# A comparative acoustic analysis of the long vowels and diphthongs of Afrikaans and South African English

by

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# Abstract

**Keywords**: Automatic speech recognition, formant extraction, statistical formant analysis, acoustic phonetics, Afrikaans and South African English vowels and diphthongs, pronunciation dictionaries.

In this study, the long vowels and diphthongs of Afrikaans and South African English are acoustically compared.

The results of this study are important to linguists in the understanding, teaching and correction of language and the development of pronunciation dictionaries. This is particularly important in the South African context where many speakers use more than one of the eleven official languages on a regular basis[1]. Further importance lies in the use of these acoustical models as a means of improving automatic speech recognition, realistic computer-speech generation and automatic accent recognition. The study will also aid in the study of acoustic phonetics.

The experimental work was performed on a database that was collected of the long vowels and diphthongs of the two languages as spoken by mother-tongue (L1) and second language (L2) speakers for four cases as shown in the table.

The vowels and diphthongs were recorded in single utterances of normal words, in isolated form and in a "pseudo-word" (h-vowel-t or h-diphthong-t) form. The data was

[1] According to the 1996 census: 23% of South Africans speak isiZulu, 18% isiXhosa, 14% Afrikaans and 9% English as their first home language.

| | |
|---|---|
| Afrikaans spoken by Afrikaans speakers | L1 Afrikaans |
| Afrikaans spoken by SA English speakers | L2 Afrikaans |
| SA English spoken by SA English speakers | L1 SA English |
| SA English spoken by Afrikaans speakers | L2 SA English |

then verified, segmented and labelled. The relevant vowels and diphthongs were then extracted and compared.

The comparison between L1 and L2 speech is based on the formant locations and the formant tracks. This involved the calculation of the resonance peak tracks (formants) of the voiced speech, visual verification of the formant tracks and then producing a graphical representation of the locations/trajectories of the vowels/diphthongs. The significance of any difference in mean location/trajectory was tested using the analysis of variance (ANOVA) statistical test.

Comparative experiments based on the pitch trajectories of the vowels and diphthongs were also performed. Finally, the level of diphthongization of the vowels and diphthongs was analysed.

The comparative experiments mostly confirm common hypotheses on the equivalence and difference between the two South African accent/language groups, but some of the findings challenge traditional views. One of these challenges arise over the classification of <o:> and <e:> as diphthongs and not as vowels as is commonly done.

# Uittreksel

**Sleutelwoorde**: Outomatiese spraakherkenning, formant ontrekking, statistiese formant analise, akoestiese fonetiek, Afrikaanse en Suid-Afrikaanse Engelse vokale en diftonge, uitspraak woordeboeke.

In hierdie studie word die lang vokale en diftonge van Afrikaans en Suid-Afrikaanse Engels akoesties vergelyk.

Die resultate van die studie is belangrik vir taalkundiges in die verstaan, onderrig en korreksie van taal en die ontwikkeling van uitspraak-woordeboeke. Dit is van besondere belang in die Suid-Afrikaanse konteks waar baie sprekers meer as een van die elf amptelike tale op 'n gereelde basis gebruik[2]. Verdere belang lê in die gebruik van die akoestiese modelle as 'n manier van verbetering van outomatiese spraakherkenning, realistiese rekenaar-spraak generasie en outomatiese aksentherkenning. Die studie sal ook bydra tot die bestudering van akoestiese fonetiek.

Die eksperimentele werk is uitgevoer op 'n versamelde databasis van die lang vokale en diftonge van die twee tale soos gepraat deur moedertaal (L1) en tweedetaal (L2) sprekers in vier gevalle soos in die tabel aangedui.

Die vokale en diftonge is in enkele uitinge van normale woorde, in geïsoleerde vorm en in "pseudo-woord" (h-vokaal-t of h-diftong-t) vorm opgeneem. Die data is dan nagegaan,

[2]Volgens die 1996 sensus: 23% van Suid-Afrikaners praat isiZulu, 18% isiXhosa, 14% Afrikaans en 9% Engels as hulle eerste huistaal.

| | |
|---|---|
| Afrikaans gepraat deur Afrikaanse sprekers | L1 Afrikaans |
| Afrikaans gepraat deur SA Engelse sprekers | L2 Afrikaans |
| SA Engels gepraat deur SA Engelse sprekers | L1 SA Engels |
| SA Engels gepraat deur Afrikaanse sprekers | L2 SA Engels |

gesegmenteer en gemerk. Die relevante vokale en diftonge is toe onttrek en vergelyk.

Die vergelyking tussen L1 en L2 spraak is gebaseer op die formantplasings en die formanttrajekte. Dit behels die berekening van die resonansiepieke (formante) van stemhebbende spraak, visuele nagaan van die korrektheid van die formanttrajekte en dan grafiese voorstelling van die plasing/trajekte van die vokale/diftonge. Die betekenisvolheid van enige verskille in gemiddelde plasing/trajek is dan deur middel van 'n analise van variansie (ANOVA) statistiese toets, beproef.

Vergelykende eksperimente is ook op die stemtoon trajekte van die vokale en diftonge gedoen. Laastens is die mate van diftongisering van die vokale en diftonge geanaliseer.

Die vergelykende eksperimente het meerendeels die algemene hipoteses oor die ekwivalensie en verskille tussen die twee Suid-Afrikaanse aksent/taal groepe bevestig, maar sommige van die bevindings bevraagteken tradisionele standpunte. Veral die klassifikasie van <o:> en <e:> as diftonge en nie as vokale nie, word bevraagteken.

# Acknowledgements

I would like to thank the following people for their help and support, without which this project would not have been possible:

- Professor Liesbeth Botha, my study leader and mentor.
- Doctor Hendrik Boshoff, for his advice and explanations on vowel space.
- My parents, for their unfailing support.
- Last, but surely not least, the Lord, who is always at my side.

# Contents

# Chapter 1

# Introduction

## 1.1 Justification

The study of the acoustic structure of languages is already a mature field. Certain influences keep it in flux though. There are new analysis techniques being developed continuously and faster computers now allow us to study at a more complex and in depth level than before. Another important factor is that although the large (in terms of speakers) languages of the world (English, French, German, Mandarin etc.) have been studied in depth, there are many smaller (yet acoustically interesting) languages still awaiting careful study. In this study we concentrate on one of these languages, namely Afrikaans, and analyse the acoustic structure of its long vowels and diphthongs as spoken by first language Afrikaans speakers and first language South African (SA) English speakers. The vowels and diphthongs of SA English are also studied and a comparison is made between first and second language speech.

There are many reasons why we would want to study the acoustic structure of a language and know what influence different mother tongue accents would have on the acoustic structure. Some of the fields which would benefit from such research are:

- Automatic speech recognition
- Automatic accent recognition
- Phonetics
- Synthetic/computer speech or text-to-speech (TTS) systems

Speech recognisers use the statistical probability of occurrence of a sequence of acoustic observations to determine what a speaker is saying. The modelling of these acoustic observations can take many forms such as Gaussian mixtures of mel scaled cepstral coefficients or linear predictive coding coefficients[1]. These "acoustic models" are then used in recognition algorithms such as Viterbi decoding used in conjunction with hidden Markov models (HMM's), dynamic time warping comparators or neural networks to perform recognition. These technologies are not directly relevant to this study, but rather the fact that they are all in some way based on a type of acoustic model of the spoken language.

The acoustic modelling entities we will use in our study are the well-known formants - the resonant frequencies of the vocal tract[2]. We will also spend some time looking at prosodic modelling (more specifically, pitch modelling) of the vowels and diphthongs as it is often in this respect that languages and accents may differ significantly. We pay special attention to the diphthongs and formulate a more accurate and informative measure of diphthongization and use this to analyse some controversial vowels.

We concentrate this study on the long vowels and diphthongs for the following reasons:

- The short vowels were addressed in a previous study[3].
- The vowels and diphthongs are arguably a larger source of differences in accents and languages than the consonants.
- They are the "glue" which hold the consonants together to form words.

- They lend themselves to acoustic analysis by being voiced and relatively easy to segment.

We aim to form simple acoustic models of the long vowels and diphthongs which can then be used to determine if and where differences occur between SA English and Afrikaans mother tongue pronunciation of these. We then determine how large these differences are. The diphthongs in particular are studied in a new way to clarify the status of certain sounds which are classified as vowels by some phoneticians and as diphthongs by others.

The envisioned uses of this knowledge in the fields mentioned above could be the following:

- Speech therapists and language teachers may use the differences in pronunciation of the vowels and diphthongs in elocution lessons to teach different accents.
- Knowledge of the differences between the acoustic models can be used in speech synthesisers to create a pleasing or different accent.
- During training of speech recognisers, certain vowels and diphthongs can be targeted for re-estimation or retraining to improve recognition rates for different accents.
- Pronunciation dictionaries[4] contain valid phonemic transcriptions of words for a particular language and dialect. This is useful in both automatic speech recognition and TTS systems. A better understanding of the vowels and diphthongs used by South African speakers will result in more accurate pronunciation dictionaries.

It is not sufficient to prove that HMM's are capable of distinguishing and recognising various accents. We need to know the specific acoustic differences between accents so that we can make justified decisions when choosing training sounds for a speech

recognition data base. "Black Box" accent/dialect recognition tests such as performed by Miller and Trischitta[5] and Teixeira et al.[6] help us to determine the flexibility of HMM's, but they do not assist us in choosing word lists or structure for the text material of future databases. By knowing which sounds differ significantly between languages and accents we can, in principle, endeavour to collect only the required adaptation data required to retrain a recogniser, thus reusing the expensive data we have already collected for an alternative accent or language. Some studies[7] propose dialect recognition using shibboleth words, but this only demonstrates that HMM's can be used to model accents. Other studies[6][5] demonstrate that HMM's can be used to recognise phonemes as belonging to a certain dialect, but this does not tell us what makes the phoneme unique, or how we can approach improving recognition by adapting existing models which may have been generated at great expense. We must analyse the structure of languages and see how they differ at a phonemic level.

We further justify studying second language structure with reference to speaker adaptation and quote from Digalakis and Neumeyer[8]:

> "Adapting the parameters of a statistical speaker-independent continuous-speech recogniser to the speaker and the channel can significantly improve the recognition performance and robustness of the system. We have recently proposed a constrained technique for Gaussian mixture densities. The recognition error rate is approximately halved with only a small amount of adaptation data, and it approaches the speaker-independent accuracy achieved for native speakers."

The hypothesis that we are going to test, is that there are measurable and significant differences between the first and second language pronunciations of Afrikaans and SA English long vowels and diphthongs. We test this under the assumption that knowledge of these differences can be used to improve the recognition rates of automatic speech recognition systems.

A side issue that we address is the issue of diphthongization of the long vowels - also in the framework of an L1-L2 comparison.

## 1.2 Background

The acoustic structures of British and American English have been studied intensively over the last hundred years. Perhaps one of the most famous researchers in this field, Daniel Jones[9] is largely responsible for the International Phonetic Association (IPA) vowel chart still used today. His research into the location of the extreme cardinal vowels is an important reference work.

Working with more realistic (natural) speech, Peterson and Barney[10] analysed the locations of the formants of male, female and child speakers of American English. This work is often used today as a reference of vowel locations and how to plan and carry out speech analysis studies.

Following on the work of Peterson and Barney, Holbrook and Fairbanks[11] analysed the paths followed in formant space by the diphthongs of American English. Although the experiments were not carried out as carefully as those of Peterson and Barney, and the analysis techniques were relatively primitive, the work is an important reference of diphthong analysis. The technique they used is explained in Chapter 2: Theoretical Framework. We do not attempt to compare their results with ours as we would not be able to determine if any differences are as a result of the different analysis technique of accent differences.

Afrikaans has remained quite unresearched in terms of acoustic modelling until 1988 when Taylor and Uys[12] with some insightful writing but inaccurate modelling (due to rounding errors and the use of a single speaker [and thus a biased pronunciation]) plotted one of the first formant maps of the Afrikaans vowels. Although Taylor and Uys did perform diphthong analysis, the techniques used consisted simply of mean

formant locations at the initial and terminal points of the diphthongs with simple linear interpolation between these points. We claim therefore that their technique was too primitive to generate any conclusive results and only indicates general trends.

More recently, Van der Merwe et al.[13] performed a more in depth study of the acoustic structure of Afrikaans vowels. A large percentage of their study revolves around the analysis of formant ratios which is controversial representation of the vowels. The formant ratio theory speculates that although the resonant frequencies (formants) of speech correlate for voiced speech sounds (and therefore appear to have relevance) there may be the possibility that voiced speech structure (and possibly understanding) results from the spacing of the formants (i.e. their ratios). This appears to have some intuitive justification, but there has not been much scientific evidence to support it.

Analysis techniques have improved since the early nineties, and the greater employment of computers to perform the formant extraction, analysis and visualisation has greatly improved the accuracy and repeatability of acoustic modelling experiments.

Perhaps one of the most recent scientific works on the acoustic structure of many of the Afrikaans vowels has been performed by Botha and Pols[3]. This study is based on a relatively large data set and the formants have been carefully extracted as stationary frequencies. These authors also emphasise the apparent relevance of the formant ratio theory. In many ways our work is a continuation of this study where we are concentrating on the long vowels and the diphthongs while paying careful attention to their dynamic nature.

The most recent work performed on certain of the aspects of some of the Afrikaans vowels and diphthongs is the work performed by Raubenheimer[14][15]. Due to the limited publication of master's dissertations and doctoral theses, our attention was only drawn to this work after our own work had been completed.

## 1.3 Method

This section deals with the experimental protocol of our analysis. The data that was used in the study is first described. Then the experiments which were performed on the data and the methods employed to achieve our aims are introduced. The actual details of these steps are discussed in greater detail in the respective chapters later in this dissertation.

We recorded spoken first and second language data of 17 male speakers from the two language groups (Afrikaans and South African English). The data was listened to and all poor recordings of incorrect utterances were discarded. The remaining data was then segmented and labelled (tagged) for the vowels and diphthongs of interest. We extracted the formants and pitch contours from each labelled segment and once again cross checked this by superimposing the formants on spectrograms. Where possible, incorrect formant trajectories were corrected, and where it was not possible, they were discarded. Pitch trajectories which were sporadic or disjoint or obviously incorrect were also discarded.

The final formant data was then used to calculate the mean locations of the vowels in formant space, and the trajectories of the diphthongs in formant space. The means and the trajectories were then subjected to analysis of variance statistical significance tests to determine whether the two language/accent groups produce equivalent or noticeably different vowels and diphthongs.

The diphthong trajectories were fitted using cubic splines, and the cubic spline coefficients were compared using analysis of variance calculations. This metric for measuring diphthongization is an important step in clarifying and classifying the status of various vowels and diphthongs.

As a further study the mean pitch contours were compared to determine if there were significant intonational (prosodic) differences between the groups.

Importantly, we are not only studying the acoustic structure of Afrikaans first language, but also Afrikaans as second language and similarly for SA English.

## 1.4 Contributions of this dissertation

The major contributions of this study are those defined by the goals, namely, the modelling of the acoustic structures of the long vowels and diphthongs of Afrikaans and South African English, both in first and second language context, and a statistical comparison of these models.

We therefore contribute:

- Static formant models of most of the Afrikaans long vowels
- Dynamic formant models of most of the Afrikaans diphthongs
- Static formant models of most of the South African English vowels
- Dynamic formant models of most of the South African English diphthongs
- Analysis of variance statistical comparisons between these sets of models where relevant
- A new measure of diphthongization and a resulting clarification on the status of certain vowels which have long been the subject of speculation.

We specifically concentrate on the long vowels and do not duplicate work already performed by Botha and Pols[3] which concentrates on the short vowels of Afrikaans and SA English.

Knowledge of the models above can be used to improve automatic speech recognition. Adaptation to speaker dependent recognition can be carried out more efficiently if we

know which speech sounds are prone to accent shift. Cross-language training of ASR systems can also be facilitated using this knowledge. Recognition databases may also be trained with prior knowledge that certain sounds may be pooled for training as they are common to both language groups whereas other sounds are characteristic of a particular group[16].

## 1.5 Organisation of this dissertation

The next chapter continues with an explanation of the background to this study. It details the concepts that we are working with and explains the mathematics behind the analysis techniques used.

Vowels are dealt with first. We explain what they are and how we represent them. We also summarise some of the research performed on vowels in the past fifty years.

The logical continuation of vowels, namely diphthongs, are then explained. Although not much research has been performed on diphthongs, we describe some of the ground-breaking work performed in this field of phonetics.

We then go on to explain a graphical technique used to visualise speech in the spectral domain known as a spectrogram. The spectrogram has been an integral part of this study in terms of labelling and data checking.

We then describe the first of the abstract concepts used in this study, namely formants. For various reasons which are explained in this section, formants were used as the primary means of acoustic modelling in this study. The algorithm for calculation of formants is also given.

It was decided that we should examine the intonation (prosody) of the vowels and diphthongs between the two groups to determine whether acoustic differences were only

visible at a phonemic level, or whether accent differences were possibly due to pitch differences. Pitch extraction is easy to achieve in conjunction with formant extraction as they are both based on the calculation of linear predictive coefficients.

We next describe the concept of equivalence classification, in other words, the concept that speakers learning a language at a late age tend to use the phonemes they already know from another language, to pronounce words in the new language. Evidence of this may be difficult to establish in the framework of the current study due to the bilinguality of the speakers, but it is an important concept which must be considered.

The last two sections of the second chapter discuss the use of cubic splines to form a low dimensional representation of the diphthong trajectories and pitch contours. We then discuss the use of analysis of variance statistical tests to determine mathematically how significant the difference in mean or mean trajectory is between the two accent/language groups.

We begin Chapter 3 that deals with our experiments with a discussion of the objectives of the study, that is, what it is we are trying to achieve with this research.

The data we have recorded and the structure of the database are discussed next. We also discuss the speakers and problems encountered with the data recording procedure. The words used and the selection process are discussed.

The "Method" section is second in importance only to the results. This section describes the way we went about verifying the recorded data before extracting the formants and pitch for analysis. It then explains the software that was written to visualise the data in useful ways and how the vowel formant means, diphthong formant trajectories and pitch contours were compared. It also explains how we determined whether a speech sound was a vowel or a diphthong. This is particularly important in sounds which are surrounded by some controversy. This matter is discussed in later sections.

The "Results" section shows the graphs generated by using the software we have written and then discusses vowel by vowel and diphthong by diphthong the conclusions we may draw by observing these graphs and analysis of variance results. We also discuss the level of diphthongization of both vowels and diphthongs.

We conclude with a summary and conclusions regarding the study in Chapter 4.

# Chapter 2

# Theoretical Framework

In this chapter we discuss the algorithms, techniques and principles employed to model the acoustic differences between Afrikaans and South African English first (L1) and second language (L2) speech.

We begin by explaining what we mean exactly by the terms "vowels" and "diphthongs". With these explanations we include summaries on some of the research performed in the fields of phonetics and phonology pertaining to vowel and diphthong modelling.

Once we have explained what it is we are studying we describe a useful 2-D visualisation tool we have used, known as a *spectrogram*. Spectrograms are easy to plot and they are extremely useful for the labelling (tagging) of speech data where it is often impossible to see phoneme transitions on a 1-D energy versus time speech signal alone.

Once we have labelled our data we need to extract the relevant features from it that we need for the "acoustic modelling". We have chosen as features the resonance peaks of the vocal tract, known as *formants*. We explain the mathematics and algorithms required to extract formants from the speech signal based on linear predictive coefficients (LPCs).

We also study whether intonation (prosody) has a large influence on the perceived accent of the speaker[17]. To this effect we have extracted the pitch contours of the utterances (vowels and diphthongs) of the speakers.

In order to put the analysis and comparisons of our data in a theoretical framework, we consider the work by Flege[18] on the concept of "equivalence classification".

As long vowels and diphthongs have dynamic formant and pitch directories, we choose to model these using cubic splines. With this technique we take multiple samples and fit them to a curve which we can represent with relatively few parameters.

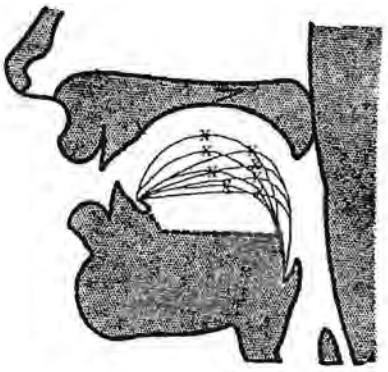
The actual method of comparison is finally explained. We have used the analysis of variance (ANOVA) test developed by Fisher[19] to perform tests which will indicate the significance of differences between the means of two sets, taking the variance into consideration.

## 2.1 Vowels

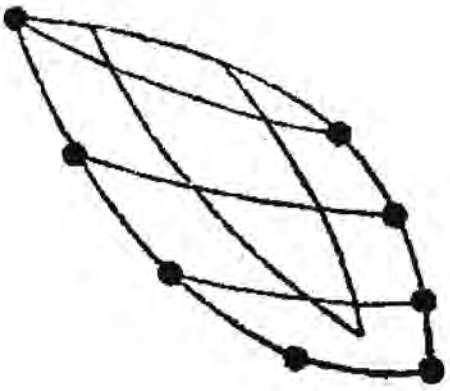
There is no simple definition of what constitutes vowels, but they are generally classified as follows[20]:

> "In ordinary speech a vowel is a voiced sound in the pronunciation of which the air passes through the mouth in a continuous stream, there being no obstruction and no narrowing such as would produce audible friction. All other sounds are consonants."

The difference in quality between vowels is caused by the movements of the tongue and lips which result in a change in the shape of the resonance chamber of the mouth. Vowels are usually classified by the part of the tongue which is raised: front, middle or



Tongue positions of the Eight Primary Cardinal Vowels.



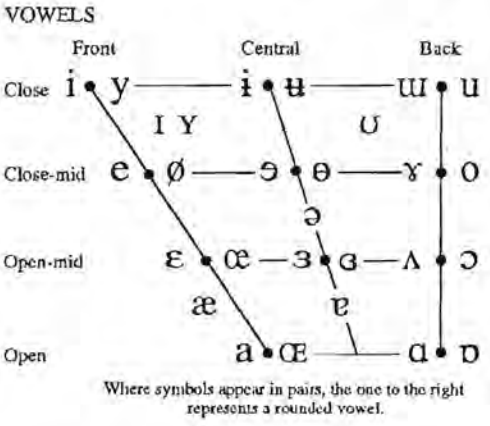



Figure 2.1: The cardinal vowels as organised by the placement of the tongue in the oral cavity. The top diagram from Ward[20] indicates the positions of the tongue which give rise to the eight cardinal vowels. This results in the middle figure (also from Ward) which has been simplified to the current IPA vowel chart seen at the bottom(from the IPA).

| Short-vowel | | Long-vowel | |
|---|---|---|---|
| i | h**i**t | i: | h**ea**t |
| u | f**u**ll | u: | f**oo**l |
| i | *w**ie**l (wheel)* | i: | *spi**eë**l (mirror)* |
| u | *k**oe**l (cool)* | u: | *b**oe**r (farmer)* |
| ɛ | *n**è** (not/no[inq.])* | ɛ: | *w**e**ns (wish)* |
| ɔ | *p**o**nt ()* | ɔ: | *p**o**nd (pound)* |
| a | *m**a**n (man)* | a: | *m**aa**n (moon)* |

Table 2.1: Examples of short vowels as opposed to long vowels in both English and Afrikaans.

back, and according to the degree of raising which takes place, namely: close, half-close, half-open and open. This is clearly illustrated in Figure 2.1.

