22, 33, 41, 55/ ($D_F = 0.99651$)
79 improved systems with two diphthongs, of which the best is
/11, 22, 32, 44, 51/ ($D_F = 0.99824$)

Example 9.
5-vowel system
point 1: (300, 600) (u-like)
point 2: (800, 1300) (a-like)
point 3: (300, 2200) (i-like)
point 4: (400, 2100) (I-like)
point 5: (350, 2150) (I-like) (changed)
short-vowel system: $D_F = 0.1991$ (monophthong formula (2))
K = 5
Number of combinations: 3125
Long-vowel system on 1854th place, $D_F = 0.54852$ (transition formula (4))
6 improved systems with one diphthong, of which the best is
/11, 22, 33, 41, 55/ ($D_F = 0.94332$)
78 improved systems with two diphthongs, of which the best is
/11, 22, 32, 44, 51/ ($D_F = 0.99814$)

The lists corresponding to this sequence of examples indicate that in case of high *local* vowel density, diphthongization always takes place between a member of the vowel cluster and one isolated vowel outside the cluster. All types of diphthong configurations occur: pointing inward or outward the cluster; chained diphthongization (the final segment of one diphthong figuring as the initial segment of another), both inwards and outwards, is also possible. Two diphthongs pointing either out of the cluster or into the cluster never have the same exterior isolated vowel in common.

5. DISCUSSION

The introduction of spectrum-like data instead of formants and the choice of the confusion function may influence the model solutions. These choices may be considered as a sort of 'modules' in the model which can be replaced by other ones.
The model allows diphthongization to be interpreted as a means for improving the perceptual quality of vowel systems. Properties of diphthongs in the vowel system as generated by the model have a parallel with properties as found in natural languages. Diphthongization appears to be favourable in case of a system containing many vowels, or in case of high local vowel density near the boundary of the vowel space. Both these aspects can be found in vowel systems of natural languages. Some of the diphthong universals (section 3.1) can be interpreted within this model. Because of the symmetry in the confusion probability formulae (2) and (4), the universal concerning the lack of contrast between final diphthong segments can not be described.
The model possesses extra-linguistic arguments only. Therefore the model proposed should *not* be expected to have a general linguistic value. A problem concerning the falsification of the model exists in the poor (or absent) phonetic specification of natural diphthongs in phonological inventories. As Maddieson (1984), Basbøll (1985) and Booij (1987) already point out, a satisfactory classification of diphthongs is troublesome. These aspects impede a profound model evaluation. However, the model clearly allows an interpretation of the most conspicuous characteristics of natural diphthongs.

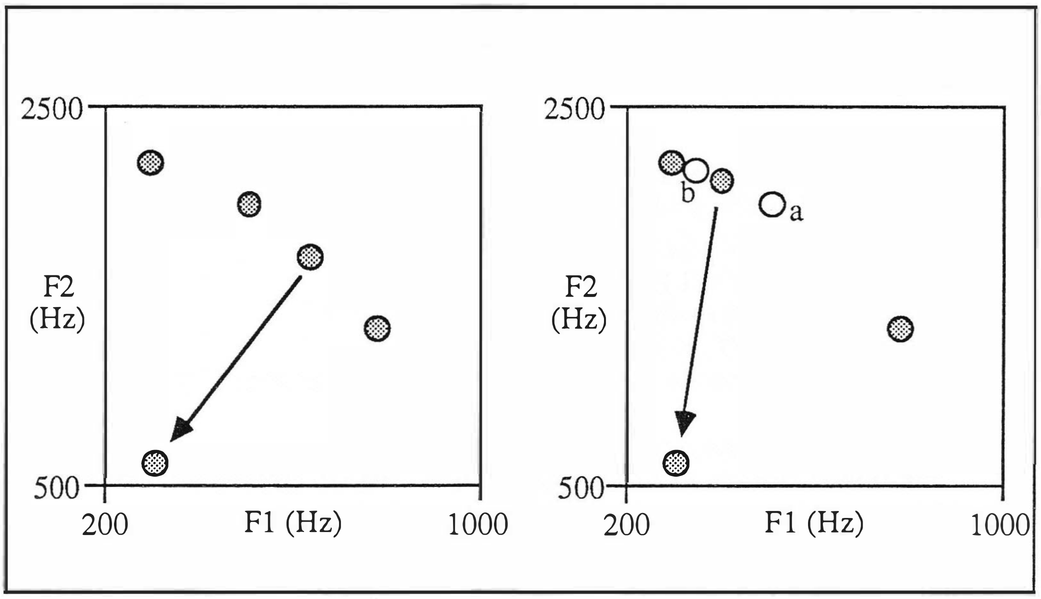

Figure 6. Best diphthongs in case of examples 6 (left), and 7 and 8 (right). In the right figure, examples 7 and 8 correspond to the four grey points plus point a and b, respectively.