In this study we have concentrated on the long vowels as opposed to short vowels (which have been analysed in a previous study by Botha[21][3].) The long vowels differ from short vowels not only in their duration but also in their quality and thus in their formant structure. Therefore, the short vowel <i> as in the word "hit" will differ significantly from the long vowel <i:> or <ɪ> found in the word "heat". Some examples of short vowels and their long vowel counterparts are given in Table 2.1. Long vowels are also considered to be prone to diphthongization and we have measured this to determine the validity of such a statement.

### Peterson and Barney

Peterson and Barney[10] performed important vowel research in 1952 by recording two lists of ten vowels from 33 men, 28 women and 15 children, thereby creating a database of 1520 words. These were all in consonant-vowel-consonant (CVC) context, and h-vowel-d was the preferred structure where possible as it was found that the consonants in this particular CVC structure were not as prone as other consonants to influencing the integrity of the vowels. Using calibrated Plexiglas templates they read the formant frequencies off spectrographs. The sounds they used are given in Table 2.2.

| Vowel | Word | Vowel | Word |
|---|---|---|---|
| i | Heed | ɔ | Hawed |
| ɪ | Hid | ʊ | Hood |
| ɛ | Head | u | Who'd |
| æ | Had | ʌ | Hud |
| ɑ | Hod | ə | Heard |

Table 2.2: The vowels studied by Peterson and Barney[10] with source words

It is important to note that Peterson and Barney only extracted instantaneous formant frequency values at a single point in a vowel sound. All their plots are also based on only these instantaneous formant frequencies. Plots of their results are given in Figure 2.2.

### Taylor and Uys

Until recently (1988) no one had performed any in depth study into the acoustic structure of the Afrikaans vowels. Taylor and Uys[12] created a small data set consisting only of vowels uttered by Uys. Using this they created a (speaker dependent) vowel map for Afrikaans. Although not a conclusive study, it is an important reference. Plots of their results are given in Figure 2.3.

### Van der Merwe et al.

Van der Merwe et al.[13] recognised the lack of any in depth study into the Afrikaans vowels and their state of change due to foreign linguistic effects. Working with a smallish corpus of 10 male, first language, middle aged speakers, they recorded 3 utterances for each of 8 Afrikaans vowels (<i>, <ɛ>, <æ>, <ə>, <a>, <u>, <ɔ> and <œ>) and processed them. They extracted the first three formants and the fundamental frequencies (pitch). Plots of their results are given in Figure 2.3. They do not state by what means they indicated to the speakers how they should know which

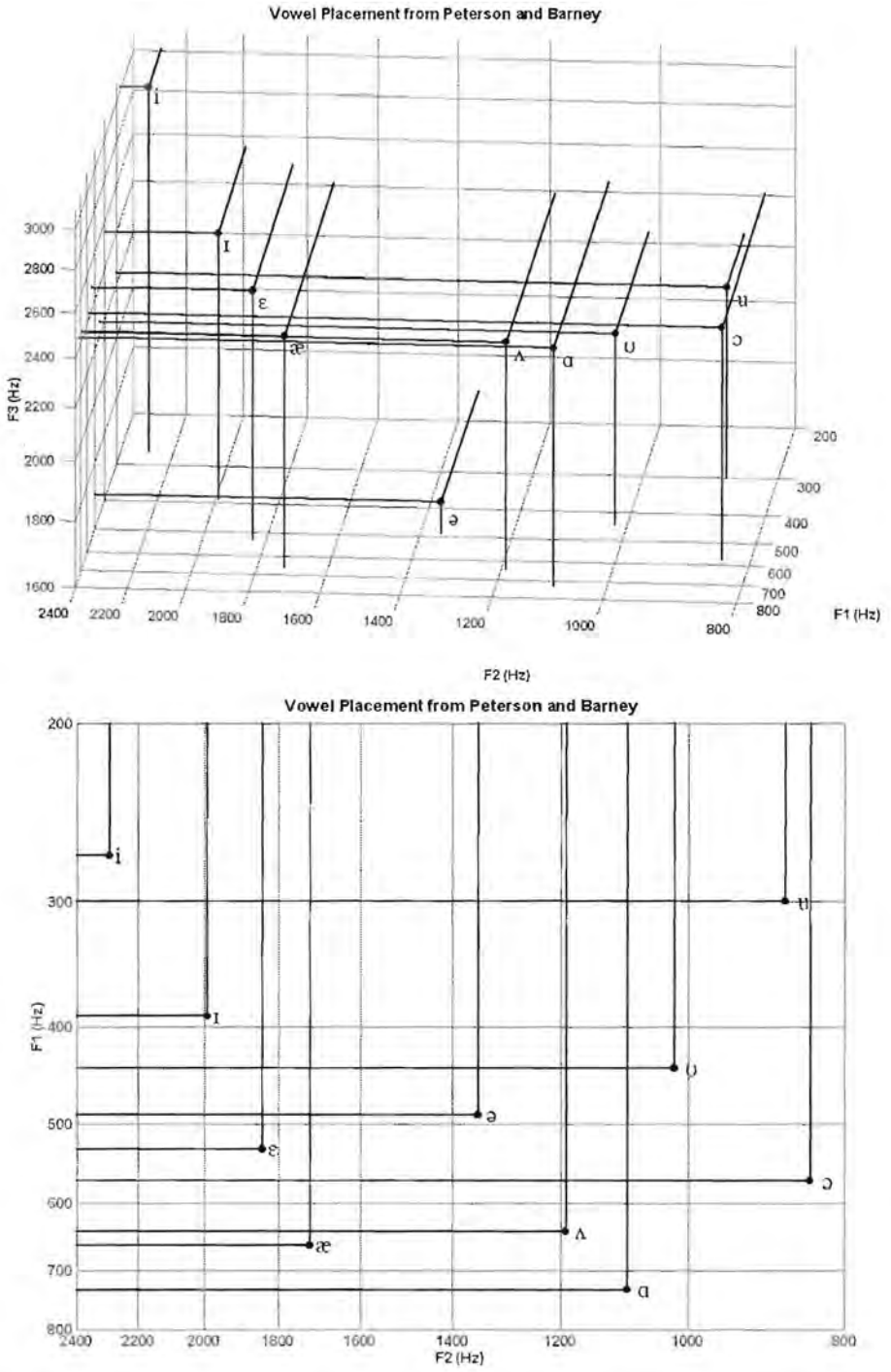



Figure 2.2: The Peterson and Barney[10] vowels in 3 dimensions (F1,F2,F3) and 2 dimensions (F1,F2). Note the similarity between the 2 dimensional plot and the cardinal vowel chart given in Figure 2.1.

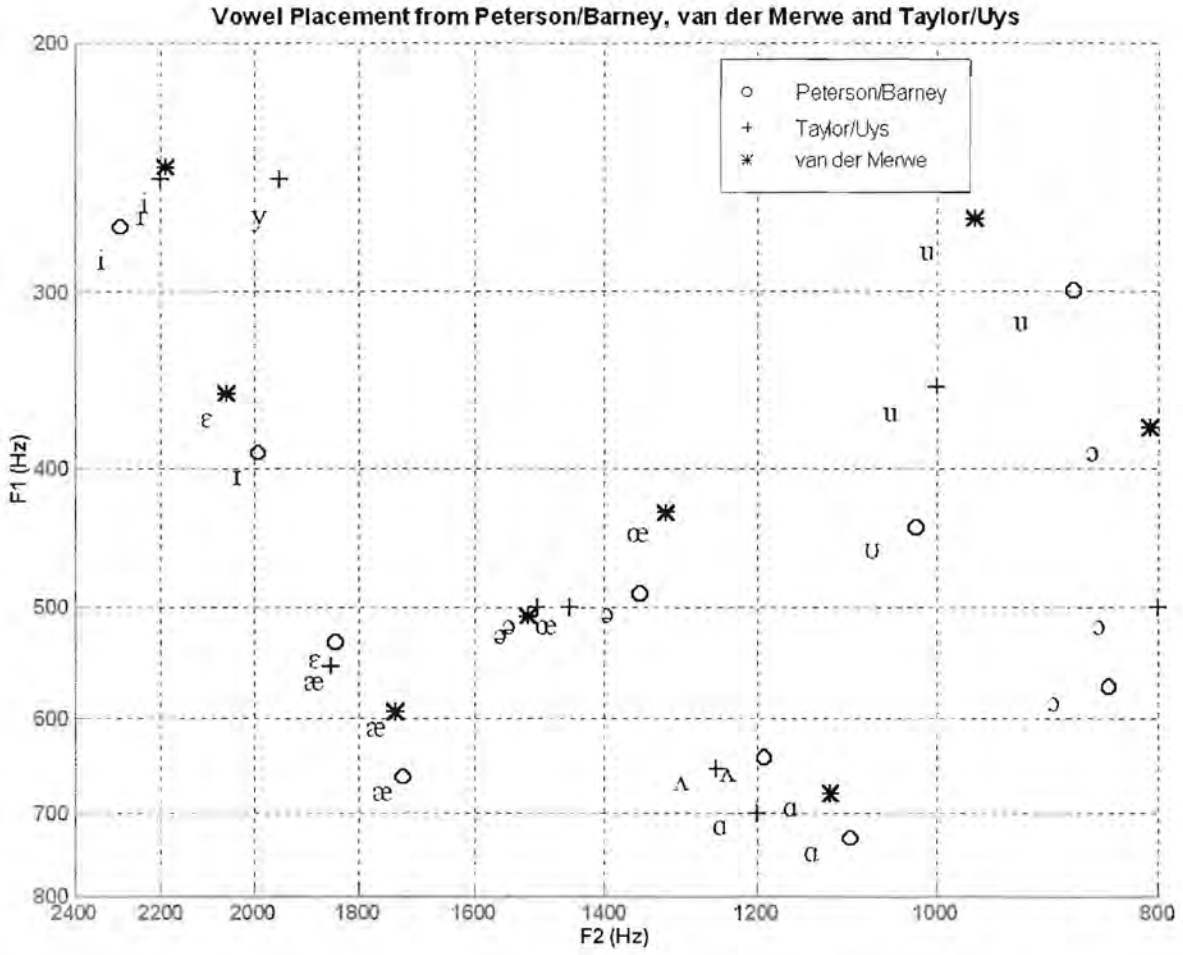



Figure 2.3: The Peterson and Barney[10], Taylor and Uys[12] and Van der Merwe[13] vowels shown in 2 dimensions (F1,F2).

of the 8 isolated vowels they were to utter. It may be as a result of this that they found no clear clustering of <æ> as was found with the other vowels.

Importantly, the authors are mostly of audiological training and found it important to analyse the formant ratios. Although there exists some controversy over the validity and usefulness of the formant ratio theory, there does, to the eye (which is a fairly good pattern recognition device) appear to be sufficient importance to warrant further study into the matter[22].

### Botha and Pols

Botha and Pols[3] performed what is probably one of the most recent studies on the Afrikaans vowel system. Their research focused on the short vowels <a>, <æ>, <ɛ>, <i>, <ə>, <œ>, <u>, <y> and <ɔ>. In particular, they studied the mean formant locations of the stationary vowels (Plots of their results are given in Figure 2.4) and the formant ratios. An important distinction of this paper from other phonetic studies is that it examines not only mother-tongue Afrikaans, but also the pronunciation of Afrikaans vowels by mother-tongue South African English speakers. Our study is a continuation of this work, with the emphasis on the long vowels and the dynamic diphthongs.

## 2.2 Diphthongs

The diphthongs are considered to be a combination of two vowels, so pronounced as to form a single syllable. A list of common diphthongs and words in which they are commonly found is given in Chapter 3 on page 55 in Table 3.2. These gliding sounds are generated on a single impulse of breath. English and Afrikaans diphthongs are of the falling type, having the greater prominence at the beginning. They are called de-crescendo diphthongs[20]. They are generally written phonologically as two

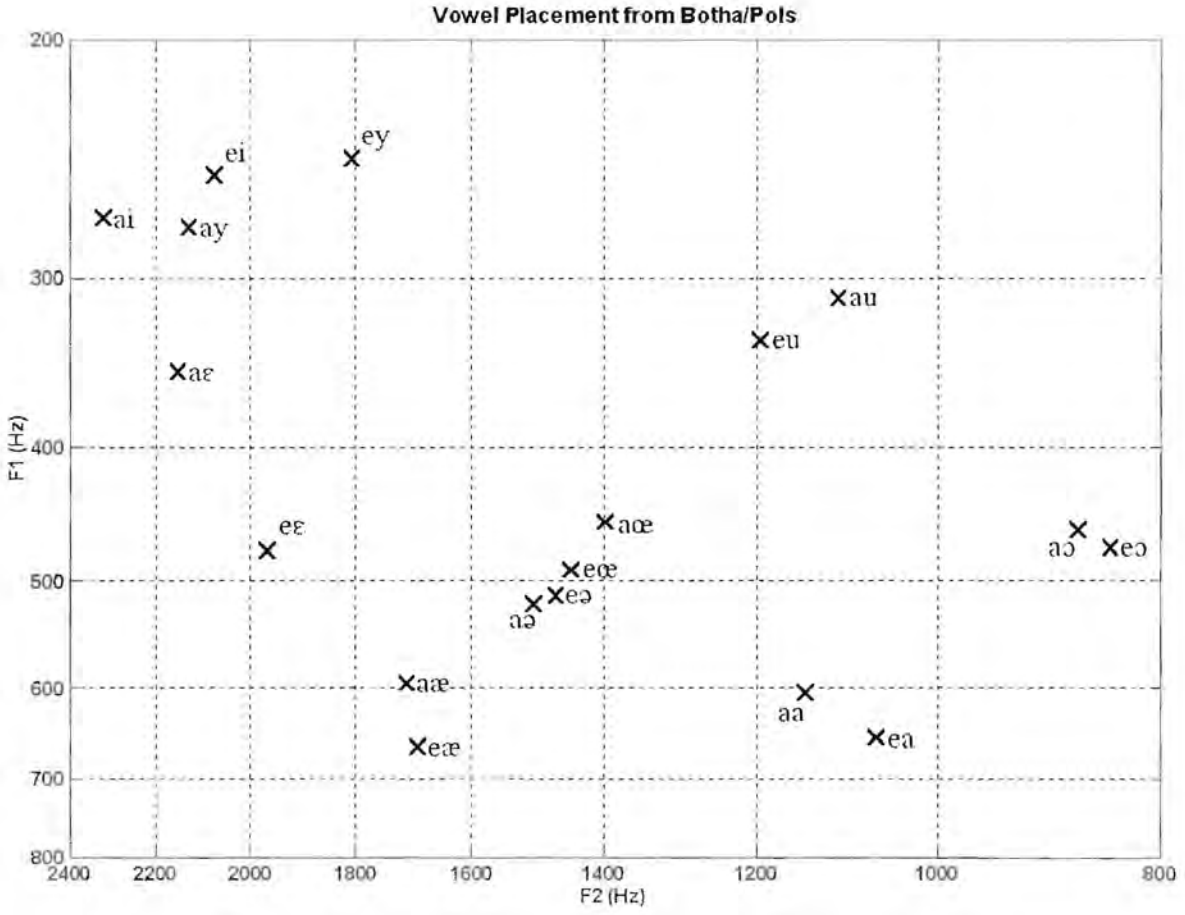



Figure 2.4: The Botha and Pols[3] vowels shown in 2 dimensions (F1,F2).

| Diphthong | Word |
|---|---|
| eɪ | Lady |
| oʊɪ | Home |
| aɪ | Time |
| aʊ | Now |
| ɔɪ | Boy |
| ɪə | Here |
| ɔə | More |
| ʊə | Your |

Table 2.3: The diphthongs commonly found in English with example words (from Ward[20]).

orthographic symbols, the first being the starting point (vowel) of the tongue and the second being the terminating point.

In principle it is possible to move from any vowel to any other and thus the number of diphthongs would seem immense. In reality, however, certain sounds are either too complex (tongue tying) or awkward sounding to be used. According to Ward[20] the majority of English speakers possess nine diphthongs. These are given in Table 2.3.

Afrikaans has a more complex diphthong structure. In Afrikaans phonologists traditionally only recognise three true diphthongs, all others are pseudo diphthongs[23]. We concur with Taylor and Uys's[12] definition of diphthongs. They go to great effort to explain their reasoning and critically evaluate the arguments (or lack thereof of others). We summarise their comments here:

Phonologists (e.g. Coetzee[23]) state:

- The three "true" diphthongs recognised are <əi>,<œy> and <œu>.
- In these true diphthongs both vocal components are of equal length, being lengthened by an equal degree when lengthened expressively.
- In pseudo diphthongs only the initial component can be stressed and only this

component can be lengthened expressively.

Taylor could find no empirical evidence to support this but do concede that this form of classification may be valid on phonological grounds.

Taylor summarises with:

- True diphthongs consist of: [VV] - where each component has short vowel status.
- Pseudo diphthongs consist of: [V:VC] - an initial long vowel [V:], another short vowel [V] and [C] representing the final [$j$] or [$w$] glide.
- Diminutive diphthongs: [CV] - There is only a single diminutive diphthong which occurs i.e. the Afrikaans "-jie" or [-ci]. Both components are very short.
- Diphthongised long half-close vowels: Seen as monophthong "vowels" by phonologists, namely [e:,o:,$\phi$]. Afrikaans linguists seem to downplay this phenomenon which produces the only centring diphthongs in the language and call them "potential diphthongs". They call the "vowels" "*swak gesnede*"(unchecked) and regard the process as of a purely mechanical and perceptually irrelevant contaminant of vowel length. Taylor labels them as [iə,uə,yə]. See Figure 3.6(bottom left) and Figure 3.7(bottom left) for confirmation of this classification for $< e :>$ and $< o :>$.

Figure 2.5 shows some of the English diphthongs indicating their origins and terminating points in relation to the standardised vowel chart.

### Holbrook and Fairbanks

Holbrook and Fairbanks[11] continued with the work of Peterson and Barney by analysing five of the common diphthongs found in American English. They are given in Table 2.4 with example words in which these diphthongs are found and the diphthongs are

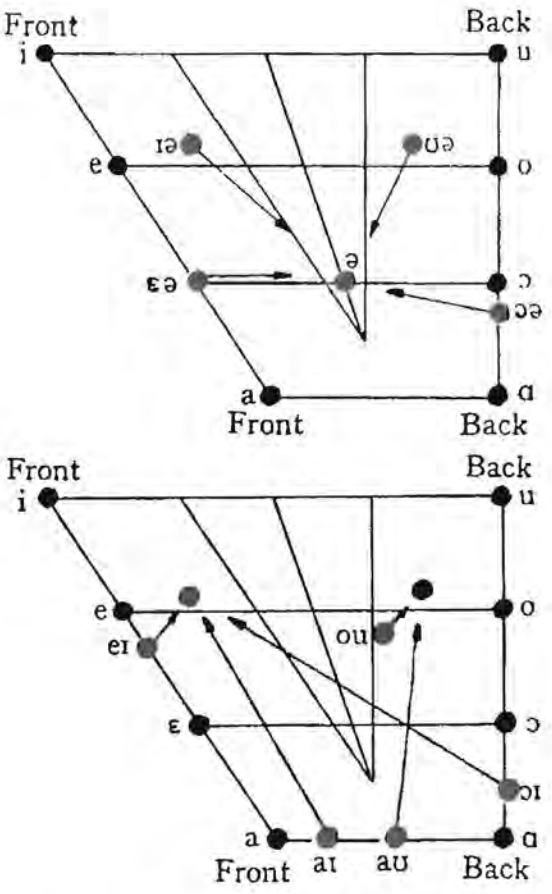



Figure 2.5: Some common English diphthongs and their movement in vowel location as described by the standardised vowel chart (from Ward[20]).

| Diphthong | Word |
|---|---|
| eɪ | Hay |
| aɪ | High |
| ɔɪ | Hoy |
| oʊ | Hoe |
| aʊ | Howe |
| jʊ | Hugh |

Table 2.4: The diphthongs used by Holbrook and Fairbanks[11] with source words

graphed in Figure 2.6. Although they used slightly more modern equipment, their technique was similar to that of Peterson and Barney. The formants were measured at five points over the period of diphthong voicing. The means of these formant points were then plotted. Essentially this was Peterson and Barney's technique at multiple points along the sound. Their results show reasonably clearly the formant movement as articulation moves from one vowel to the next.

### Taylor and Uys

Although Taylor and Uys[12] did process some of the Afrikaans diphthongs, their analysis methods were somewhat rudimentary and we can make no comparison between their results and the results found in this study. Their analysis technique consisted of averaging the formant values of the first quasi-stationary section of the diphthong and then plotting a linear interpolation to the average of the last quasi-stationary section of the diphthong. We therefore make no further mention of their diphthong analysis.