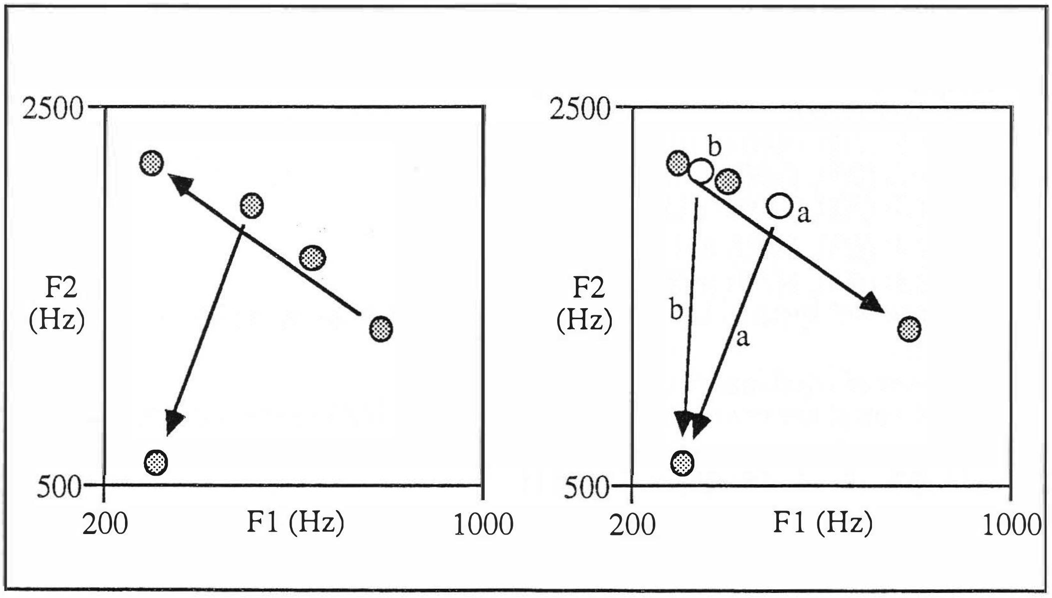

Figure 7. Most optimally improved systems containing two diphthongs in case of examples 6 (left), and 7 and 8 (right). In the right figure, example 7 corresponds to the four grey points, point a and diphthong a. Example 8 corresponds *m.m.* to b.

ACKNOWLEDGEMENTS

I wish to thank L. Pols for improving earlier versions of this paper.
Until September 1987, this research was sponsored by the Netherlands Organization for the Advancement of Pure Scientific Research ZWO, under contract nr. 300-161-030.

REFERENCES

Almeida, A., Drommel, R.H. and Fiedler, Th. (1977). A mathematical approach to the acoustics of diphthongs. IP Köln Berichte 7. 73-83.

Basbøll, H. (1985). Review of 'Patterns of sounds', I. Maddieson. (With a chapter contributed by S.F. Disner.). Phonology Yearbook 2. Cambridge University Press. 343-353.

Bladon, A. (1985). Diphthongs: A case study of dynamic auditory processing. Speech Communication 4. 145-154.

Booij, G.E. (1987). Review of 'Patterns of sounds', I. Maddieson. (With a chapter contributed by S.F. Disner.) Cambridge University Press. In: Studies in Language. Vol. 11, 255-258.

Bosch, L.F.M. ten, Bonder, L.J. and Pols, L.C.W. (1987). Static and dynamic structure of vowel systems. Proc. of the 11th. Intern. Congress of Phonetic Sciences, Tallinn, Estonia, USSR. Vol 1, 235-238.

Catford, J.C. (1977). Fundamental problems in phonetics. Edinburgh University Press.

Disner, S.F. (1980). Insights on vowel spacing: results of a language survey. UCLA WPP 50, University of California, LA. 70-92.

Disner, S.F. (1983). Vowel quality. The relation between universals and language specific factors. UCLA WPP 58, University of California, LA.

Koopmans-van Beinum, F.J. (1980). Vowel contrast reduction. An acoustic and perceptual study of Dutch vowels in various speech conditions. Doctoral thesis, University of Amsterdam.

Lass, R. (1984). Phonology. An introduction to basis concepts. Cambridge Textbooks in Linguistics. Cambridge University Press.

Liljencrants, J. and Lindblom, B.E.F. (1972). Numerical simulation of vowel quality systems: the role of perceptual contrasts. Language 48. 839-862.

Lindblom, B.E.F. (1975). Experiments in sound structure. Paper read at the 8th. Intern. Congress of Phonetic Sciences, Leeds (plenary address).

Lindblom, B.E.F. (1986). Phonetic universals. In: Experimental Phonology. Ohala, J.J. and Jaeger, J.J., eds. 13-44.

Maddieson, I. (1984). Patterns of sounds. Cambridge studies in speech sciences and comunication. Cambridge University Press.

Peeters, W.J.M. (1987). Acoustic Structure and perceptual relevance of 'steady states' and 'glides' within formant trajectories of diphthongs, complex vowels and vowel clusters. Proc. of the European Conference on Speech Technology, Vol. 1. Edinburgh: CEP Consultants. 42-45.

Pols, L.C.W. (1977). Spectral analysis and identification of Dutch vowels in monosyllabic words. Doctoral thesis, Free University, Amsterdam.

UPSID (1981). UCLA Phonological Segment Inventory Database. UCLA WPP 53, University of California, LA.

Yang Shun-an (1987). An articulatory dynamic model for diphthongs and triphthongs in Chinese. Proc. of the 11th Intern. Congress of Phonetic Sciences, Tallinn, Estonia, USSR. Vol. 1, 239-242.