## 2.3 Spectrograms

To effectively label the long vowels and diphthongs within the speech segments we have recorded, and in order to check formant extraction, we require a simple way of

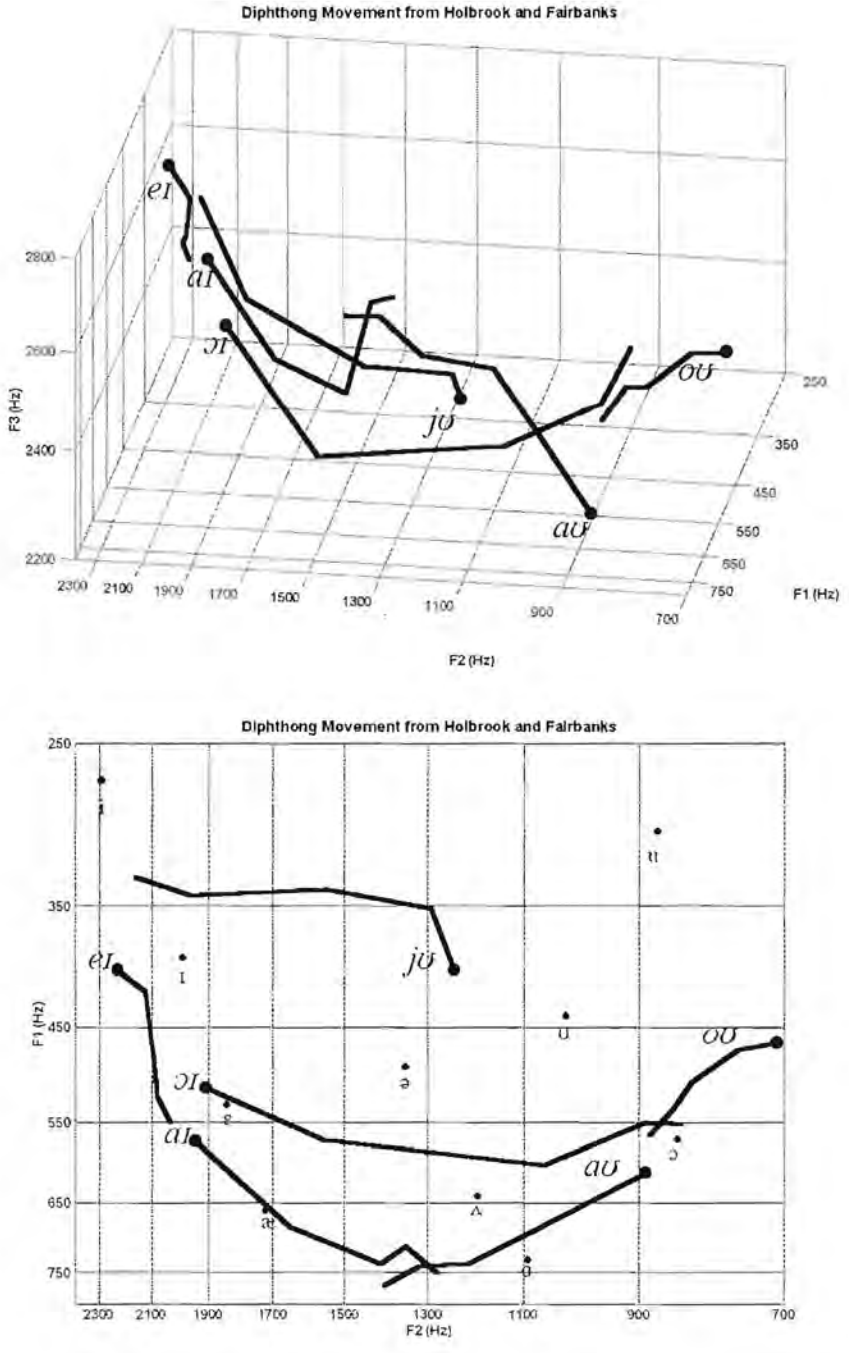



Figure 2.6: The top diagram indicates the Holbrook and Fairbanks[11] diphthongs and their movement in 3 dimensions (F1,F2,F3) and the bottom does likewise in the more traditional 2 dimensions (F1,F2). Also indicated on the bottom plot(as points) are the Peterson and Barney[10] vowels. The terminating point is indicated by a large node(•).

observing the spectral structure and dynamic change of the sound segment over time. This is achieved with the aid of the spectrogram.

Essentially, the spectrogram is a series of Fourier transforms taken over small, overlapping frames of data cut from the original data segment.

The Fourier transform is given as:

$$G(f) = \int_{-\infty}^{\infty} g(t)e^{-j2\pi ft}dt, \tag{2.1}$$

and the short time discrete Fourier transform of samples $g_0$ to $g_{N-1}$ is:

$$G_k = \sum_{n=0}^{N-1} g_n e^{\frac{-j2\pi}{N}kn} \qquad k = 0, 1, \ldots, N-1 \tag{2.2}$$

If we plot these Fourier transforms vertically, line them up horizontally and then map colour to the magnitude of the spectrum, the image observed from above is the spectrogram. This process is displayed in Figure 2.7.

## 2.4 Formants

Formants are the resonance peaks of the vocal tract during speech production and they have been used by many researchers as the primary model of voiced speech for many years[2]. Formants can only be extracted (or only have meaning) for voiced speech, such as vowels, where distinct resonance patterns can be associated with a particular

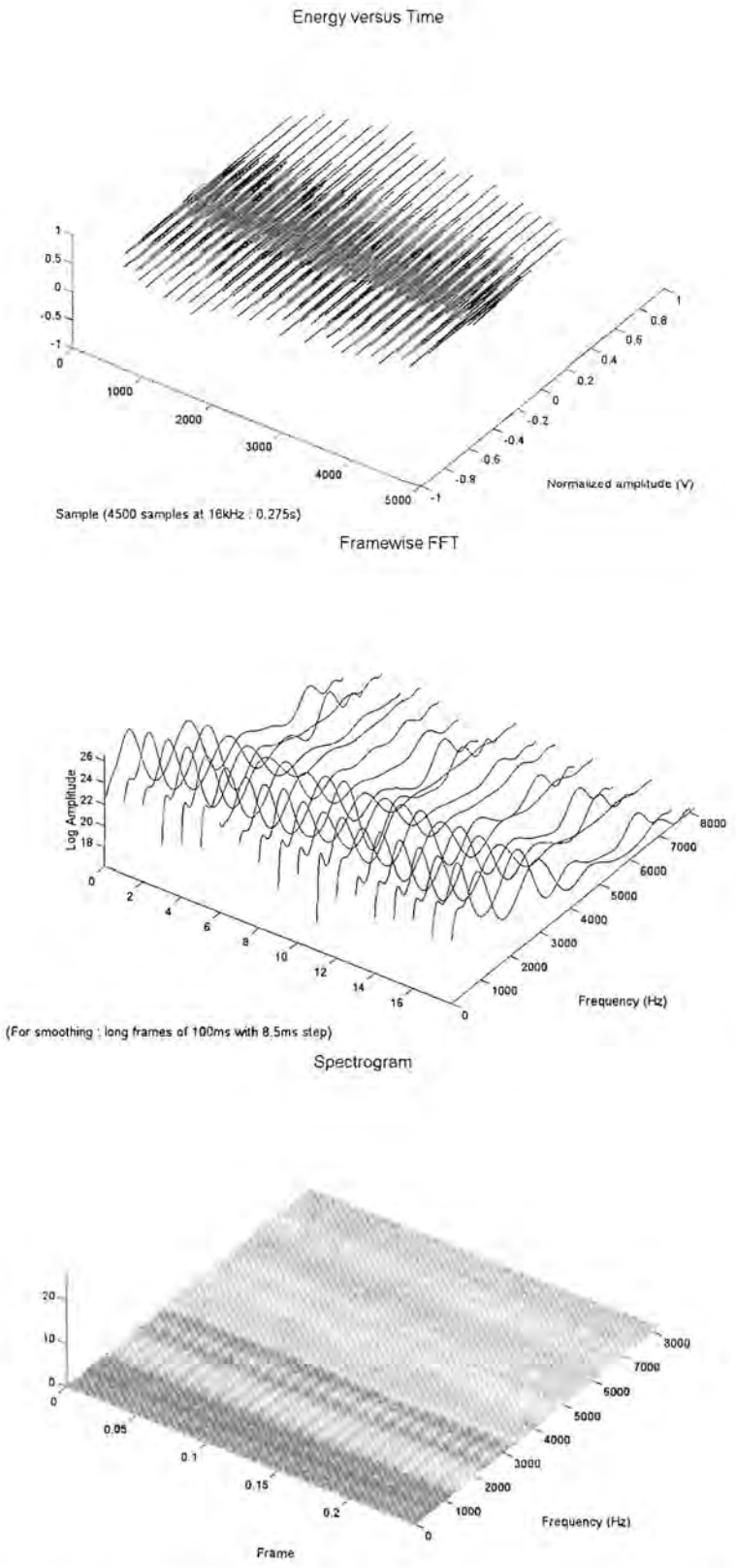



Figure 2.7: Spectrogram extraction illustrated. The time-energy signal is given at the top, the frame-wise spectrum in the middle and the colour-height mapped spectrogram at the bottom.

vowel sound[1]. For this reason they can not be used to analyse consonants (which have no distinct resonance structure which can be associated with any one particular consonant). Formants are used for voiced speech due to their many attractive features, some of which are:

- intuitiveness,
- robustness against channel noise and distortion,
- low dimensionality and hence easily perceived and analysed by a human,
- most immediate source of articulatory information and
- there is a close relation between formant parameters and model-based approaches to speech perception and production.

Formant extraction is the process of determining the most probable resonance frequencies corresponding to peaks in the frequency domain and calculating a temporal path to represent the vocal tract changes (resonant frequency changes) during speech production. It is in principle a very simple process (as will be demonstrated shortly), but it has proven to be complex enough in practice to warrant the efforts of continuing studies. Formant detection becomes a very complex task when the formants merge or lie very close to each other. Excessive noise and signal clipping also pose problems as the spectrum often becomes grossly distorted.

Perhaps the most simplistic means of formant extraction involves spectrum determination, polynomial fitting (or some other spectrum smoothing technique) and then peak picking. Visually this can be represented as in Figure 2.8.

More advanced techniques exist and are commonly used such as:

[1] Whispered speech is the exception to this rule, where, although not voiced, formants may still exist

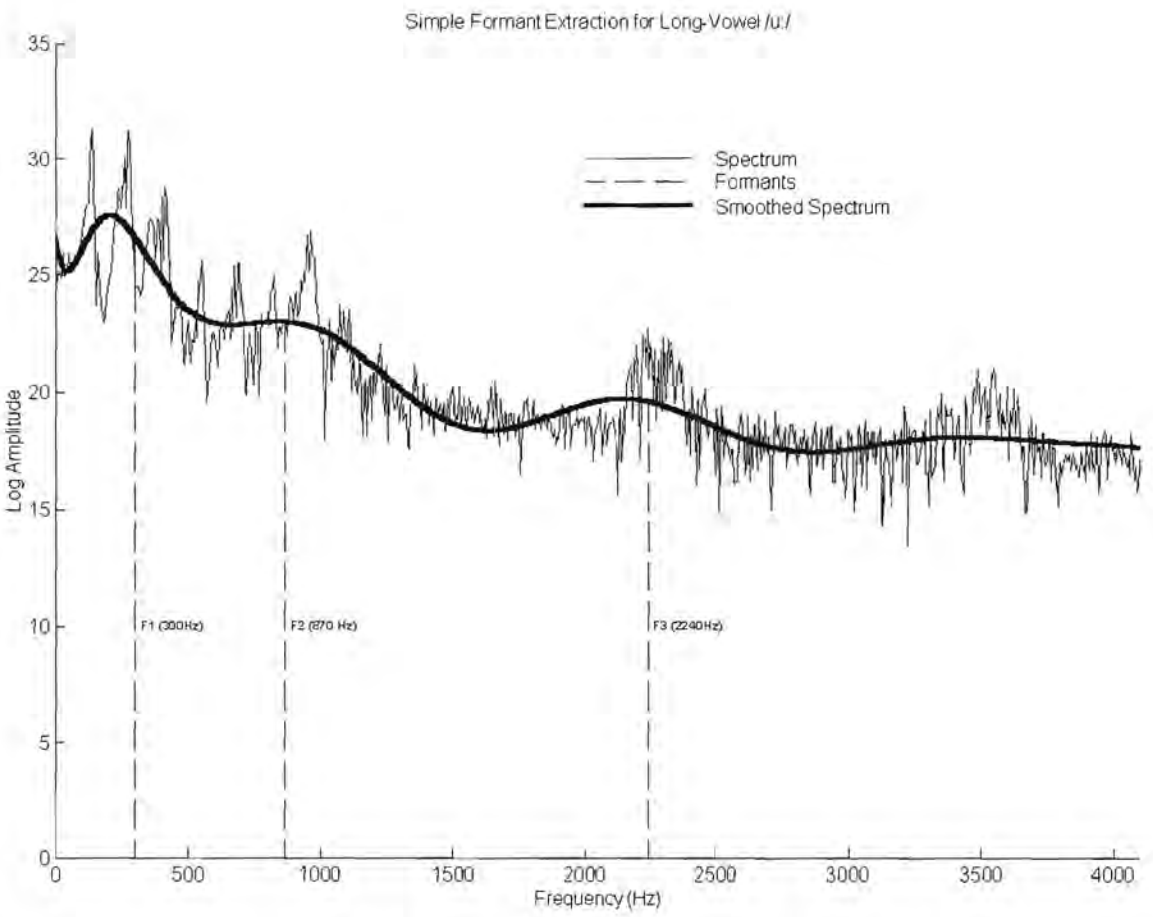



Figure 2.8: A smoothed Fourier Transform demonstrates how simple the concept of Formant extraction(in principle) is.

- Split Levinson algorithm [24]
- Linear prediction spectra [25][2]
- Gaussian mixture fitting [26]
- Contour integration [27]
- Digital resonators [28]

to name only a few.

The Split Levinson algorithm was developed by Delsarte and Genin[29] and requires about half as many computations to determine the LPCs as opposed to traditional techniques such as the Levinson[30] algorithm. The algorithm makes use of singular predictor polynomials to split the classic Levinson algorithm into 2 simpler algorithms.

Linear prediction techniques are explained in Section 2.4.1 as this is the technique we have chosen to use.

The Gaussian mixture fitting technique developed by Zolfaghari and Robinson[26] makes use of the Discrete Fourier Transform (DFT) and tries to fit a Gaussian mixture distribution to the magnitude spectrum. This is essentially an improvement on the basic peak picking technique described earlier in this section.

Snell and Milinazzo[27] developed an interesting technique for efficiently calculating roots within the unit circle once filter coefficients had already been determined using LPC techniques. By integrating over an arc of predetermined size it is possible to determine the presence of zeros within that arc and thereby, to arbitrary precision, it is possible to determine the location and number of roots. This in turn gives us the location of the formants.

A technique making use of decomposing the short-time power spectrum in segments has been proposed by Welling and Ney[28]. Each segment is modelled by a digital resonator

and the segment boundaries are then optimised using dynamic programming.

Each technique has its merits and failings. As a result of the many failings of these techniques, formant extraction, for accurate modelling purposes, must be an interactive process whereby the formants extracted must be verified manually and often recalculated using the various techniques mentioned above until satisfactory results are achieved.

This does not mean that the formants are recalculated until they fit the presupposed model of the researcher! This merely means that if the extracted formants are superimposed on a spectrogram and the results are seen to be flawed then recalculation may well be called for.

Holmes[31] has argued that formants may be used to significantly improve recognition in automatic speech recognition (ASR) systems by simply adding formant values and their accuracy probabilities to standard hidden Markov model (HMM) recognisers as additional features. Until recently, formants, although they have definite phonetic significance, have generally only been studied by linguists and largely been forgotten by speech recognition researchers. This is probably due to the complexity of reliable automatic formant extraction.

### 2.4.1 Linear prediction coefficients

In this study we have decided to use linear prediction coefficients (LPC) as our means of formant extraction. Various techniques were evaluated and compared on a subset of the data we have used in this study and LPC was found to extract the most correct formants most of the time.

The algorithm we found to perform almost as well as LPC concerning pitch extraction was the Split Levinson algorithm. Figure 2.9 demonstrates how formant algorithms may fail to locate the spectral peaks if forced to try and fit more formants than they can

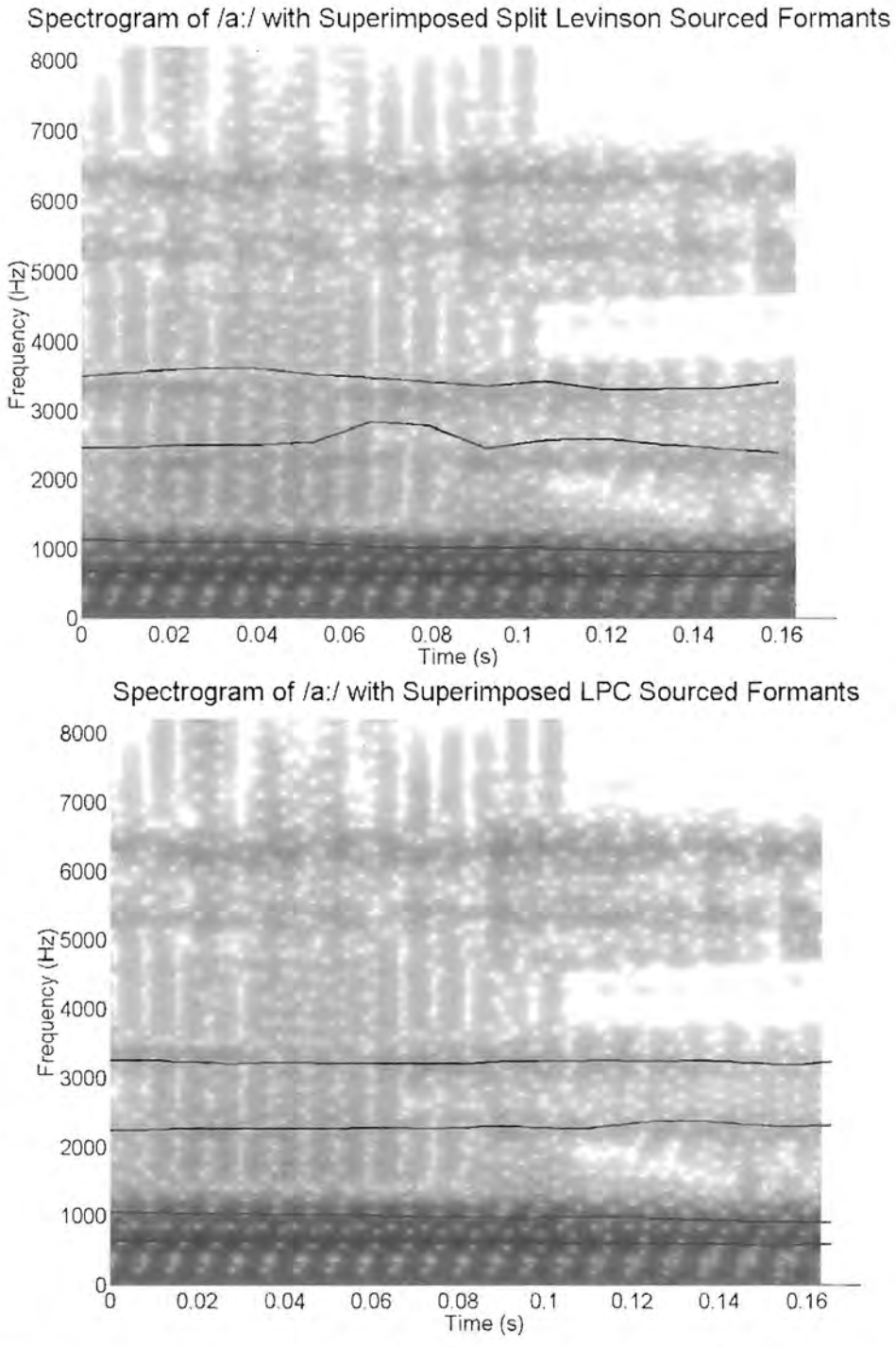



Figure 2.9: Formant extraction using Split Levinson (top) and LPC (bottom). We can see that in this case, LPC has managed to track the formants more accurately.

find. We see that forcing the Split Levinson algorithm to find 4 formants has resulted in incorrect placement of the formants (as shown by the black lines superimposed on the spectrogram). The LPC technique we decided to use is also prone to these errors, but was found to perform consistently well. Its formant extraction for the same piece of speech is shown by the black lines superimposed on the spectrogram in the bottom half of Figure 2.9.

LPC is based on the following principles[2]:

If there is no excitation, then the value of $s_n$ (a speech sample at discrete time $n$) is correlated with the values of $s_{n-1}, s_{n-2}, ...s_{n-p}$ for some appropriate $p$. This is as a result of redundancy in the signal representation.

This correlation is due to the limits of how fast the vocal tract can move and change compared to $f_s$, the sampling frequency. We can therefore write:

$$s_n = f(s_{n-1}, ...s_{n-p}) + x_n. \tag{2.3}$$

where $x_n$ denotes the excitation signal and we assume that $x_n$ doesn't fit the correlation model that we're assuming for $s_n$.

We assume the $f$ is a linear function of $s_n$, with $p$ coefficients $a_i$, so:

$$s_n = \underbrace{\sum_{i=1}^{p} a_i s_{n-i}}_{f} + x_n. \tag{2.4}$$

For a short speech frame we may assume that the "filter" which generates the speech

from the source remains more or less constant. Using our assumption for $s_n$ we have the z-transform of $H(z)$ of $s_n$ given by:

$$H(z) = \frac{1}{1 - \sum_{i=1}^{p} a_i z^{-i}}. \tag{2.5}$$

$H(z)$ has $p$ poles, where the poles are real, or they are complex conjugate pairs; there are no zeros.

The prediction error is defined as:

$$e_n = s_n - \sum_{i=1}^{p} a_i s_{n-i}. \tag{2.6}$$

It is assumed that the error is due to the excitation since the models for excitation do not exhibit the correlation we're assuming for $s_n$.

For example, for voiced speech shorter or equal to one pitch cycle a simple model would be:

$$x_n = \begin{cases} 1 & at\ pitch\ pulse \\ 0 & elsewhere. \end{cases} \tag{2.7}$$

For unvoiced speech, $x_n$ is modelled as noise, which is by definition uncorrelated.

The squared prediction error is defined as:

$$E = \sum_n e_n^2. \tag{2.8}$$

For the minimum error the partial derivative of $E$ with respect to $a_i$ is set equal to zero for each $p$, which gives $p$ equations with $p$ unknowns:

$$\sum_{k=1}^{p} a_k \sum_n s_{n-k} s_{n-i} = \sum_n s_n s_{n-i}. \qquad 1 \leq i \leq p \tag{2.9}$$

and the range of $n$ is dependent on the frame size. Then, using equations 2.6 and 2.8 and the $a_k$'s from equation 2.9 we get:

$$E_{min} = \sum_n s_n^2 - \sum_{k=1}^{p} a_k \sum_n s_n s_{n-k}. \tag{2.10}$$

From this the $a_k$'s (LPC's) still have to be determined. There are two ways to determine these: either an autocorrelation or cross-correlation based technique may be used. Each technique has its pros and cons.

For the autocorrelation technique:

- The disadvantages are:
    - The effect of the autocorrelation window (we need to correlate a windowed segment with itself) which must be used:
        - At beginning of the window non-zero values must be predicted from 0

values outside the window.

◇ At end of window, very small values must be predicted from larger values.

◇ Tapering of the signal due to the window leads to slight distortion.

- On the other hand, the advantages are:

  ○ The autocorrelation technique is computationally simple to perform:

  ◇ The matrix is symmetric, and on every diagonal, you get the same element. This is known as a "Toeplitz" matrix.

  ◇ Solution methods are fast - $a_i$'s are calculated using an iterative method of $O(p^2)$, whereas general matrix inversion is of $O(p^3)$.

  ◇ The solution method is not sensitive numerically: can use fixed point (integer) math and the filter you get using the computed $a_i$'s is guaranteed to be stable. Some methods find $a_i$'s that correspond to poles outside the unit circle as an approximation to the true poles. This can't happen with the autocorrelation method.

For the cross-correlation technique:

- The disadvantages are:

  ○ The technique is computationally expensive:

  ◇ The number of computations is of $O(p^3)$ to solve for the $a_i$'s.

  ◇ The technique is numerically sensitive.

  ◇ Can lead to unstable filters.

- On the other hand, the advantages are:

  ○ No distortion due to windowing as no Hamming window is used.

To solve using the autocorrelation technique we first define autocorrelation as:

$$R(i) \triangleq \sum_{n=-\infty}^{\infty} s_n s_{n+i} \tag{2.11}$$

which, if we substitute into equations 2.9 and 2.10 give us:

$$\sum_{k=1}^{p} a_k R(\mid i-k \mid) = R(i). \qquad 1 \leq i \leq p \tag{2.12}$$

and

$$E_{min} = R(0) - \sum_{k=1}^{p} a_k R(k). \tag{2.13}$$

Using the fact that the short term autocorrelation function $R_N(i)$ can be defined as:

$$R_N(i) = \sum_{n=0}^{N-i-1} s_n^{'} s_{n-i}^{'}. \qquad 0 \leq i \leq p \tag{2.14}$$

where: $s_n^{'}$ is the windowed $s_n$ with $w_n$ the windowing function, i.e.

$$s_n^{'} = \begin{cases} s_n w_n & 0 \leq n \leq N \\ 0 & elsewhere. \end{cases} \tag{2.15}$$

Equation 2.12 can be written in matrix form as:

$$\begin{bmatrix} R_N(0) & R_N(1) & \dots & R_N(p-1) \\ R_N(1) & R_N(0) & \dots & R_N(p-2) \\ \vdots & \vdots & \ddots & \vdots \\ R_N(p-1) & R_N(p-2) & \dots & R_N(0) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_p \end{bmatrix} = \begin{bmatrix} R_N(1) \\ R_N(2) \\ \vdots \\ R_N(p) \end{bmatrix} \tag{2.16}$$

Similarly, using cross-correlation we can also determine the LP coefficients. The mathematics is slightly more complex and computationally expensive, but as this technique is generally not used in speech-recognition systems and we have not used this technique we do not go into the details.

LPC is relatively simple to implement as can be demonstrated by a piece of Matlab code written by Levent Arslan[32] and quoted in Appendix A.1. The technique used by him is the autocorrelation technique with Durbin recursion and root finding.

The first requirement (when using the autocorrelation technique) is to find the autocorrelation coefficients and once these have been found, Durbin recursion may be used to calculate the LP coefficients, in other words, solve equation 2.16. Formant extraction then consists of the procedure of calculating the roots of the windowed frames of speech (Equation 2.4) and translating those roots into formant frequencies.

The algorithm in Appendix A.1 makes use of root finding which is relatively expensive computationally, although quite accurate. With modern computers the time spent determining the roots is becoming negligible, but with small devices this may still be an issue. If accuracy is not as important as timing (for example in real time speech communications) we may make use of various other techniques such as one suggested by Markel[2] where we evaluate the estimate of the vocal tract input response at various discrete points and then determine the peaks of the polynomial which fits these points.

We, however, did not use this technique.

Whichever technique we use, we can only expect about 85-90% accuracy for formants lower than 3kHz. This is still acceptable for male voices, but performance degrades significantly for female and child voices. A path tracking algorithm is therefore required to "join the dots" of the most probable of all the possible candidate formants we extract. The is achieved using a number of heuristics such as defining a maximum allowable frequency "jump" from frame to frame and observing that a similar number of peaks should keep appearing between troughs. Cost function techniques such as that used by Boersma[33] (and discussed in Section 3.3: Pitch Extraction) for pitch trajectory tracking may also be used to great effect.

## 2.5 Pitch

The pitch (also known as the fundamental frequency or $F_0$) is a very important characteristic to study when evaluating accent and pronunciation differences between language groups. Pitch is a voice characteristic which results from glottal closure and the frequency of this occurrence is known as the pitch of someone's voice. The intonation (or change in pitch with time) may vary greatly between languages, for example, French and Zulu are "musical" or "singing" languages (which results from a modulation of the pitch), Mandarin is a intonational language where a different meaning can be imparted to a word by changing the intonation (pitch). There are many such examples, but most importantly the intonation learnt carries over from a speaker's mother tongue to his second language, especially if the second language is learnt when the speaker is mature. Although from experience it is obvious, it is important to note that there is a great difference in pitch between male (low pitch), female (medium pitch) and child (high pitch) speakers. This implies that we must be careful when comparing the intonation of various speakers. This is one of the reasons why the study was restricted to male speakers of similar age. The effects of gender and

age have far reaching consequences such as poorly defined formants at higher pitched voices[34] and poor hidden Markov model recognition across gender data sets.

Various techniques exist for pitch extraction and there have been attempts to evaluate the effectiveness of these various algorithms[35].

We have already explained autocorrelation in Section 2.4.1 and we now follow up on this with how autocorrelation may be used for pitch extraction.

We have already defined the short-time or windowed autocorrelation function in equation 2.14 as:

$$R_N(i) = \sum_{n=0}^{N-i-1} s'_n s'_{n-i} \qquad 0 \leq \imath \leq p$$

So, if we evaluate $R_N(i)$ for i in the vicinity of $\frac{1}{F_0}$ (i.e. around a reasonable estimate for the inverse of the pitch) then we expect maxima at i=0, $\frac{1}{F_0}, \frac{2}{F_0}, \ldots$, and the pitch is $\frac{1}{F_0}$.

This is one of the oldest and most simple techniques of pitch extraction. This technique can be enhanced by filtering techniques.

Another technique which appears to work well under most situations is the CLIP or centre clipping pitch detection algorithm[35]. This involves pre-processing the speech frame $s_n$ in an attempt to remove the formant information or minimise the vocal tract effects. This is done by low pass filtering the signal to 900 Hz.

We then set a clipping level $C_L$ and centre clip the signal by only retaining samples which exceed $|C_L|$ by subtracting $C_L$ for positive samples and adding $C_L$ for negative samples.

The value of the autocorrelation function for a range of lags using the centre clipped signal is then calculated. The autocorrelation function is then searched for the maximum normalised value and (generally) if it exceeds 0.3 the section is considered voiced and the pitch period is determined from the location of the maximum. We have not used the CLIP technique as experiments by Rabiner et al.[35] seem to indicate that CLIP does not perform as well as LPC techniques, especially on low pitched voices such as male voices (which is what our database is made up of).

## 2.6 Equivalence classification

The theory of equivalence classification is that all speakers[2] of a certain region or socio-economic grouping, tend to possess equivalent phoneme sets as long as they have resided in that area while learning the language as a child. The theory states that speakers learning a new language at a late age tend to use the phonemes they already know from the first language, to pronounce the words in the new language. This type of study has generally been performed on populations where this is easily determinable, for example, by studying adults who immigrated into a region at various ages, and then studying their phone structures. James Flege has performed many studies on groups like: Italians who had immigrated to America[36] and French speakers living in Canada with various levels of learning immersion at different ages[18].

The age of learning (AOL) has proven to be a critical factor in the phone make-up of speakers. Our study differs significantly from Flege's research in the fact that most white South Africans are familiar with both English and Afrikaans through media such as the radio and television. This is especially true for young first language Afrikaans speakers who may have watched a large amount of British and especially American television series while growing up. The reverse is not necessarily true for young first language English speakers who may not have watched much Afrikaans television. This

[2]Excluding speakers with pathological speech problems.

trend will continue to grow as fewer programs are translated into Afrikaans and as English channels such as subscription and satellite television become more prominent.

It would be inappropriate to make any deductions from the research by Flege on the phone make-up of speakers in a multi-lingual society such as South Africa's. We would assume that if speakers learn multiple languages at a young age that they would be capable of producing native phones for each of those languages. This is in fact confirmed when we hear many young South African children from multi-lingual families switching between languages. This of course complicates our study and we have therefore asked the speakers in our database to ascertain their own fluency in each of the two languages in question (see Figure 3.1 on page 52).

We find that most of the speakers consider themselves to be fairly bilingual. This makes it far more difficult to determine the acoustic differences between the two language groups. If, however, differences are observable with such a marginal group then it bodes well on further research into groups which we know will be acoustically more separated.

## 2.7 Cubic splines

The dynamic features of the vowels and diphthongs, namely the diphthong formants and pitch contours, have been analysed using curve fitting techniques. In particular, the cubic spline has been used to achieve this[37]. The use of curve fitting is justified by the need to compare the dynamic pitch and formant trajectories. This can not be performed at a point wise level due to the semi-instantaneous jumps which are a result of pitch and formant extraction algorithm shortcomings. These small jumps would unfairly boost the variance of the trajectory and cause analysis of variance tests to judge even similar trajectories as different. We therefore fit a curve to the general trend of the pitch or formant trajectory.

The curve fitting is done in the following way:

- We fit the data using a cubic spline such that the spline fits through every one of the data points we have extracted for the formants or pitch trajectories.
- We resample this cubic spline to give us 128 samples, irrespective of how many points we had originally. We now have a linear time-scaled curve of normalised length.

We now want to reduce this into a simple, low-order dimensionality vector for comparison purposes. It was decided to do this by calculating four points which if fitted by a curve would represent reasonably closely the trajectory we began with. So:

- We make the first of the 128 points the first point of the curve. Formant extraction tends to be difficult at the start and end of voiced speech segments. This is why it is important that we make sure that the formant extraction is correct as described in Section 3.3.1 on page 58.
- We divide the 128 point formant or pitch trajectory into three equal sections (as can be seen in Figure 2.10 (middle)). The second and third points are then calculated as being the mean formant or pitch values of a section centred around the first and second divisions (as seen by the horizontal bars in the middle figure).
- The fourth point is equal to the last of the 128 point vector.

We once again perform a cubic spline fit, this time fitting just the four points we have calculated. If we define the cubic spline by:

$$S_k(x) = a_{k,3}(x - x_k)^3 + a_{k,2}(x - x_k)^2 + a_{k,1}(x - x_k) + a_{k,0} \tag{2.17}$$

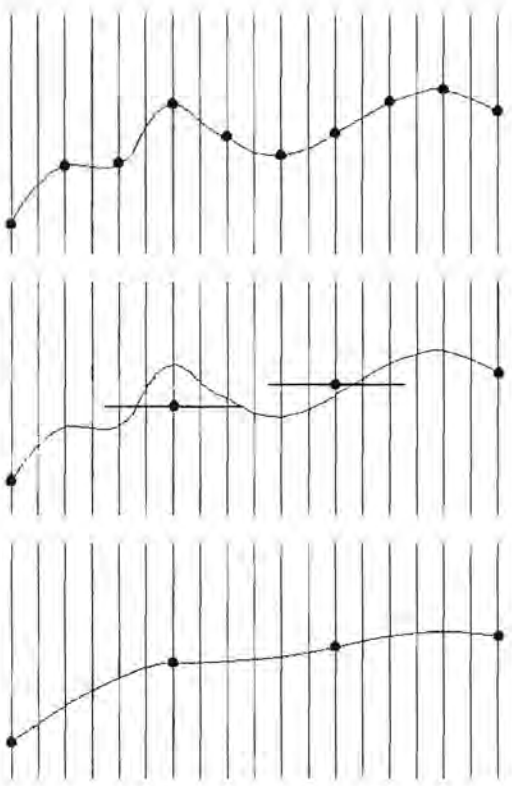


Figure 2.10: Reduction of a multi-dimensional formant or pitch trajectory to a low-dimension cubic-spline for ANOVA comparison purposes.

then, as we are fitting three sections and we have four coefficients per section, we end up with twelve coefficients per formant or pitch trajectory. We are now able to perform ANOVA tests of significance between trajectories of various speakers and using mean trajectories, between the two accent groupings. We have chosen to work with three formants and one pitch trajectory. As it carries little perceptual information to give the exact coefficient which was found to be significantly different, we simply display whether or not we found significant differences within a trajectory. This is displayed in the results tables in Section 3.4 by using dark gray boxes. The magnitude of this difference could only be estimated in an artificial way which we have decided to avoid as we have deemed it sufficient to demonstrate that there is a significant difference between the two language groups. The magnitude of this difference can then be judged by the reader from the trajectory plots, remembering of course that the plots are just mean plots and carry no variance information.

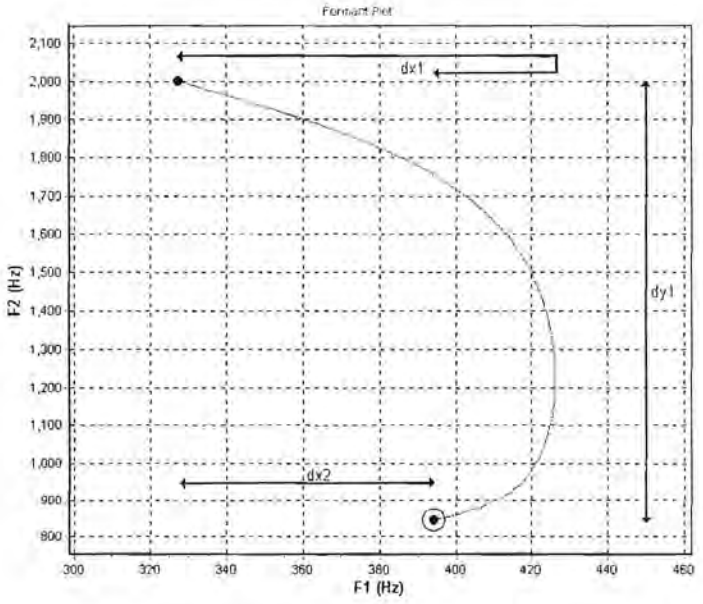



Figure 2.11: We have used two measures of diphthongization. The first is the displacement along the axis between the initial and terminating points(dx2 and dy1) and the second is the cumulative absolute distance traversed along the axis(dx1 where the cumulative absolute value of the arrowed distance is used).

## 2.8 Diphthongization

We have discussed diphthongs in Section 2.2. We have also discussed the cubic spline in Section 2.7. We can use the cubic spline to form a low order representation of the diphthong formant trajectories. Using this principle we can measure the frequency displacement a diphthong undergoes while moving from the initial "vowel" to the terminating "vowel". We have decided on two measurements of diphthongization, and these are demonstrated in Figure 2.11. We have included the nett formant displacement (dx2 and dy1) and the gross formant displacement (dx1) as our diphthongization metrics.

## 2.9 Statistics: Tests of hypotheses and significance

Using the notation of Spiegel[38] we state that in statistics we may define a null hypothesis (denoted $H_0$) which may be used to test the structure of given populations. We may for example make the null hypothesis that the means of the formants for English first language and Afrikaans first language speakers are statistically equal for certain vowel sounds. We may then apply various statistical tests to confirm or deny our hypotheses.

There are two types of errors. Type I errors occur when we reject a hypothesis we should have accepted and Type II errors are said to occur when we accept a hypothesis we should have rejected. Unfortunately we find that when we attempt to minimise Type I errors we ultimately increase our probability of making Type II errors and vice-versa. Usually one of the error types is more critical and this must be taken into account when we define the hypothesis.

The maximum probability with which we are willing to risk a Type I error is called the *level of significance*. We usually specify a level of significance of 0.01 or 0.05. A 0.01 significance level indicates that we are 99% confident that we have made the right decision.

### 2.9.1 Analysis of variance (ANOVA) test

Fisher[19] developed and used the F distribution to perform "analysis of variance" tests on two or more populations (independent groups of samples).

If $x$ is a sample, then the total variation (variance) of $x$ is defined as:

$$v = \sum_{j,k} x_{jk}^2 - \frac{\tau^2}{n} \tag{2.18}$$

where $j = 1, 2, \ldots, a$ is the number of independent groups (in the sample) of $k = 1, 2, \ldots, b$ measurements each. The variation between the $a$ independent groups is:

$$v_b = \sum_{j} \frac{\tau_j^2}{n_j} - \frac{\tau^2}{n} \tag{2.19}$$

where:

$$\tau = \sum_{j,k} x_{jk} \qquad \text{the total of all the values } x_{jk} \tag{2.20}$$

and

$$\tau_j = \sum_{k} x_{jk} \qquad \text{is the total of the values in the } j^{th} \text{ independent group.} \tag{2.21}$$

Also,

$$n = \sum_{j} n_j \qquad \text{is the total number of observations in all the independent groups} \tag{2.22}$$

where $n_j$ is the number of observations in the $j^{th}$ independent group.

| Variation | Degrees of Freedom | Mean Square | F |
|---|---|---|---|
| Between groups, $v_b = \sum_j n_j(\overline{x}_j - \overline{x})^2$ | $a-1$ | $\hat{S}_b^2 = \frac{v_b}{a-1}$ | $\frac{\hat{S}_b^2}{\hat{S}_w^2}$ with $a-1, n-a$ degrees of freedom |
| Within groups, $v_w = v - v_b$ | $n-a$ | $\hat{S}_w^2 = \frac{v_w}{n-a}$ | |
| Total, $v = v_b + v_w = \sum_{j,k}(x_{jk} - \overline{x})^2$ | $n-1$ | | |

Table 2.5: Analysis of Variance Table

If the group means are not equal i.e. the null hypothesis ($H_0$) is not true then we can

expect $\hat{S}_b^2$ to be greater than the variance ($\sigma^2 = \sum(x-\mu)^2 f(x)$) and this becomes larger as the difference in means increases. We also know that $\hat{S}_w^2$ (which is given in Table 2.5 and is an unbiased estimate of $\sigma^2$) is always equal to $\sigma^2$ irrespective of mean differences. It seems therefore that a good statistic for testing $H_0$ is $\frac{\hat{S}_b^2}{\hat{S}_w^2}$ which we call $F$ in Table 2.5 where $a$ is the number of groups measured. The distribution of this statistic is known as the $F$ distribution in honour of Sir Ronald Fisher.

The calculations required to perform an analysis of variance test are often summarised in tabular form as in Table 2.5. In practice we calculate $v$ and $v_b$ and then deduce $v_w$. The $\overline{x}$ indicated in the table means the mean value of $x$. There are $a-1$ degrees of freedom (dimensional elements) between groups and $n-a$ degrees of freedom within the groups. Notice that these formulas are the same as those in the functions mentioned above, with substitutions having been performed and more compact notation being used.

Of course, as we are simply comparing Afrikaans and English, $a$ (the number of independent groups) is only 2 which allows us to simplify things, but for generality we have described a complete analysis of variance, where an analysis of variance consists of calculating the $F$ ratio. To determine whether a particular $F$ ratio indicates a significant difference in means for a particular significance level, we generally use the the $F$ distribution tables published in Fisher's book[19]. The exact value which the $F$ ratio must exceed to indicate a significant difference is dependent on the degrees of freedom i.e. the number of treatments and the total number of observations.

# Chapter 3

# Experiments

This chapter describes the experiments performed on the data described in Chapter 2. The objectives (in other words, what we are trying to achieve) are described and then the techniques used to meet these objectives are explained. Finally we discuss the results obtained, show graphs of the processed data and discuss our interpretation of the experimental results.

## 3.1 Objectives

Our primary objective with this study is to create acoustic models of Afrikaans vowels and diphthongs as spoken by mother-tongue speakers. We then want to create acoustic models of Afrikaans vowels and diphthongs for mother-tongue English speakers and compare these models with the Afrikaans models. We would then like to determine whether there are significant differences between the two accent groups.

A further objective which follows from the first is to add South African English vowels and diphthongs to the models and also compare these with the Afrikaans models of the same sounds. This will help us to determine how much of an influence Afrikaans

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A further objective which follows from the first is to add South African English vowels and diphthongs to the models and also compare these with the Afrikaans models of the same sounds. This will help us to determine how much of an influence Afrikaans

has had on South African English in this respect and vice versa.

Our third objective is to determine if intonation (the change in pitch [one of the prosodic effects] over time) has a large influence on how vowels and diphthongs are perceived between the two accents as was found to be the case for French, German and English by Grover, Jamieson and Dobrovolsky[17]. They found that adult French, English and German speakers differ in the slopes of their continuative intonation, and that, dependent on the age at which the language was acquired, a speaker would use either native (if learned at a young age, say 10) or foreign intonation (if learned at an older age, say 16). We do not perform perceptual test here, but simply analyse the intonation curves of the accent groups.

Analysts such as Rousseau[39] and Flege[18] have noted that second-language speakers often substitute phonetically "close" sounds from their first-language when they do not possess the sounds in their personal phoneme space. This phenomenon is known as equivalence classification, as explained in Chapter 2.

Thus, for example, Flege proposes that because English does not possess the <y> sound phone which occurs in French, L1 English speakers will classify an L1 French speaker's <y> as his <u> and pronounce a <u> when trying to articulate a <y>, even though there are significant differences in the F2 frequencies of the two vowels when spoken by French speakers.

Rousseau goes further to suggest that if such a substitution is heard often enough and seen as acceptable then the substitution may become permanent, ironically enough, in the second language. For example, Rousseau theorises that the use of <i> instead of <ə> in Afrikaans words such as : "*ignoreer*" [ixnuriər], "*imbesiel*" [imbəsiəl], "*Indië*" [indiə] and "*industrie*" [indəstri] are all as a result of the influence of English.

Our first objective then can be seen as a desire to determine where we observe elements of equivalence classification in South African English and Afrikaans speech. This process is complicated by the bilinguality of the speakers.

One of our objectives in this study is also to determine whether <e:> and <o:> are long vowels or diphthongs and ideally suggest a means of measurement which will make it possible to qualify a voiced sound as either a vowel or diphthong.

## 3.2 Data

It was found by Peterson and Barney[10] that female speech formant frequencies differ from mens' by significant, yet consistent amounts. Knowing that this would unnecessarily complicate our study, and as only the cross accent trends are of interest to us, we concentrated this study exclusively on men. We also know that age has a distorting effect. Children generally have voices which are even higher pitched than those of women, and older people often display a change in timbre. Peterson and Barney observed these factors with their study. We therefore once again constrained the database to men aged between 20 and 40 years rather than to have to perform complex speaker normalisation and/or run the risk of biasing the data.

De Villiers[40] states:

> "As is explained with the discussion of the speech organs, there are differences between speakers, and especially between the three big groups: children, men and women. It is understandable that the three groups speak the same speech sounds with different fundamental frequencies and formants, but the ratios between the formants of the different groups are not so entirely different and this probably explains why people understand each other in spite of the differences which are observed in the individuals or groups."

We argue therefore that it is also important to analyse the formant ratios, not only due to the seemingly inherent speaker normalisation effect, but to further investigate the validity of the formant ratio theory.

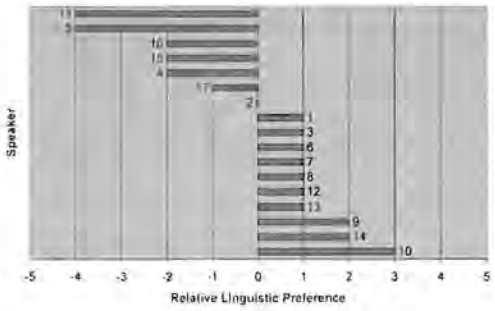



Figure 3.1: A bar graph displaying the linguistic preference of the speakers in the database.

To ensure that erroneous data (data which was incorrectly recorded or incorrectly spoken) could be excluded while minimising the effect on the statistical significance of our measurements, we decided to create a sizeable database with a significant number of utterances for each vowel per person.

### 3.2.1 Data structure

The data used in this study was collected from 17 speakers, 10 of whom are L1 (first language) Afrikaans speakers and 7 are L1 South African English speakers. Most of the speakers were relatively bilingual, but during the data recording process they were asked to indicate their language preference. The results of this query can be seen in Figure 3.1.

We make note here that we are aware that the research only holds true for a particular group of speakers in South Africa. There are a couple of L1 accents for both Afrikaans and South African English. The Cape Coloured community in the Cape Province generally speak L1 Afrikaans with an markedly different accent to that of the white Afrikaner population of the Gauteng Province.

The data was recorded in an anechoic chamber at the University of Pretoria using a ROSS RMA-102 Boom Microphone Headset and a Creative Labs Sound Blaster 16 at a sampling frequency of 16384 Hz. The data was recorded and written in 16 bit WAV

format.

Using various recognised phonetic sources[23][41][40][1][20][42] we compiled a list of candidate words which contain most of the long vowels and diphthongs found in Afrikaans and South African English.

Please note that we have made an error in requesting that the speakers base their pronunciation of the vowel <ɛ:> on the Afrikaans word "*êrens*". In the Cape Province amongst a section of the population this would have resulted in the correct vowel being uttered. Phonetically, in the Cape Province, we could write the word as [ɛ:rəns] whereas in Gauteng Province where the data was recorded, a more correct phonetic transcription would be [æ:rəns]. As a result we have no examples of <ɛ:> and can therefore not determine its location in formant space.

A further error has been made in the data recording process, where we have requested that speakers utter the long vowel <ɔ:>. We have in fact indicated example words which are based on the short vowel <ɔ>. We should have in fact used example words like "*sôe*" (sows) and "*rôe*" (rays [fish]). This mistake was, however, spotted too late to re-record the required long vowel. Further studies should attempt to study this vowel as we believe it is also prone to diphthongization.

Using Tables 3.1 and 3.2 we produced a sub-list (given in Table 3.3) which was used for the data recording. Tables 3.1 and 3.2 are lists of vowels and diphthongs respectively, drawn up from examples cited by some commonly referenced phoneticians. The lists are drawn up using the phonetic symbols used by the respective authors and we make no attempt at this point to distinguish between phonetic or phonological labelling used by the authors. As a result we find in Table 3.1 that Coetzee and de Villiers annotate <ɛ:> as being a common vowel in all their example words on that line. This is in fact not true for all accent groupings of Afrikaans and this resulted in an error when the final reduced list was created. We choose the words for the reduced word list based on their familiarity and unambiguity (both of meaning and intended vowel/diphthong

| SYMBOL | Afrikaans (Coetzee)[23] | Afrikaans (Wissing)[41] | Afrikaans (De Villiers)[40] | English (De Villiers) | English (Rabiner)[1] | English (Ward)[20] |
|---|---|---|---|---|---|---|
| a: | | *baat* | | | | |
| ɑ: | *aan, klaar, are, snare* | | | | | |
| æ: | *ver, sê* | *ver* | | | | |
| e: | *eensaam, leen, bene, see* | *beet* | *bees* | | | |
| ɛ: | *êrens, bêre, lê* | | *sê, ver* | | | |
| ə | *is, rit, middel, tevrede* | *bid* | *wit* | bird | about | about |
| i: | *Ier, mier* | *fier* | *dier* | heat | | |
| o: | *oor, boom, bore, glo* | *boot* | *kool* | | | |
| ɔ: | *op, klop* | *bot* | *dom* | hot | bought, all | bought |
| $\phi$: | *Europa, kleur* | *neus* | *reus* | | | Fr.peu |
| œ: | *brûe* | *lus* | *hut* | | | Fr.sœur |
| u: | *oer, vloer* | *voer* | *boer* | too | | soon |
| y: | *uur, muur* | *vuur* | *uur* | | | |

Table 3.1: A list of long vowels and words which contain these sounds.

| SYMBOL | Afrikaans (Coetzee)[23] | Afrikaans (Wissing)[41] | Afrikaans (deVilliers)[40] | Afrikaans (Combrink)[42] | English (Rabiner)[1] | English (Ward)[20] |
|---|---|---|---|---|---|---|
| œu / əu | ***bou**, blou, oud, troue* | *bout* | | *lou* | | poor |
| əi | ***by**, ry, bly, eier, rys* | *byt* | | *ly* | | |
| œy | ***bui**, trui, uit, buite* | *buit* | *uit, ruik* | *lui* | | |
| ɔi | *hondjie* | *bodjie, botjie* | *boikot* | | | boy, noise |
| ɑi | *matjie* | *badjie* | *aits, aitsa* | | | my, time |
| o:i | ***ooi**, nooit, mooi* | *looi* | *sooi, nooit* | *looi* | | |
| e:u | ***eeu**, speeus, leeu* | *leeu* | [eu]*leeu* | [Eu]*leeu* | | |
| ui | *moeite, koei* | *loei* | *moeite, boei* | *loei* | | |
| ou | | | *oud, gou* | | | go, home |
| ei | | | *peil, pyl, ryk* | | | play, lady, make |
| ɑ:i | ***aai**, saaier, blaai* | | *raai, laai* | [Ai]*laai* | | [ai]my |
| iu | | | *leeu, spreeu* | | | |
| ɑu | | | cum laude | | | now, round |
| æu | | | *Crouse* | | | |
| iə | | | *weer* | | | here, beard, idea |
| uə | | | *koor* | | | pure, your |
| yə | | | *neus* | | | |
| ɛə | | | *werk* | | | there, fair, scarce |
| iɛ | | | *elke* | | | |
| əi | *litjie* | | | | | |
| $\phi$:i | *neutjie* | | | | | |
| ɔə | | | | | | more, board |
| $\alpha^y$ | | | | | buy | |
| $\mathfrak{o}^y$ | | | | | boy | |
| $\alpha^w$ | | | | | down | |
| $e^y$ | | | | | bait | |

Table 3.2: A list of diphthongs and words which contain these sounds. Included in square brackets are alternative (yet similar) notations used by some phoneticians.

| Phonetic Symbol | AFR. | ENG. |
|---|---|---|
| Long vowels | | |
| a: | *klaar*(finished) | father |
| æ: | *werk*(work) | hat |
| e: | *bees*(cattle) | |
| ɛ: | *êrens*(somewhere) | |
| ə: | *wîe*(wedges) | about |
| i: | *dier*(animal) | heat |
| o: | *kool*(coal) | |
| ɔ: | *dom*(dumb) | bought |
| u: | *boer*(farmer) | soon |
| y: | *uur*(hour) | |
| oe: | *brûe*(bridges) | |
| Diphthongs | | |
| œu | *blou*(blue) | |
| əi | *bly*(happy) | |
| œy | *trui*(jersey) | |
| ɔi | *hondjie*(small dog) | boy |
| o:i | *mooi*(pretty) | |
| a:i | *haai*(shark) | time |
| ou | *gou*(quickly) | home |
| ei | *ryk*(rich) | play |

Table 3.3: The reduced long-vowel and diphthong word list used in the database recording.

intended to be pronounced).

A summary of possible recording structures is given in Table 3.4. The database consists of two main sections namely long vowels and diphthongs. Each of these main sections is divided into three sub-sections called isolated, context and pseudo-context. "Isolated" means the vowel or diphthongs were recorded in isolation as nothing more than a vowel or diphthong. For example, just the <a:> in father. By "context" we mean the vowel or diphthong was recited as part of a word, for example "father". Lastly, by "pseudo-context" we are referring to the h-vowel-t structure, similar to the one used by Peterson and Barney. "h" and "t" were chosen for their limited influence on the articulation of vowels, thus for example the person had to say [hi:t] as in "heat". Quite often though, no h-vowel-t word with that vowel, or especially diphthong exists. Nevertheless, the

| Number of Utterances | Sound | Placement | Playback |
|---|---|---|---|
| 2 | Long vowel | Isolated | No |
| 2 | Long vowel | Isolated | Yes |
| 2 | Long vowel | Context | No |
| 2 | Long vowel | Context | Yes |
| 2 | Long vowel | Pseudo-context | No |
| 2 | Diphthong | Isolated | No |
| 2 | Diphthong | Isolated | Yes |
| 2 | Diphthong | Context | No |
| 2 | Diphthong | Context | Yes |
| 2 | Diphthong | Pseudo-context | No |

Table 3.4: The various ways is which the data was recorded.

speakers were instructed to attempt, for example, to articulate sounds such as [hət] (which is a non-existant word) using the <ə> vowel found in the word **a**bout. By "playback" we mean that in that particular section the sound was either played back to the speaker for him to evaluate and re-record if desired, or not played back at all with no chance of altering the sound once recorded. The reasoning behind this is that some speakers may alter their pronunciation when hearing themselves and we wanted examples of both possibilities.

This gives us a potential database of ten utterances per long vowel of which we have seventeen cases (counting SA English and Afrikaans individually) and ten utterances per diphthong of which we have twelve cases (again counting SA English and Afrikaans individually). A potential two hundred and ninety words were thus recorded per speaker. This gives a total of 4930 words.

The raw WAV data comprises about 350 megabytes.

## 3.3 Method

Now that we have described the data we used to meet the objectives of this study we will describe the methods employed to check and process the data.

### 3.3.1 Data recording and verification

The data for each person was recorded in a single thirty minute session. The data was recorded over a number of days with English and Afrikaans speakers randomly distributed. Recording instructions were given in the speaker's first language before the speaker entered the anechoic chamber.

The data recording session took place with the speaker alone in the anechoic chamber. They were prompted by text on a computer screen to recite the vowels and diphthongs one by one in ten stages (as layed out in Table 3.4). Each utterance was automatically detected and saved to a separate file before the next prompting took place. The order of the words was purely random with two utterances of each word/vowel/diphthong being recorded to ensure redundance. Where possible, both recorded instances were used. Afrikaans source words were highlighted in green and English source words in red. Before the commencement of each section a text paragraph was displayed and a voice recording explaining the next section was played with an example of what was expected. One speaker complained of difficulty reading some of the words due to colour blindness but stated that he did not think it had influenced the accuracy of his utterances. Playback of his data confirmed this. One other speaker was allowed to re-record his entire session due to multiple mistakes, the cause of which he could not explain.

The software was written and run under the Linux operating system in plain text mode and using alphanumeric colour codes to generate the desired red and green colours.

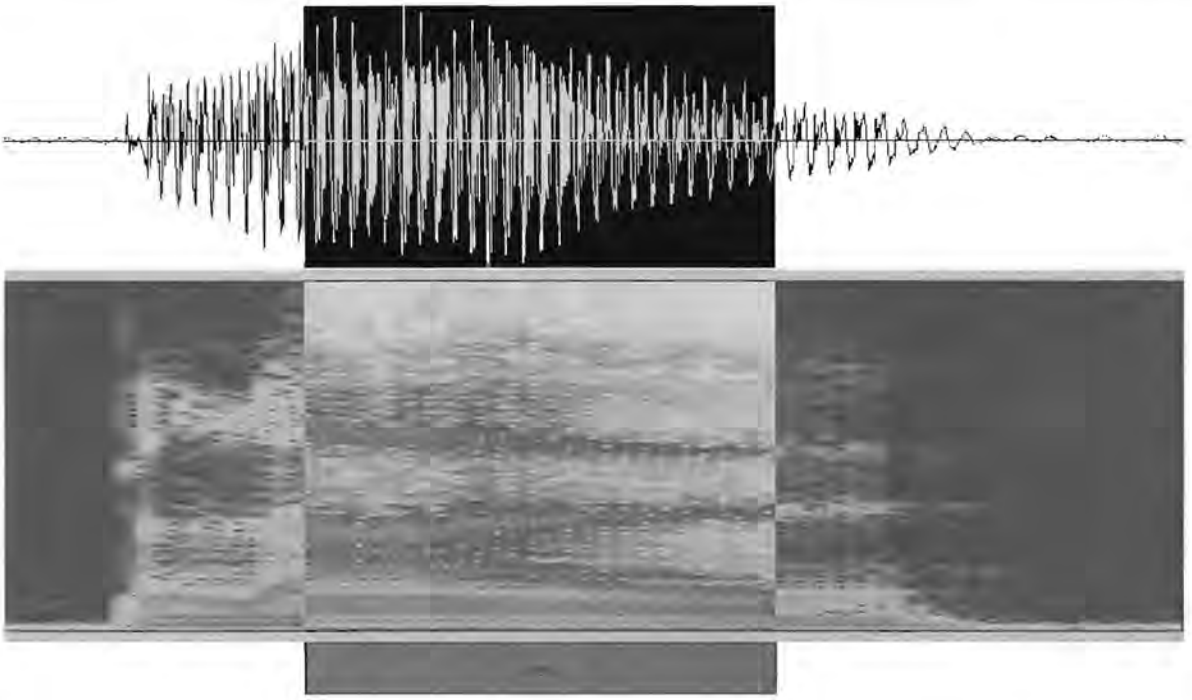


Figure 3.2: This figure demonstrates diphthong extraction. The top half shows the time-energy waveform, the bottom half the spectrogram and the very bottom shows the label (tag) given to the diphthong segment (in this case <œu> from "*blou*" (blue)).

The recorded "words" are then processed manually to extract the vowel or diphthong which we require. This process is called segmentation and labelling (tagging). Using the time-energy waveform, spectrogram and sound playback, we extract only the section from the recording which we require. This process is demonstrated in Figure 3.2.

Before we began processing the data we listened to all the sounds in each of the categories listed in Table 3.4 and then removed the sounds which differed too excessively or were not consistent within a vowel grouping or did not "sound" correct to the data labeller. It was found that certain of the speakers misunderstood some of the instructions or misread certain of the words. This can partially be attributed to the lengthy process of recording almost 300 words, but, alternatively, it can be argued that without such an exhaustive sampling session, if a few mistakes were made, simple errors would be a far more significant percentage of the database. A few of the words had to be discarded due to excessive clipping of the signal due to a change in volume of the speaker and some of the recordings were of lip smacks or coughs. The amount

of data thrown out in this initial stage was about 10% of the initial data.

The second stage of data checking took place after the formants and pitch trajectories had been extracted. This, in the case of formants, involved superimposing the extracted formants onto the same section of speech's spectrogram. We then manually observed each of the almost five thousand words and where necessary and possible, manually corrected the trajectories. This usually occurred when a few of the points could be seen to have been incorrectly extracted. This is demonstrated in Figure 3.3. This step is essential as a few large misplaced values can have drastic effects on the means and variances of the data and this carries over and biases the statistical significance of differences between the two language groups.

It is important to note that we decided to exclude all the normal word-in-context data, i.e. the vowels and diphthongs which were recorded as complete words (not the h-vowel-t or h-diphthong-t structure). It was found after exhaustive plotting in formant space that the influence of the consonants was far too excessive to make for any useful comparison or pooling with the isolated and h-structure-t data.

When checking the pitch trajectories we simply discarded any utterance in which we observed unrealistic fundamental frequencies. De Villiers[40] states that under normal relaxed speech conditions, males speak with a fundamental frequency of 109 to 163 Hz. To be safe we plotted pitch trajectories from 75 to 250 Hz and then discarded those where sudden large (25 Hz) jumps occurred. The remaining trajectories are then used to determine mean intonations for the vowels and diphthongs for each of the language groups.

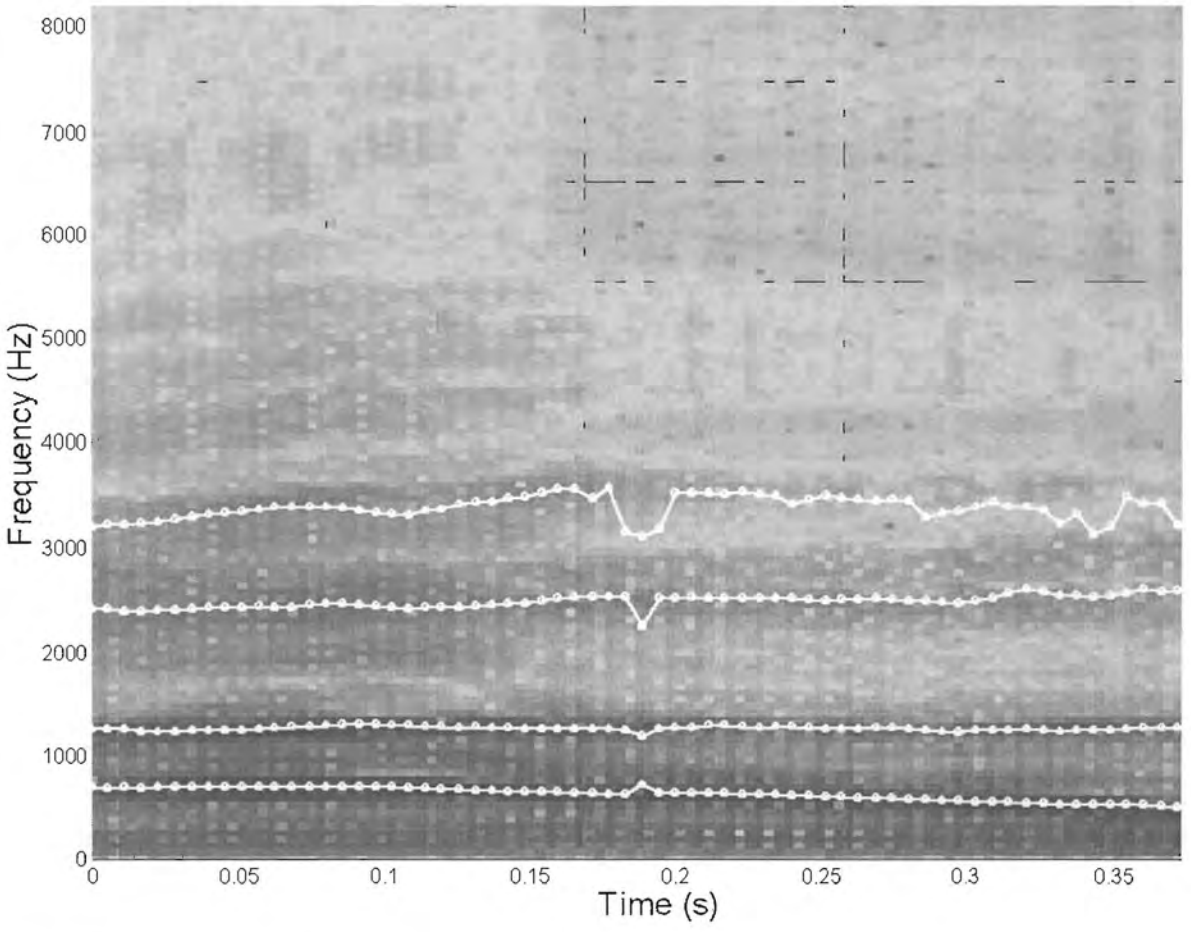



Figure 3.3: Miscalculated formant values at time 0.19s superimposed on a spectrogram and requiring correction.

### 3.3.2 Formant extraction

The formants were extracted using the techniques described in Section 2.4 on page 26 and using the functions found in the program Praat[1] with the following parameters:

- LPC Prediction order : 17
- Analysis width : 25ms
- Time step : 5ms
- Pre-emphasis from : 50Hz

We have used a rather high LPC order. This was determined experimentally, using Praat and iteratively trying various orders with various recordings. This was the value which tracked the formants most accurately.

Each segmented file was processed individually and the extracted formants then saved to separate files. This allowed for editing of the formant trajectories if required. This process was described in Section 3.3.1.

Although the formant extraction process is relatively quick, the checking and correcting of poorly extracted formants is an arduous task requiring many days to complete.

### 3.3.3 Pitch extraction

The pitch trajectories were extracted using one of Praat's pitch extraction techniques using a modified autocorrelation technique developed by Boersma[33]. The algorithm corrects many of the problems associated with standard autocorrelation techniques discussed in Sections 2.4.1 and 2.5. This method is more accurate, noise-resistant

[1]Praat by Paul Boersma. A system for doing phonetics by computer, IFA, University of Amsterdam

and robust than methods based on cepstrum, combs or the original autocorrelation methods. The reason why other methods were invented was the failure to recognise the fact that if you want to estimate a signal's short-term autocorrelation function, you should divide the autocorrelation function of the windowed signal ($r_{xw}(t)$) by the autocorrelation function of the window ($r_w(t)$). This is represented by:

$$r_x(\tau) \approx \frac{r_{xw}(\tau)}{r_w(\tau)} \tag{3.1}$$

A summary of the complete 9-parameter algorithm, as it is implemented in the speech analysis and synthesis program Praat, is given in Appendix A.2.

With reference to the algorithm described, we have used the following parameter values:

To find pitch candidates:

- Time step : 10ms
- Minimum pitch : 75Hz
- Maximum number of candidates : 5

And to find a path:

- Silence threshold : 3% (0.03)
- Voicing threshold : 45% (0.45)
- Octave cost : 0.01
- Cost of octave jump : 0.35
- Voiced/Unvoiced cost : 0.14

- Ceiling : 600Hz

The *Silence threshold* is the point at which all frames with amplitudes less than this normalised (relative to the global maximum amplitude) value are considered to be silence.
The *Voicing threshold* is the strength of the unvoiced candidate, relative to the maximum possible autocorrelation.
The *Octave cost* is the degree of favouring of high-frequency candidates, relative to the maximum possible autocorrelation. This is necessary because even (or, especially) in the case of a perfectly periodic signal, all under-tones of $F_0$ are equally strong candidates as $F_0$ itself.
The *Octave jump cost* is the degree of disfavouring of pitch changes, relative to the maximum possible autocorrelation.
The *Voiced/unvoiced cost* is the degree of disfavouring of voiced/unvoiced transitions, relative to the maximum possible autocorrelation.

### 3.3.4 Data visualisation and comparison

Due to the graphical nature of data plotting, and the desire to make a single application which could be used to view and analyse the data, it was decided to write a program to run on the Windows operating system using the Borland C++ Builder development platform. The resulting program allows for the following:

- Formant plotting

  1) Each extracted formant point for each utterance - useful for spotting rogue data or poorly extracted formants.

  2) The mean location of the formants for each utterance - used to determine the mean formant frequencies for each of the accent groups' vowels.

3) Individual formant trajectories for each utterance - useful for spotting rogue data or poorly extracted formant trajectories for diphthongs.

4) Mean formant trajectories for a number of utterances - used to determine the mean trajectories of the diphthongs for each of the accent groups.

- Pitch plotting

1) Individual pitch trajectories - useful for spotting poorly extracted pitch contours.

2) Mean pitch trajectories - used to plot the mean pitch trajectories (for a number of utterances) for the different accent groups.

When plotting the mean formant positions (as in Figure 3.4 on page 70) of each utterance we also plot a mean/variance cluster bubble around the data, so orientated to indicate the direction of maximum variance. The centre of the bubble lies at the mean of the formant values (these values can be seen in Table 3.5 on page 69). The border of the bubble indicates the mean variance of the data set. The variance ($\sigma^2 = \frac{[(x_1-\mu)^2+(x_2-\mu)^2+\cdots+(x_n-\mu)^2}{n}$) is a measure of the dispersion or scatter of the local mean formant values around the global mean formant value. If the values tend to be concentrated near the mean, the variance is small and the bubble will be small. So as to include most of the points within the variance bubble we actually plot the border at twice the variance. We also calculate the direction of greatest variance and rotate the oval bubble to reflect this direction.

When plotting diphthong trajectories (as in Figure 3.6 on page 79) we plot a small circle around the originating point to show the direction of articulation i.e. where the diphthong starts and by implication, where it ends.

The program also allows for swapping the axes and inverting them. The orientation used in the plots given in this dissertation was chosen so that the data always fits in with the IPA vowel chart. The locations of the Peterson and Barney vowels are also plotted for reference purposes.

The plotting software also allows us to perform analysis of variance comparisons between any two batches of data (section 2.9.1 on page 46). For the vowel formants the independent groups of samples are simply the mean formant frequencies for each utterance. For the diphthong formants and pitch trajectories we make our comparison between the cubic spline coefficients as determined and explained in Section 2.7 on page 42. For cubic spline comparisons we end up with multiple indicators of difference (12 per formant or pitch trajectory) which is not an efficient means of indicating trajectory differences. To this effect we have utilised simple "or" logic, if any one of the coefficients differs significantly, then we consider the entire trajectory to differ. We indicate this in the tables (for example Table 3.7 on page 78) with black blocks indicating a significant difference. We have also used gray blocks to indicate significant differences in the third formant. F3 is more prone to tracking errors and we have therefore just indicated this difference to remind readers of this possibility.

## 3.4 Results

### 3.4.1 Long vowel results

We present here a discussion of the long vowels analysed and try to explain the trends visible in the figures and tables offered in this section.

We have decided to work at the 99% level of significance. All $F$ ratios which exceed the 99% significance level are indicated in the tables by grayed boxes. The degrees of freedom are also indicated and the tables can therefore be used to determine the significance level at 95% if required by checking which $F$ ratios exceed those indicated on a $F$ distribution table at a 95% significance level.

We have summarised the analysis of variance results for the long vowels in Table 3.5. The table is structured as a number of sets of rows. Each of these sets represents a

specific long vowel (indicated in a black block) and consists of a number of rows where each row is the mean result for a specific group of utterances. Note that the words indicated with the vowels in the table do not imply that these are the results of instances of vowels in context. The words are merely given as example or context. For example in Table 3.5 at the top left hand corner we see "aa" in a black block which indicates the set of results for the long vowel <a:>. Under this we see "*a klaar*" which indicated to us that these results pertain to the long vowel extracted when the Afrikaans ("a") mother-tongue speakers were told to utter the long vowel in the word "*klaar* (finished)". The next three columns contain the mean formant values for F1,F2 and F3 in hertz. The fifth column (labelled "Num") indicates the number of utterances which were used to determine the mean. We then have a number of "blocks" of 4 columns which indicate the ANOVA $F$ ratio results (as described in Section 2.9). For example, referring to our previous example for <a:> we see that the $F$ ratio value for a comparison of the means of F1 for the Afrikaans first language <a:> from "*klaar*" and the Afrikaans second language <a:> from "*klaar*" is 0.05. There were 38 utterances used for the Afrikaans L1 mean and 26 utterances used for the Afrikaans L2 mean. This leads us to 62 degrees of freedom(indicated in the ninth column). At a significance level of .99 we require a $F$ ratio in excess of 7.08 (according to the Fisher tables[19]) and can therefore safely state that the means are statistically equal. In cases where the $F$ ratio has exceeded the $F$ distribution values we highlight the value with a dark block.

The graphs of the individual utterance means and their cumulative means are shown in a number of sub-figures in Figures 3.4 and 3.5.

We did not show <e:> and <o:> with the long vowels but rather plotted them in Figures 3.6 and 3.7, with the diphthongs. During the recording session we indicated to the speakers that these were vowels (as many phonologists state), however, after analysis and confirmation from various references such as Taylor and Uys[12] we concluded that these "vowels" are in fact diphthongs. We have therefore plotted them as diphthong trajectories and we will discuss and analyse them as such. Further justification for this decision is provided by an experiment and the results are given in

Section 3.4.5.

### <i:> and <y:>

<i:> (unrounded) and <y:> (rounded) are high front vowels found in words like ["*dier*" and "heat"] or ["*uur*"] respectively.

Rousseau[39] claims that English has had such a large influence on the development of Afrikaans that <i:> has pushed aside many "traditional" or "correct" ways of saying words, for example [ji:sɔs] ("*Jesus*") instead of [je:sɔs]. This intense replacement may even have had a large effect on the pronunciation of <i:>. There is no way for us to say where <i:> may have lain historically, but as we state later, it appears that Afrikaans and English mother-tongue speakers now appear to use statistically similar versions of <i:>.

De Villiers[40] states that the unrounding of <y:> to <i:> is quite common (for example in "*askies*" in stead of "*ekskuus*"(excuse me)). He goes further to say that <y> is seldom still found in general speech, except amongst older people and in careful and cultured speech. As a result of this, when this vowel is expected to be produced it is quite often hyper-corrected. We can therefore expect that our data may not entirely correctly reflect the position of <y:>. It is found that when <y> is used, it is often in a stressed position, such as in words like "*luuks*" and "*muur*". In unstressed positions it is often replaced by its unrounded companion <i:> as in words like "*murasie*".

Ward[20] states that in some types of South African speech <ɪ> is a close variety, often approaching <i>.

Looking at Table 3.5 (row group "ii") we see the following:

- Although <y:> does not occur in English, we can not at a 99% level of surety state that the first and second language speakers generated a different sound (first line,

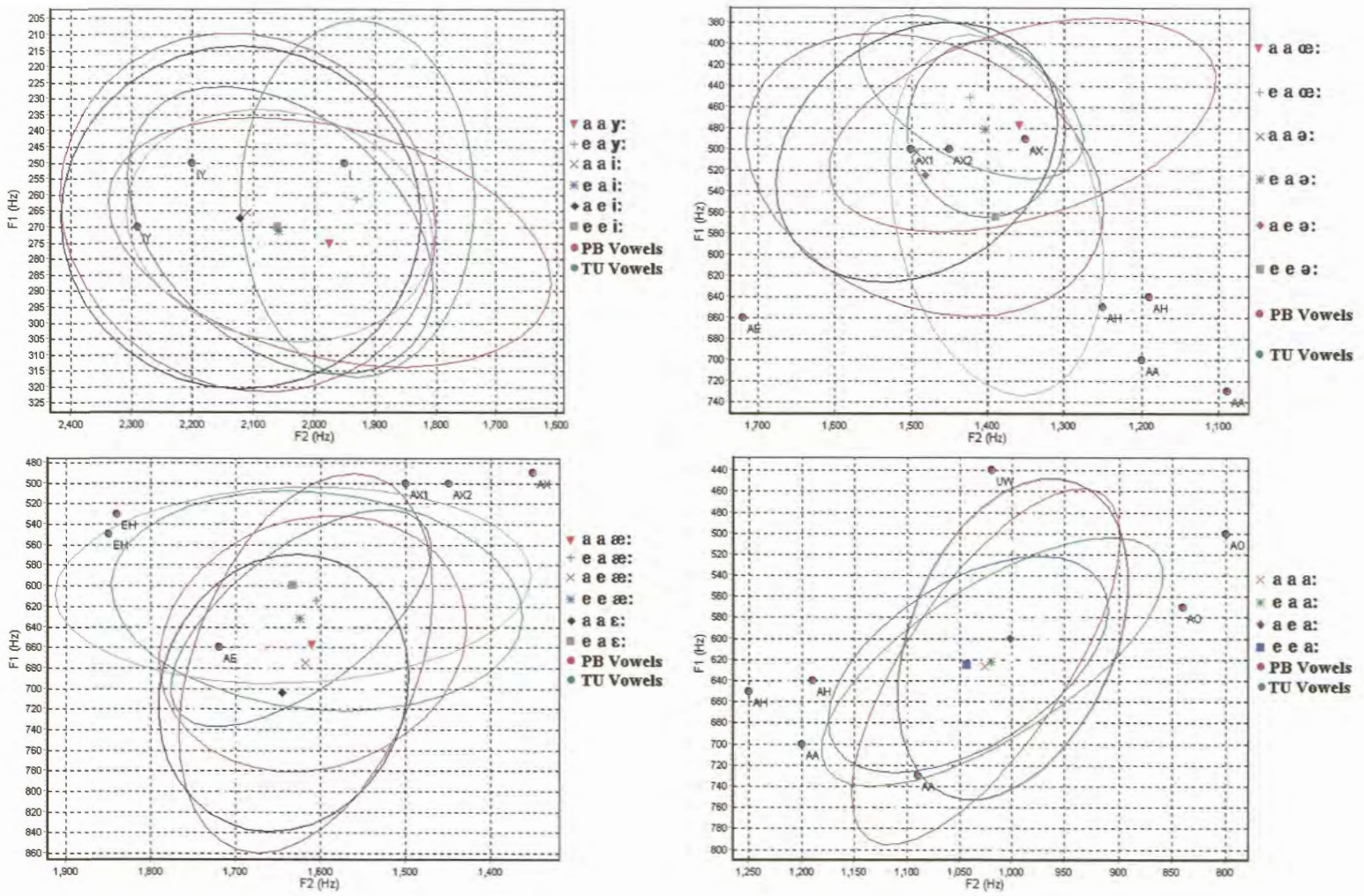



Figure 3.4: Vowel formant clusters: [<y:> in "*uur*" and also <i:> in "*dier*" and "heat"], [<œ:> in "*brûe*" and also <ə:> in "*wîe*" and "about"], [<æ:> in "*werk*" and "hat" and also the incorrectly used <ɛ:> in "*êrens*"] and [<a:> in "*klaar*" and "father"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

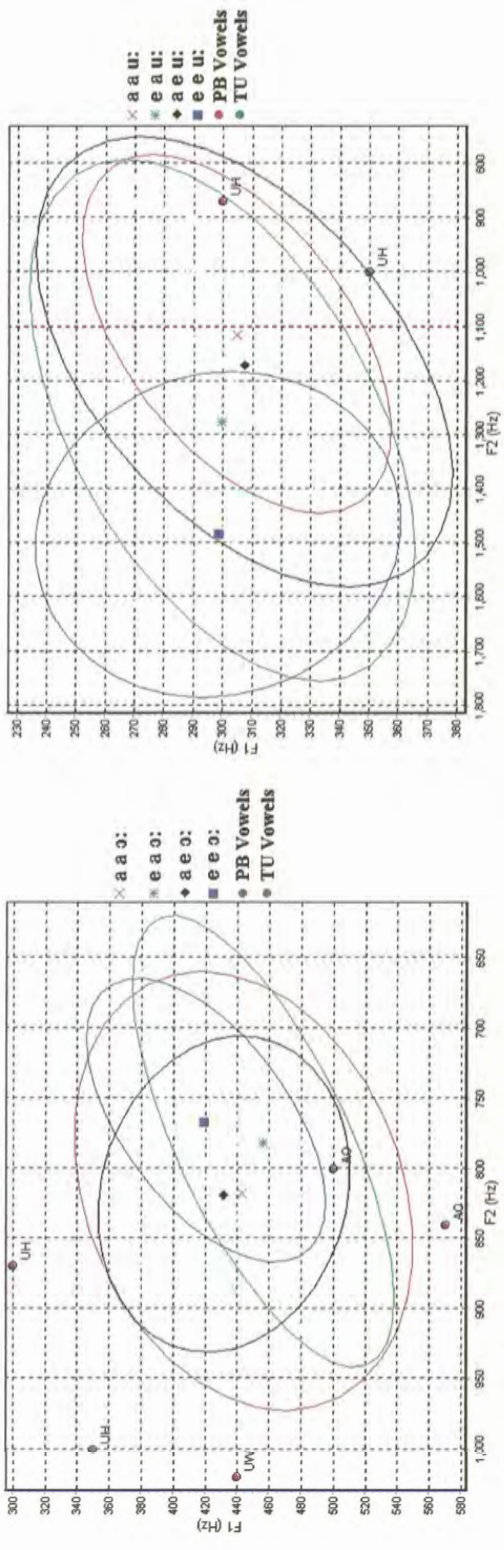



Figure 3.5: Vowel formant clusters: [<ɔ:> in "*dom*" and in "bought"] and [<u:> in "*boer*" and "soon"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

*Vowel Formant Analysis of Variance*

| Vwls | mF1 | mF2 | mF3 | Num | anovaF1 | anovaF2 | anovaF3 | DOF | anovaF1 | anovaF2 | anovaF3 | DOF | anovaF1 | anovaF2 | anovaF3 | DOF | anovaF1 | anovaF2 | anovaF3 | DOF | anovaF1 | anovaF2 | anovaF3 | DOF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ii | | | | | a uur | | | | e uur | | | | a dier | | | | e dier | | | | a heat | | | |
| a uur | 275.07 | 1973.32 | 2441.90 | 26 | | | | | | | | | | | | | | | | | | | | |
| e uur | 261.46 | 1927.86 | 2576.43 | 27 | 3.89 | 1.26 | 5.93 | 51 | | | | | | | | | | | | | | | | |
| a dier | 265.78 | 2108.04 | 2959.45 | 31 | 1.85 | 8.81 | 122.29 | 55 | 0.33 | 26.56 | 52.97 | 56 | | | | | | | | | | | | |
| e dier | 271.30 | 2054.40 | 2858.13 | 26 | 0.36 | 3.36 | 72.57 | 50 | 1.85 | 16.40 | 25.69 | 51 | 0.60 | 1.95 | 4.62 | 55 | | | | | | | | |
| a heat | 267.06 | 2120.98 | 2940.84 | 34 | 1.54 | 11.57 | 121.82 | 58 | 0.62 | 33.20 | 51.70 | 59 | 0.03 | 0.12 | 0.18 | 63 | 0.40 | 3.28 | 3.30 | 58 | | | | |
| e heat | 269.87 | 2056.36 | 2872.16 | 31 | 0.97 | 3.95 | 103.69 | 55 | 1.83 | 17.97 | 36.75 | 56 | 0.44 | 2.02 | 4.53 | 60 | 0.06 | 0.00 | 0.11 | 55 | 0.23 | 3.45 | 3.00 | 63 |
| oe | | | | | a brûe | | | | e brûe | | | | a wie | | | | e wie | | | | a about | | | |
| a brûe | 477.66 | 1355.69 | 2272.02 | 31 | | | | | | | | | | | | | | | | | | | | |
| e brûe | 451.18 | 1421.00 | 2357.21 | 25 | 4.25 | 4.75 | 6.61 | 52 | | | | | | | | | | | | | | | | |
| a wie | 502.97 | 1492.98 | 2389.88 | 17 | 2.29 | 14.89 | 7.22 | 46 | 10.06 | 7.15 | 0.75 | 38 | | | | | | | | | | | | |
| e wie | 481.41 | 1401.34 | 2427.22 | 15 | 0.06 | 1.74 | 16.37 | 44 | 4.83 | 0.77 | 7.58 | 36 | 1.23 | 10.75 | 0.78 | 30 | | | | | | | | |
| a about | 525.15 | 1481.58 | 2380.37 | 19 | 7.75 | 11.93 | 6.79 | 48 | 18.64 | 4.00 | 0.42 | 40 | 1.00 | 0.10 | 0.04 | 34 | 4.53 | 5.78 | 1.35 | 32 | | | | |
| e about | 563.39 | 1388.35 | 2447.83 | 14 | 16.84 | 0.79 | 17.95 | 43 | 27.68 | 1.70 | 9.21 | 35 | 4.87 | 11.38 | 1.53 | 29 | 10.14 | 0.30 | 0.48 | 27 | 1.92 | 6.65 | 2.30 | 31 |
| ae | | | | | a werk | | | | e werk | | | | a hat | | | | e hat | | | | a ërens | | | |
| a werk | 656.97 | 1608.55 | 2475.03 | 21 | | | | | | | | | | | | | | | | | | | | |
| e werk | 615.20 | 1603.68 | 2469.95 | 27 | 5.99 | 0.02 | 0.03 | 46 | | | | | | | | | | | | | | | | |
| a hat | 675.76 | 1616.59 | 2466.57 | 25 | 0.61 | 0.10 | 0.06 | 44 | 8.25 | 0.20 | 0.01 | 50 | | | | | | | | | | | | |
| e hat | 632.06 | 1622.29 | 2503.01 | 28 | 2.24 | 0.32 | 0.85 | 47 | 1.35 | 0.45 | 1.43 | 53 | 4.48 | 0.07 | 1.31 | 51 | | | | | | | | |
| a ërens | 703.92 | 1643.67 | 2503.22 | 17 | 4.72 | 1.59 | 0.53 | 36 | 22.29 | 1.43 | 0.89 | 42 | 1.11 | 1.28 | 0.81 | 40 | 15.35 | 0.81 | 0.00 | 43 | | | | |
| e ërens | 599.94 | 1631.33 | 2488.42 | 19 | 9.93 | 0.36 | 0.15 | 38 | 0.95 | 0.49 | 0.34 | 44 | 10.24 | 0.19 | 0.35 | 42 | 4.41 | 0.08 | 0.20 | 45 | 27.35 | 0.10 | 0.12 | 34 |
| aa | | | | | a klaar | | | | e klaar | | | | a father | | | | | | | | | | | |
| a klaar | 627.06 | 1025.16 | 2416.62 | 38 | | | | | | | | | | | | | | | | | | | | |
| e klaar | 622.65 | 1019.34 | 2472.76 | 26 | 0.05 | 0.10 | 1.99 | 62 | | | | | | | | | | | | | | | | |
| a father | 600.59 | 999.95 | 2391.09 | 31 | 1.79 | 2.89 | 0.45 | 67 | 1.41 | 1.10 | 3.95 | 55 | | | | | | | | | | | | |
| e father | 625.21 | 1041.80 | 2468.83 | 23 | 0.01 | 0.90 | 1.58 | 62 | 0.03 | 1.14 | 0.01 | 50 | 1.91 | 6.49 | 3.24 | 55 | | | | | | | | |
| openo | | | | | a dom | | | | e dom | | | | a bought | | | | | | | | | | | |
| a dom | 444.51 | 816.22 | 2329.01 | 24 | | | | | | | | | | | | | | | | | | | | |
| e dom | 456.53 | 780.91 | 2404.74 | 8 | 0.33 | 1.12 | 0.70 | 30 | | | | | | | | | | | | | | | | |
| a bought | 431.48 | 819.02 | 2372.11 | 30 | 1.04 | 0.02 | 0.63 | 52 | 2.38 | 2.24 | 0.20 | 36 | | | | | | | | | | | | |
| e bought | 420.83 | 765.86 | 2426.15 | 14 | 2.09 | 4.39 | 2.01 | 36 | 4.03 | 0.26 | 0.07 | 20 | 0.69 | 8.85 | 0.96 | 42 | | | | | | | | |
| uu | | | | | a boer | | | | e boer | | | | a soon | | | | | | | | | | | |
| a boer | 305.09 | 1114.15 | 2136.03 | 27 | | | | | | | | | | | | | | | | | | | | |
| e boer | 300.06 | 1273.04 | 2151.85 | 21 | 0.37 | 7.03 | 0.15 | 46 | | | | | | | | | | | | | | | | |
| a soon | 307.27 | 1167.23 | 2185.32 | 29 | 0.07 | 1.07 | 1.68 | 54 | 0.57 | 2.65 | 1.29 | 48 | | | | | | | | | | | | |
| e soon | 298.71 | 1482.48 | 2113.45 | 25 | 0.64 | 67.46 | 0.39 | 50 | 0.02 | 12.37 | 2.95 | 44 | 0.90 | 38.12 | 7.36 | 52 | | | | | | | | |

Table 3.5: An analysis of variance table of the long-vowel formants.

| Vowel | Strong Form | Replaced Form |
|---|---|---|
| ɛ | pence [pɛns] | sixpence [sikspəns] |
| æ | valid [ˈvælɪd] | validity [vəˈlɪdɪtɪ] |
| *a* | particle [pɑtikl] | particular [pəˈtɪkjʊlə] |
| ɔ | ward [wɔ:d] | backward [ˈbækwəd] |
| u | to [tu:] | today [təˈdeɪ] |
| ʌ | some [sʌm] | handsome [ˈhænsəm] |
| ɜ | Bert [bɜt] | Herbert [ˈhɜbət] |

Table 3.6: Examples of the neutral vowel <ə> replacing the strong forms.

second column). We can with safety state though that both groups' <y:> differ significantly from both the English and Afrikaans utterances of <i:> (columns two and three). This would seem to contradict the research of Flege[18] on "equivalence classification", but it may however be attributed to the bilinguality of the two groups.

- The <i:> uttered by both groups in both first and second languages were found to be statistically identical (fourth, fifth and sixth columns). Therefore we can say that South African English and Afrikaans speakers use the same <i:>, even when speaking their second language.

**<œ:> and <ə:>**

<œ:>(rounded) and <ə>(unrounded) are central vowels. The results are in row group "oe" of Table 3.5.

<ə> is an interesting vowel in that it tends to replace all vowels that are in unstressed positions[43]. There are two exceptions: <i> unstressed becomes <ɪ> and <ɪ> unstressed remains <ɪ>[20]. Besides these exceptions though we can generalise by saying the neutral vowel replaces the strong forms as in Table 3.6. This is especially noticeable in continuous, fluent speech.

- <œ>, although lying in the general vicinity of <ə> is seen to be statistically separate from it. It is seen to be an identical sound for the two language groups though (first row, second column).

- The <ə:> spoken by Afrikaans speakers when saying "*wîe*" is seen to be the same sound as when they say the <ə:> in "about" (third row, fourth column), and this sound is statistically distinct from the <ə:> uttered by the English speakers (first and third rows, fourth column). So the Afrikaans speakers use the same <ə:> when speaking their mother-tongue or a second language, and this <ə:> is significantly different from the <ə:> used by mother-tongue English speakers.

- For reasons which we can not explain the <ə:> produced by the English speakers saying "*wîe*" is greatly different from that which they used when saying "about" yet it is statistically similar to the <ə:> produced by the Afrikaans speakers saying "about". This may be due to a labelling error caused by the diphthongization some speakers enforce, especially the English speakers pronouncing "*wîe*", saying something more in the line of [w-œ-ə]. This is observable in Figure 3.4 (top right). This may also be as a result of the unfamiliarity of the word *wîe* as it not a common word and possibly new to many of the SA English speakers.

- The <ə:> used by Afrikaans and English speakers to pronounce "about" appears to be identical (sixth column). This ability of the Afrikaans speakers to produce authentic Afrikaans and English sounds seems to support our suspicions that Afrikaans mother-tongue speakers are more bilingual than English mother-tongue speakers. We do not have enough data to confirm this though.

### <æ:> and <ɛ:>

<æ> is traditionally considered to be a short vowel but there seems to be a recent tendency for people to lengthen it as in "bad" [bæ:d]. It was therefore recorded and analysed as a long vowel. The results are in row group "ae" of Table 3.5.

It is important to note (as Ward[20] states) that many people find it difficult to pronounce an isolated <ɛ> and quite often end up saying something which approaches <ɝ> as in "bird"[2].

We have no useful data for <ɛ> as we made the error of requesting that the speakers utter <ɛ> as in "*êrens*". This would have worked in certain regions of the Cape (where we would have got [ɛrəns], but in the region where the data was recorded the acceptable pronunciation tends toward [ærəns]. This problem could have been rectified by using an Afrikaans source word such as "*hê*" and an English source word like "bet". This use of <æ> instead of <ɛ> is quite clear in the clustering observable in Figure 3.4 on page 70.

Interestingly enough, this phenomenon of the loose definition(the same symbol being used to indicate 2 different phonemes) of <ɛ> does not only occur in Afrikaans but also in British English. Ward[20] observes that <ɛ> can be as close as in "bet" and as open as in "bell" and goes on to note that many areas in the United Kingdom may pronounce an <æ> verging on <ɛ>.

Referring to Table 3.5 we see that the <æ> spoken by the Afrikaans speakers in "*werk*" only differs significantly from the unfortunate <æ> in "*êrens*" spoken by the English speakers (fifth row, first column). After this we see the general trend that the Afrikaans speakers' utterances differ from the English speakers' utterances, whether in first or second language words. In other words the <æ> spoken by Afrikaans speakers is always the same, whether it is spoken in the mother-tongue or not, and the same is true for the English speakers. More importantly, there is a noticeable difference between the Afrikaans and English speakers' versions of the vowel. This is also observable in Figure 3.4 where the English mother-tongue speakers consistently utter their versions of <æ> with lower F1's (as is demonstrated by the black blocks showing significant differences in the "anovaF1" columns).

[2]This may however be peculiar to British English

<ɑ:>

<ɑ:> is a back, open, unrounded long-vowel. The results are in row group "aa" of Table 3.5.

According to Ward[20], South African English uses an <ɑ> which is very near to the cardinal <ɑ>. According to De Villiers[40], <ɑ> and <ɑ:> differ from each other phonemically e.g.: "*dan*" versus "*Daan*" and "*man*" versus "*maan*" although Taylor[12] claims that length is dependent on syllable structure i.e. length is not phonemic in Afrikaans.

If we look at Table 3.5 on page 69 we see that the $F$ ratios calculated for the analysis of variance of the <ɑ> in "*klaar*" and "father" indicate that there is no significant difference between the four possibilities i.e. Afrikaans word spoken by Afrikaans speaker, English word spoken by Afrikaans speaker and the same for an English Speaker. The $F$ ratio for F1 between the Afrikaans first language "*klaar*" and Afrikaans second language "*klaar*" is 0.05. The $F$ ratio for F1 between the Afrikaans first language "*klaar*" and English second language "father" is 1.79. The $F$ ratio for F1 between the Afrikaans first language "*klaar*" and English first language "father" is 0.01. As none of these values exceed the 99% percentile values for the respective degrees of freedom it follows that Afrikaans and English speakers use the same <ɑ>.

<ɔ:>

<ɔ:> is classified as a back, open-mid, rounded vowel. The results are in row group "openo" of Table 3.5.

Rousseau[39] contends that the use of <ɔ> instead of many other vowels is as a result of the influence of English. For example, <o> is replaced by <ɔ> in "*dokument*" and replaces <o:> in "*horisontaal*" and also <u> in "*moderniseer*".

It is possible that this overwhelming usage of the English <ɔ> may have resulted in Afrikaans speakers using the same vowel sound as mother-tongue English speakers. Whatever the cause, we find that Afrikaans speakers generally appear to use the same sound as their English speaking counterparts, except that the English speakers demonstrated a significantly lower F2 when saying "bought" than the Afrikaans speakers. This can be observed by the mean F2 values shown in the third column of Table 3.5 on page 69 in the subsection labelled "openo"(<ɔ>) where the Afrikaans speakers spoke with a mean F2 of 819 Hz as opposed to the English speakers who spoke with a mean F2 of 766 Hz. This proves to be statistically significant as we have indicated in the last block of the <ɔ> section where the second language "bought" is compared with the first language "bought". We see that for F2 in 42 degrees of freedom we have a F ratio of 8.65 which is greater then 7.31 (the value determined from the F distribution) and therefore significant.

**<u:>**

Ward[20] identifies two varieties of this vowel. The first occurs in words like "fool" where the vowel is followed by a dark l. The second lies in a slightly more forward position and is found in words like "rude". The <u:> associated with the source words "*boer*" and "soon" would most likely be the first and second kinds respectively.

Ward claims that many people diphthongise this vowel considerably, however we only found this (see Section 3.4.5) to a small extent with the Afrikaans mother-tongue speakers, as Ward suggests, moving from <ʊ> to <u>. A measure of the diphthongization of vowels and diphthongs is given in Section 3.4.5.

From the $F$ ratios of row group "uu" in Table 3.5 we can easily deduce (and confirm in Figure 3.5) that the English speakers have generated an <u:> with significantly higher F2 in their first-language than in their second language (which is statistically similar to the utterances by the Afrikaans speakers). It would appear therefore that if we take

Ward's reasoning further, that the Afrikaans speakers produce a single version of <u:> which is like the <u:> Ward identifies with words like "rude" and lies in a slightly more forward position. The English speakers on the other hand appear to demonstrate both types of <u:>. The one used in their utterance of "soon" is of the type which Ward identifies as usually being followed by a dark l. This would place it closer to a cardinal <o> which has a lower F1 but a higher F2. This is indeed the case as can be deduced from Figure 3.5 where the right hand diagram clearly portrays the Afrikaans utterances of first(×) and second(♦) language <u:> as lying in the same location and the English second(∗) language cluster of utterances lying in a similar position. The English first(■) language <u:> is clearly seen to have a higher F2 though.

### 3.4.2 Diphthong results

As we mentioned with the discussion of the long vowels, in continuous, fluent speech, a neutralisation of the strong forms of the vowels takes place, moving toward the location of <ə>. In the same way, many of the diphthongs are prone to neutralisation. Examples of this are given in Table 3.8, for example, face([feɪs]) as compared to preface([ˈprɛfəs]). It is important to record the data in context, but it is more important to record the diphthongs in isolation or pseudo-word context where the chosen consonants for the pseudo-word must have minimal effect on the diphthong and not warp the inherent diphthong structure.

We will now discuss each of the diphthongs in turn. We have drawn up a summary shown as Table 3.7. Similarly to Table 3.5 we have clusters of rows where the clusters consist of a specific diphthong's analysis. For example, the first cluster of rows in Table 3.7 represent the ANOVA results for the diphthong <ei>. The first column shows the word that was given to the speaker to indicate (in some context) which diphthong to utter. The "a" and "e" indicate whether the utterances are those of Afrikaans mother-tongue or English mother-tongue speakers respectively. The second column indicates the number of utterances which were used in the processing. We have analysed each

*Diphthong Formant Analysis of Variance*


Table 3.7: An analysis of variance table of the diphthong formants. (See text on page 77 for explanation.)

Figure 3.6: Diphthong formant trajectories: [<ei> in "*ryk*" and "play" and also <əi> in "*bly*"], [<œy> in "*trui*" ] and [<ou> in "*gou*" and "home" and also <œu> in "*blou*"]. The first $a/e$ indicates the mother-tongue of the speakers and the second $a/e$ indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

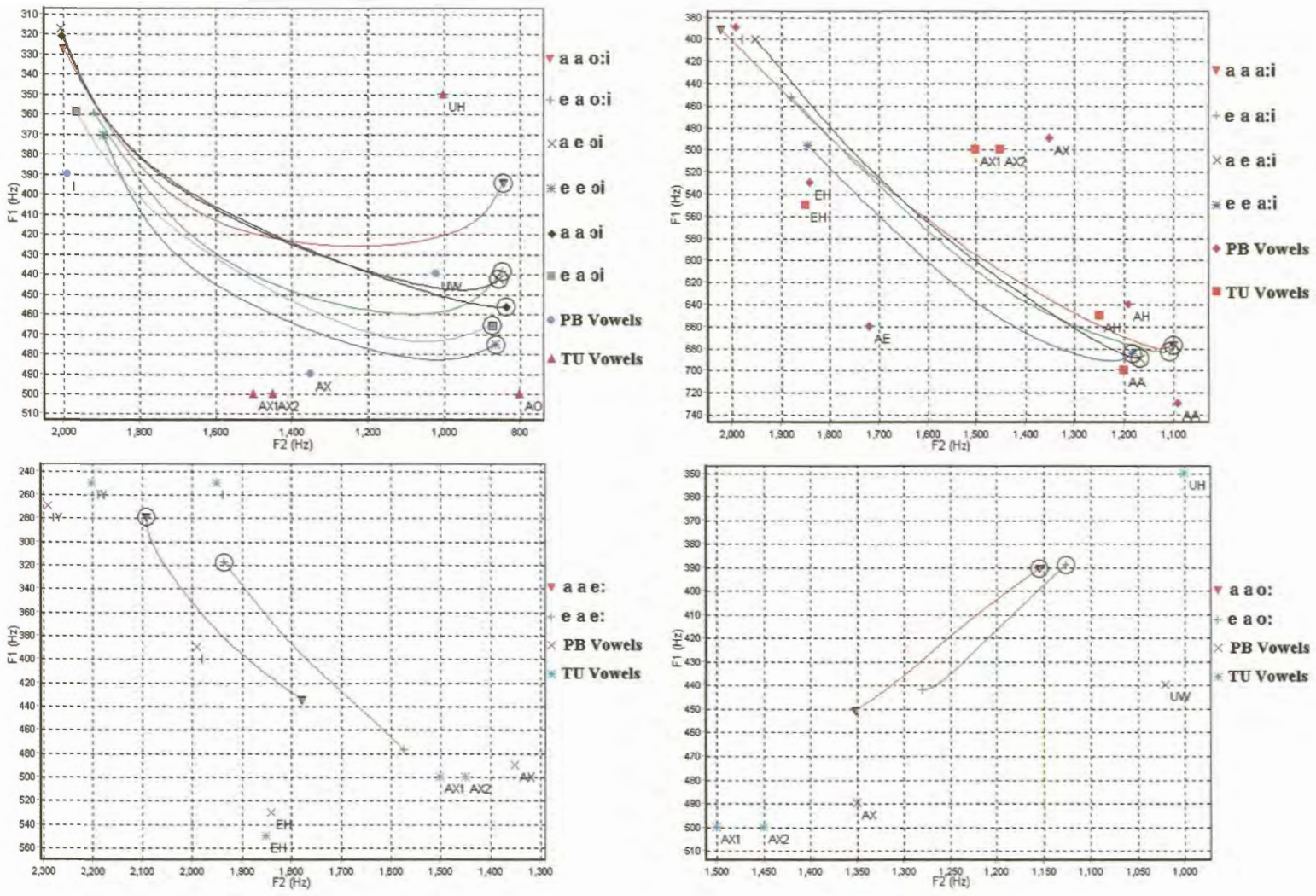



Figure 3.7: Diphthong formant trajectories: [<o:i> in "*mooi*" and also <ɔi> in "*hondjie*" and "boy"], [<a:i> in "*haai*" and "time"], [<e:> in "*bees*"] and [<o:> in "*kool*"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

| Diphthong | Strong Form | Replaced Form |
|---|---|---|
| eɪ | face [feɪs] | preface [ˈprɛfəs] |
| oʊ | most [moʊst] | topmost [ˈtɒpməst] |
| aʊ | mouth [maʊΘ] | Plymouth [plɪməΘ] |
| aɪə | shire [ʃaɪə] | Yorkshire [ˈjɔkʃə] |

Table 3.8: Examples of the neutral vowel <ə> replacing the strong forms.

diphthong in 3 sections and therefore, seeing as we are observing 3 formants, the next 9 columns of each set in Table 3.7 consist of a number of blocks indicating the presence of significant differences. Unlike Table 3.5 we do not indicate the actual $F$ ratio values as they have no intuitive meaning(comparing curve coefficients may have significant meaning, but the values are not meaningful if simply observed). Returning to our example in Table 3.7 we see that in an ANOVA comparison between the L1 utterances of "*ryk*"(42 utterances) and the L2 utterances of "*ryk*"(38 utterances) we find a significant difference in the final section for F2(this is duly indicated by a black block). We also find significant differences in all three sections of F3, but due to the seemingly "unstable"(due to difficult extraction) nature of F3 we consider this to be less important and therefore indicate all significant differences in F3 by gray boxes in stead of black ones.

Reminder: We have placed a circle around the originating point in the figures.

**<ei>**

We notice in Table 3.7 that the differences observable within the diphthong <ei> are only in the second and third formants. We find it difficult to find any consistent differences between the two accent groups. From the graphs in Figure 3.6 (top left) we can see that it appears as if the Afrikaans speakers' formant trajectories (▼×♦) occur at a slightly higher F2 than the English trajectories (+∗■). The statistical significance of this seems to be reflected in Table 3.7 except for the English speakers saying <ei> as in

"play" which begins in the vicinity of the Afrikaans speakers' beginning of articulation. Interestingly enough it still terminates in the vicinity of the Peterson and Barney <ɪ> where the other English spoken <ei> and <əi> terminate. The Afrikaans speakers on the other hand tend to terminate the diphthong closer to the Peterson and Barney <i>.

<œy>

The diphthong <œy> shows clear separation between the two groups in Figure 3.6 (top right). This diphthong does not occur in English, and this explains the difference. The English speakers pronounce a formant trajectory which begins more or less at their mother-tongue <ə> and then stops well short of <y>. The Afrikaans speakers on the other hand begin in the vicinity of their <œ> and finish fairly close to their location of <y>. This can be seen quite clearly from Figure 3.6, especially if we substitute the vowel locations from Table 3.5, namely the mean formant values calculated and shown in columns 2,3 and 4 (row group "oey"). The analysis of variance results in Table 3.7 echo this large difference with the only region not being significantly different being the first formant about half way along the trajectory.

We can argue that the substitution of <ə> for <œ> by the English speakers is due to the phenomenon of equivalence classification. The closest "vowel" to <œ>, the rounded version of <ə> is naturally <ə>. <ə> is used frequently in English, but <œ> is not. The fact that the English speakers do not reach <y> is once again support of the concept of equivalence classification. The interesting paradox, however, is the fact that in our vowel analysis we found that the English speakers managed to articulate <y> to the point that it was statistically equivalent to that of the Afrikaans speakers. Perhaps this can be explained by the dynamic nature of diphthongs and a difference in articulation of diphthongs and vowels between the two groups (i.e. "laziness" or neutralisation). We continue this argument when discussing <e:>. It is also important to note that in the long vowel analysis the emphasis was only on the single vowel

whereas in diphthong analysis this is only partially true.

<ou>

The <ou> cluster consists of diphthongs with two distinct transcriptions. The first is <ou> and is used by De Villiers[40] in words like "*oud*" and "*gou*" and the second is <œu> and is used by Coetzee[23] in words like "*blou*" and "*troue*". We suspect that this was merely a difference in transcription labels, but as we wanted an acoustic model for this diphthong anyway, we decided to include both in the recording session. As surmised, the two transcriptions do represent the same diphthong. For the two accent groups this diphthong has significantly different trajectories.

The diphthongs begin in more or less the same vicinity (as can be seen in Figure 3.6 (bottom right) F1=540 Hz, F2=1225 Hz, which has no vowel associated with this location) and then the English speakers articulate in the direction of the location of the vowel they pronounced when saying the vowel <u:> from the Afrikaans word "*boer*".[3] The Afrikaans speakers on the other hand move towards the location of their <u:> as formed in the word "*boer*". We may have expected the English <ou> to migrate to a much higher F2. We attribute the lack of this to the effect of hyper-correction, in other words, the English speakers may have forced an unnaturally long diphthong in the (wrong) assumption that they were helping to create better data. This problem has been noticed throughout the data and especially prominent with certain speakers and can be heard when playing back the data. Although this effect appears to have had some influence on the results, we can not easily determine how much, and must therefore carry on regardless. Nevertheless, what is noticeable is that there is a significant observable difference(Figure 3.6 (bottom right)) between the English (+∗■) and Afrikaans (▼ × ♦) pronunciation of <ou>, and it may be slightly larger than we have measured.

[3]Notice that the location of the <u:> spoken by the English speakers when using the English word "soon" has an even greater F2.

The mean diphthong tracks plotted in Figure 3.6 (bottom right) and the staggering of the black blocks in Table 3.7 (the third row group "ou") clearly demonstrate the separation between the two pronunciations. Remember that the presence of a black block indicates that there is a significant difference. Therefore the staggered black blocks are as a result of the Afrikaans versus Afrikaans diphthong comparisons (which are similar in this case and therefore do not give rise to black blocks) and the Afrikaans versus English comparisons (which are dissimilar and therefore give rise to black blocks). For example, the first language English utterance of <ou> as in "home" is dissimilar to the Afrikaans first language <ou> as in "*blou*" (and therefore gives rise to black blocks in F2), but it is similar to the <ou> as in second language Afrikaans "*blou*" and therefore does not give rise to black blocks.

<o:i>

The <o:i> diphthongs have proven difficult to define as consistently different between the two groups. Although they can be proven significantly different (see row group "ooi" in Table 3.7) they are also different within the two groups, and this gives rise to a complex "black block" structure in the table.

The English and Afrikaans groups terminate in clusters which we can associate with those languages i.e. the Afrikaans speakers terminate in a cluster which has a higher F2 and lower F1 than the English group(as can be seen in Figure 3.7 (top left)). This follows the same trend as was observed with the vowel <i:> discussed in Section 3.4.1.

Of interest and harder to explain, is that the initial F1 points are distributed over a range of just less than 100 Hz. The greatest culprit causing this large range is the Afrikaans utterance of <o:i>[▼] (compare this to the trajectory of the Afrikaans utterance of the Afrikaans <ɔi>[♦] which is clustered closer to the <o:i> and <ɔi> utterances from the English speakers[■∗]). The extreme curvature observable in this trajectory (and that of the Afrikaans utterance of the English <ɔi>) is most likely

due to a segmentation and labelling error where F1 was regularly incorrectly estimated due to poor formant definition (flat peaks) in the initial stages of the segment. The sharpness of the curve would lead us to suspect that this is a justifiable explanation of this phenomenon. This type of error could occur quite easily if we consider that we are speaking of an F1 deviation of about 50 Hz which would be quite unobservable on a spectrogram with a range of 4 kHz or more (i.e. about a 1% shift in the scale or a couple of pixels on a computer screen).

**<a:i>**

The <a:i> diphthong has an interesting trajectory structure. We find that the initiating articulator or diphthong half vowel is fairly similar for the two language groups (as is expected from the statistical similarity of the vowel <a:> in the two groups as discussed in Section 3.4.1), but what is interesting is a contrary language clustering visible in Figure 3.7 (top right). In other words, the English utterance for the Afrikaans <a:i> is similar to the Afrikaans utterance for the Afrikaans <a:i> and likewise for the English utterance <a:i>. This is reflected in Table 3.7 (the fifth row group "aai") where we can see that the first part of F1 does not differ significantly between the English "*haai*" and Afrikaans "time" or between the Afrikaans "time" and English "time". On the graph this is visible as [$*$ and $\times$] and [■ and ♦] starting together in clusters, but ending clustered as [$*$ and ■] and [$\times$ and ♦].

In spite of this initial "cluster swapping" the diphthong trajectories *terminate* in language clusters as we would have expected. Even though they form language clusters, there are still significant differences between the two groups of utterances by the individual language groups i.e. the <a:i> spoken by the Afrikaans speakers for both English and Afrikaans source words were different and is also evident for the English speakers (third columns).

### 3.4.3 Diphthongization of <e:> and <o:>

<e:>

<e:> is regarded as a high middle vowel or potential diphthong to some phoneticians but a definite diphthong to others.

Like Taylor[12], De Villiers[40] recognises that <e:> is only found as a vowel in areas of the Cape Province's rural districts, but otherwise it is in fact a diphthong <iə>. This is clearly seen in Figure 3.7. <e:> is prone to becoming <i:> in diminutives as for example in *"seun"*[siən]→*"seuntjie"*[<si:ŋki>].

The Afrikaans speakers are found to produce a diphthong which begins in the location of <y> (close to the point where their articulation of <œy> ends) and ends before reaching their <ə>. The English speakers produce an interesting phenomenon. Like the Afrikaans speakers they begin the diphthong articulation at a point very close to where their <œy> ended giving credence to our previous statement that this may be a articulatory characteristic of English speakers in fluent speech.

The large displacement between the two groups' diphthongs <e:> is quite clearly seen in Figure 3.7 (bottom left). Once again, this is also directly echoed by the overwhelming presence of black blocks (which indicate significant differences) in Table 3.7 (second last row cluster).

<o:>

Like <e:>, <o:> is recognised as being a potential diphthong or by some as a centring diphthong transcribed as <uə>. We confirm this with the plot in Figure 3.7. English does not appear to have a vowel or diphthong similar to <o:>. This may have had an influence on the diphthongization which <o> has undergone in Afrikaans.

The Afrikaans and SA English utterances of this diphthong are proven to be statistically similar. This can be see by the absence of black blocks in Table 3.7 (row group "oo").

### 3.4.4 Long vowel and diphthong results - ratios

The vowel formant ratios largely reflect the results discussed above for the direct formant values. Tables 3.9 and 3.10 summarise the results of the formant ratios for the long vowels and diphthongs respectively. We note that some of the accent clustering trends visible in the normal formant data as discussed above becomes even more noticeable in the formant ratio data.

The way the tables are layed out and the use of black squares and $F$ ratio values (in the long vowel ratio chart) are the same as in Tables 3.5 and 3.7.

Generally the normal formant long vowel and formant ratio tables (Tables 3.5 and 3.9) correlate quite well. We do see some differences though. These are:

- Row group "ii", the comparison between "e uur" and "a uur". The difference lies in the second and third columns of the ratio table. Most likely this is due to an F3 extraction problem.
- Row group "oe", all fields. The fairly low $F$ ratio values indicate that <œ:> and $< e :>$ are similar, yet noticeably different. We can not account for the exact differences between the normal formant and ratio formant ANOVAs, but we would prefer to go with the normal analysis and commentary due to the proven value of the standard formant principles.
- Row group "ae". Only a single marginal difference is noted between "a hat" and "e werk".
- Row group "openo", the comparison between "e bought" and "a bought". Once again, a marginal difference which if probably as a result of an F3 extraction

*Vowel Formant Ratio Analysis of Variance*

| Vwls | mF2/F1 | mF3/F2 | mF3/F1 | Num | anovaF2/F1 | anovaF3/F2 | anovaF3/F1 | DOF | anovaF2/F1 | anovaF3/F2 | anovaF3/F1 | DOF | anovaF2/F1 | anovaF3/F2 | anovaF3/F1 | DOF | anovaF2/F1 | anovaF2/F2 | anovaF3/F1 | DOF | anovaF2/F1 | anovaF3/F2 | anovaF3/F1 | DOF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | | | | | a uur | | | | e uur | | | | a dier | | | | e dier | | | | a heat | | | |
| a uur | 7.24 | 1.24 | 8.93 | 20 | | | | | | | | | | | | | | | | | | | | |
| e uur | 7.45 | 1.34 | 9.95 | 27 | 0.68 | 12.78 | 10.48 | 51 | | | | | | | | | | | | | | | | |
| a dier | 8.04 | 1.41 | 11.30 | 31 | 7.45 | 39.19 | 41.39 | 55 | 4.88 | 10.24 | 11.73 | 56 | | | | | | | | | | | | |
| e dier | 7.66 | 1.39 | 10.66 | 29 | 2.02 | 43.28 | 23.33 | 50 | 0.61 | 10.25 | 3.26 | 51 | 1.64 | 0.67 | 2.30 | 55 | | | | | | | | |
| a heat | 8.04 | 1.39 | 11.16 | 34 | 8.14 | 42.21 | 38.20 | 58 | 5.32 | 8.31 | 9.86 | 59 | 0.00 | 0.90 | 0.12 | 63 | 1.77 | 0.03 | 1.49 | 58 | | | | |
| e heat | 7.66 | 1.40 | 10.71 | 31 | 3.05 | 49.52 | 40.36 | 55 | 1.01 | 12.56 | 5.75 | 56 | 2.22 | 0.23 | 2.74 | 60 | 0.00 | 0.25 | 0.02 | 55 | 2.41 | 0.38 | 1.67 | 63 |
| ie | | | | | a brûe | | | | e brûe | | | | a wie | | | | e wie | | | | a about | | | |
| a brûe | 2.86 | 1.69 | 4.80 | 31 | | | | | | | | | | | | | | | | | | | | |
| e brûe | 3.18 | 1.66 | 5.26 | 29 | 10.43 | 0.39 | 11.09 | 52 | | | | | | | | | | | | | | | | |
| a wie | 3.01 | 1.60 | 4.81 | 17 | 2.11 | 4.42 | 0.01 | 46 | 1.64 | 4.14 | 7.18 | 36 | | | | | | | | | | | | |
| e wie | 2.93 | 1.73 | 5.06 | 15 | 0.61 | 1.30 | 3.14 | 44 | 3.99 | 5.44 | 1.27 | 36 | 0.39 | 26.74 | 2.05 | 30 | | | | | | | | |
| a about | 2.87 | 1.61 | 4.61 | 18 | 0.02 | 3.35 | 1.18 | 48 | 4.80 | 2.37 | 12.69 | 40 | 0.82 | 0.09 | 0.87 | 34 | 0.17 | 18.14 | 4.98 | 32 | | | | |
| e about | 2.53 | 1.77 | 4.43 | 14 | 8.28 | 3.00 | 4.49 | 43 | 19.36 | 7.47 | 21.83 | 35 | 9.95 | 20.20 | 3.31 | 25 | 8.75 | 5.83 | 10.70 | 27 | 4.45 | 14.16 | 0.64 | 31 |
| ae | | | | | a werk | | | | e werk | | | | a hat | | | | e hat | | | | a ârens | | | |
| a werk | 2.47 | 1.54 | 3.80 | 21 | | | | | | | | | | | | | | | | | | | | |
| e werk | 2.63 | 1.55 | 4.04 | 27 | 3.04 | 0.01 | 5.47 | 46 | | | | | | | | | | | | | | | | |
| a hat | 2.44 | 1.53 | 3.72 | 23 | 0.13 | 0.24 | 0.31 | 44 | 4.12 | 0.41 | 6.48 | 50 | | | | | | | | | | | | |
| e hat | 2.58 | 1.54 | 3.98 | 26 | 2.73 | 0.00 | 3.56 | 47 | 0.55 | 0.01 | 0.54 | 53 | 3.61 | 0.52 | 4.72 | 51 | | | | | | | | |
| a ârens | 2.36 | 1.53 | 3.59 | 17 | 1.74 | 0.29 | 2.65 | 36 | 8.87 | 0.45 | 16.63 | 42 | 0.66 | 0.01 | 0.67 | 40 | 13.86 | 0.69 | 14.49 | 43 | | | | |
| e ârens | 2.74 | 1.53 | 4.17 | 13 | 7.66 | 0.12 | 10.51 | 38 | 1.20 | 0.23 | 1.79 | 44 | 8.37 | 0.01 | 9.58 | 42 | 5.07 | 0.29 | 4.54 | 45 | 15.84 | 0.05 | 22.34 | 34 |
| ao | | | | | a klaar | | | | e klaar | | | | a father | | | | | | | | | | | |
| a klaar | 1.65 | 2.37 | 3.91 | 35 | | | | | | | | | | | | | | | | | | | | |
| e klaar | 1.64 | 2.44 | 4.00 | 40 | 0.09 | 1.60 | 0.49 | 62 | | | | | | | | | | | | | | | | |
| a father | 1.69 | 2.40 | 4.04 | 31 | 0.59 | 0.42 | 0.92 | 67 | 1.00 | 0.56 | 0.08 | 55 | | | | | | | | | | | | |
| e father | 1.67 | 2.38 | 3.98 | 40 | 0.26 | 0.05 | 0.24 | 62 | 0.90 | 1.09 | 0.05 | 50 | 0.11 | 0.14 | 0.23 | 55 | | | | | | | | |
| openo | | | | | a dom | | | | e dom | | | | a bought | | | | | | | | | | | |
| a dom | 1.86 | 2.89 | 5.31 | 24 | | | | | | | | | | | | | | | | | | | | |
| e dom | 1.71 | 3.11 | 5.31 | 8 | 2.18 | 1.24 | 0.00 | 30 | | | | | | | | | | | | | | | | |
| a bought | 1.92 | 2.92 | 5.54 | 36 | 0.75 | 0.04 | 1.46 | 52 | 4.94 | 1.65 | 0.78 | 36 | | | | | | | | | | | | |
| e bought | 1.83 | 3.18 | 5.81 | 14 | 0.14 | 3.88 | 4.14 | 36 | 3.14 | 0.24 | 2.65 | 20 | 1.54 | 5.44 | 1.56 | 42 | | | | | | | | |
| oo | | | | | a boer | | | | e boer | | | | a soon | | | | | | | | | | | |
| a boer | 3.65 | 1.96 | 7.06 | 27 | | | | | | | | | | | | | | | | | | | | |
| e boer | 4.25 | 1.76 | 7.24 | 21 | 10.56 | 3.47 | 0.56 | 46 | | | | | | | | | | | | | | | | |
| a soon | 3.81 | 1.93 | 7.21 | 25 | 0.98 | 0.07 | 0.37 | 54 | 4.51 | 2.41 | 0.01 | 48 | | | | | | | | | | | | |
| e soon | 5.02 | 1.44 | 7.15 | 25 | 55.41 | 53.44 | 0.16 | 50 | 11.02 | 12.77 | 0.15 | 44 | 35.98 | 38.59 | 0.06 | 52 | | | | | | | | |

Table 3.9: An analysis of variance table of the vowel formant ratios. See text on page 87 for explanation.

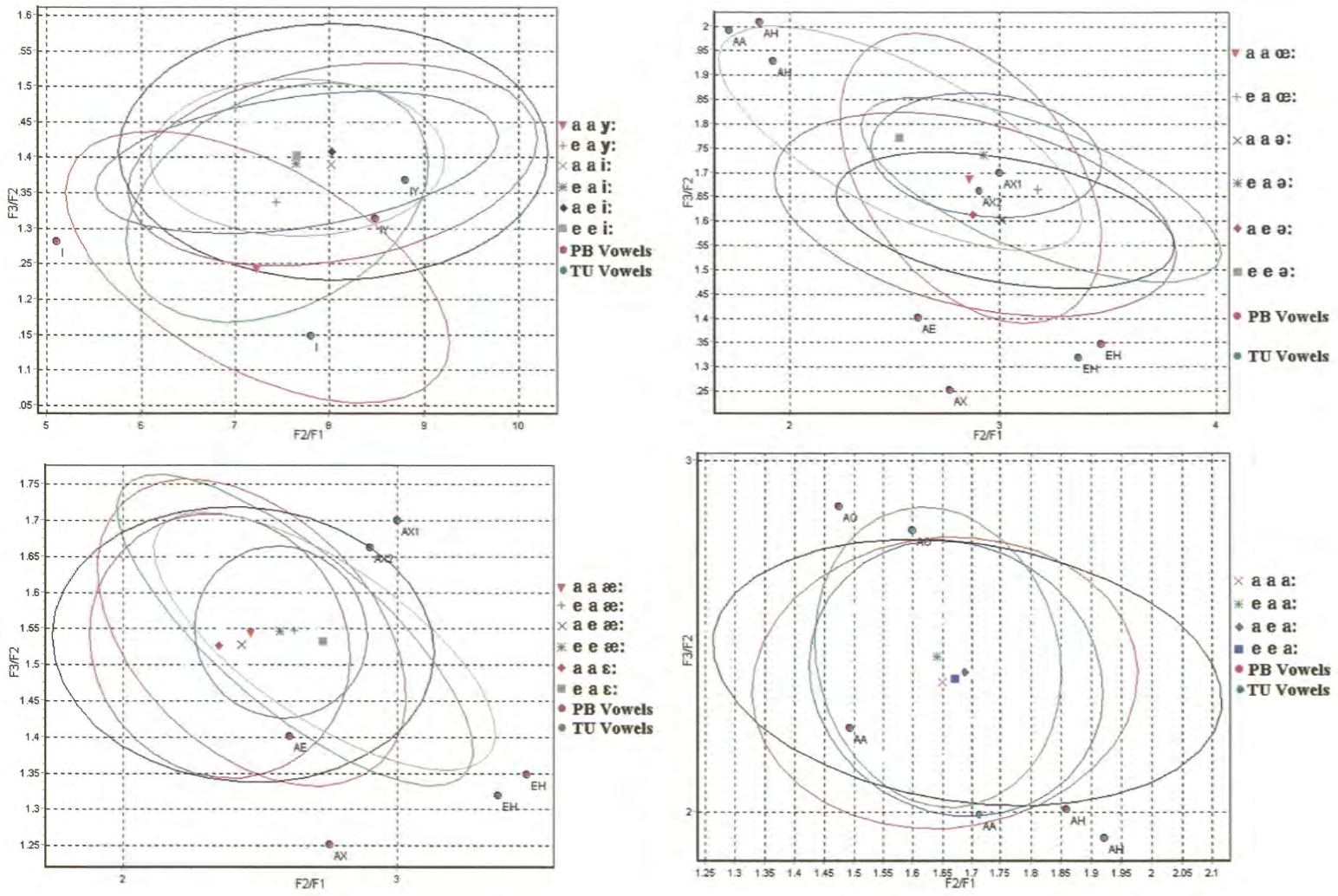



Figure 3.8: Vowel formant ratio clusters: [<y:> in "*uur*" and also <i:> in "*dier*" and "heat"], [<œ:> in "*brûe*" and also <ə:> in "*wîe*" and "about"], [<æ:> in "*werk*" and "hat" and also the incorrectly used <ɛ:> in "*êrens*"] and [<a:> in "*klaar*" and "father"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

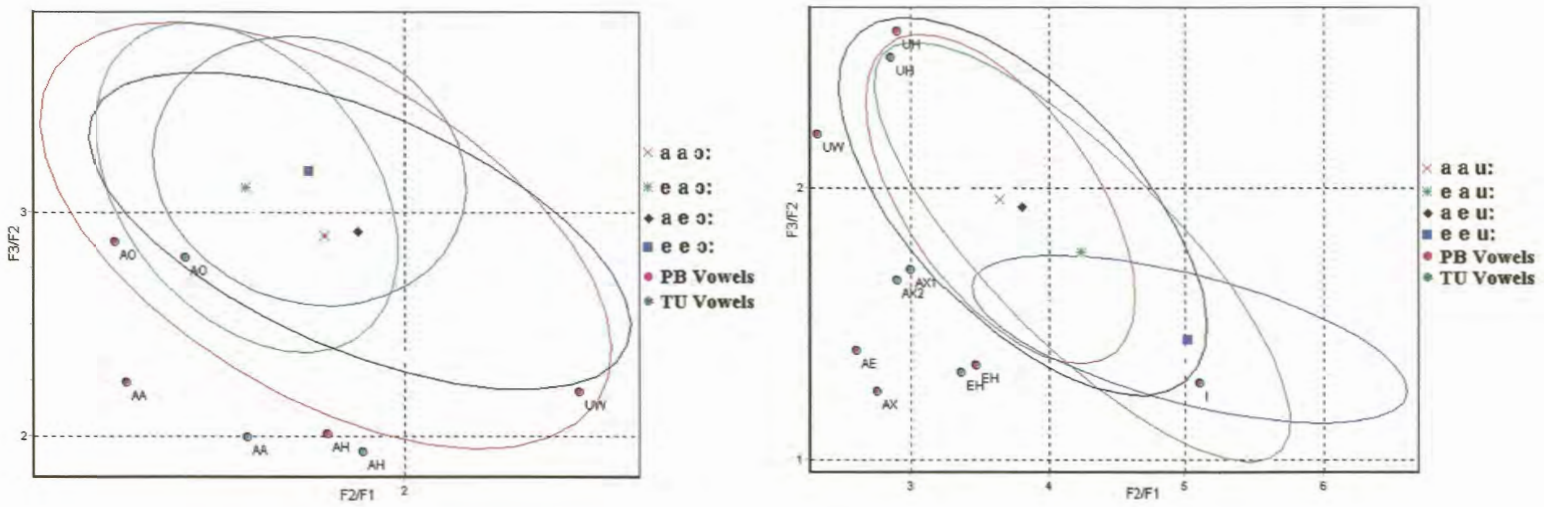



Figure 3.9: Vowel formant ratio clusters: [<ɔ:> in "*dom*" and in "bought"] and [<u:> in "*boer*" and "soon"]. The first $a/e$ indicates the mother-tongue of the speakers and the second $a/e$ indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

*Diphthong Formant Ratio Analysis of Variance*

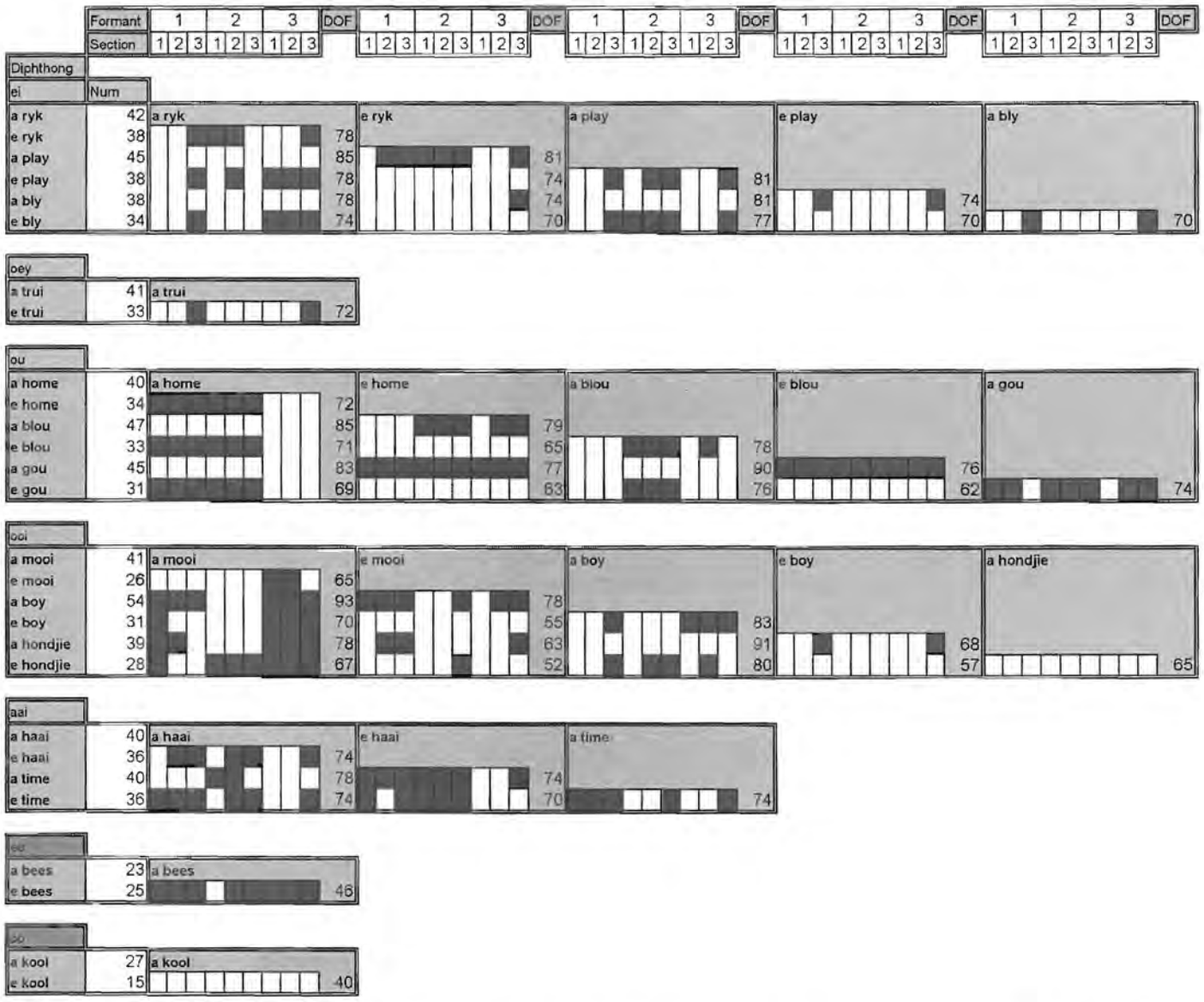



Table 3.10: An analysis of variance table of the diphthong formant ratios. See text on page 87 for explanation.

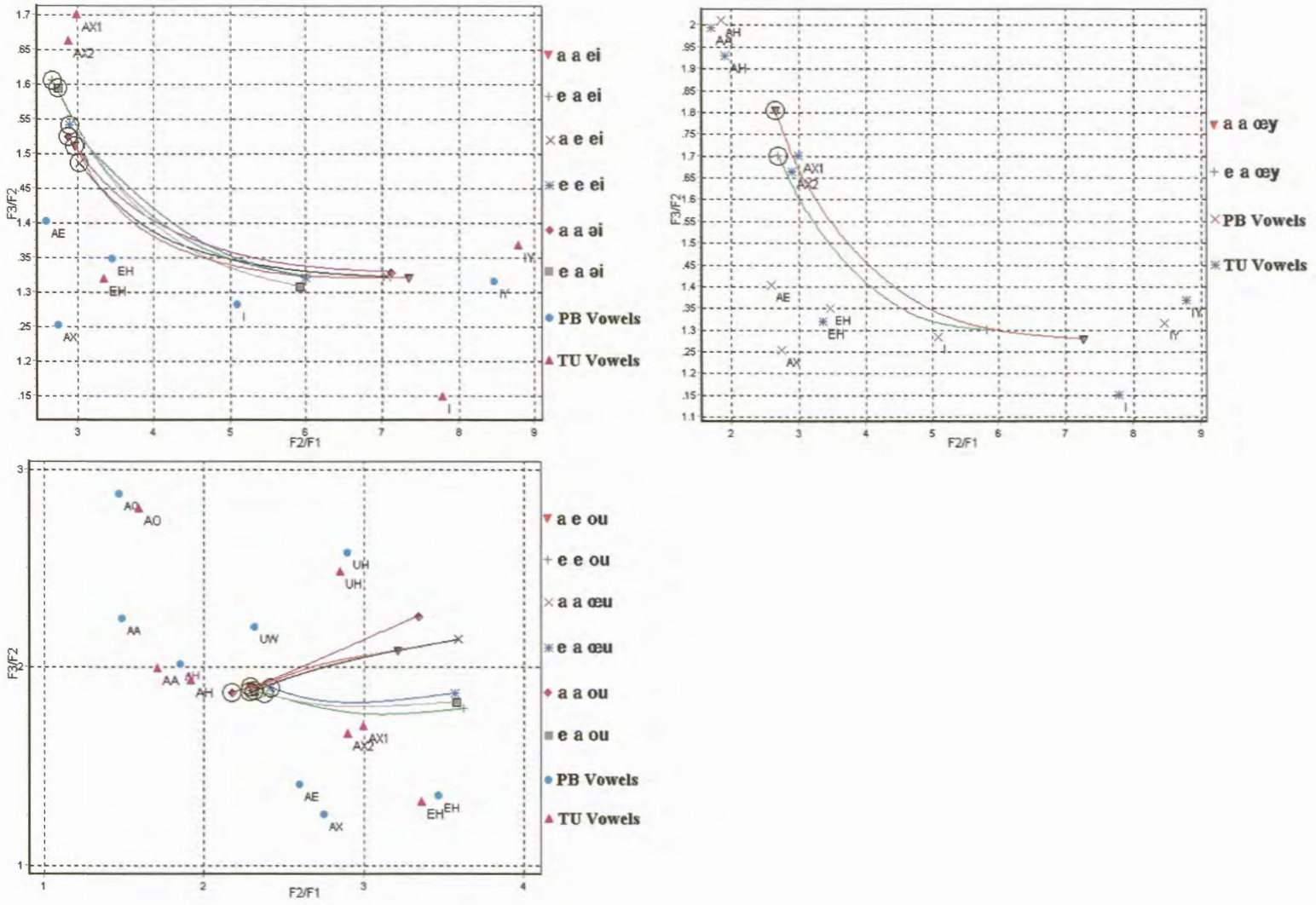



Figure 3.10: Diphthong ratio formant trajectories: [<ei> in "*ryk*" and "play" and also <əi> in "*bly*"], [<œy> in "*trui*" ] and [<ou> in "*gou*" and "home" and also <œu> in "*blou*"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from. *PB Vowels* are the Peterson and Barney vowels and the *TU Vowels* the Taylor and Uys vowels.

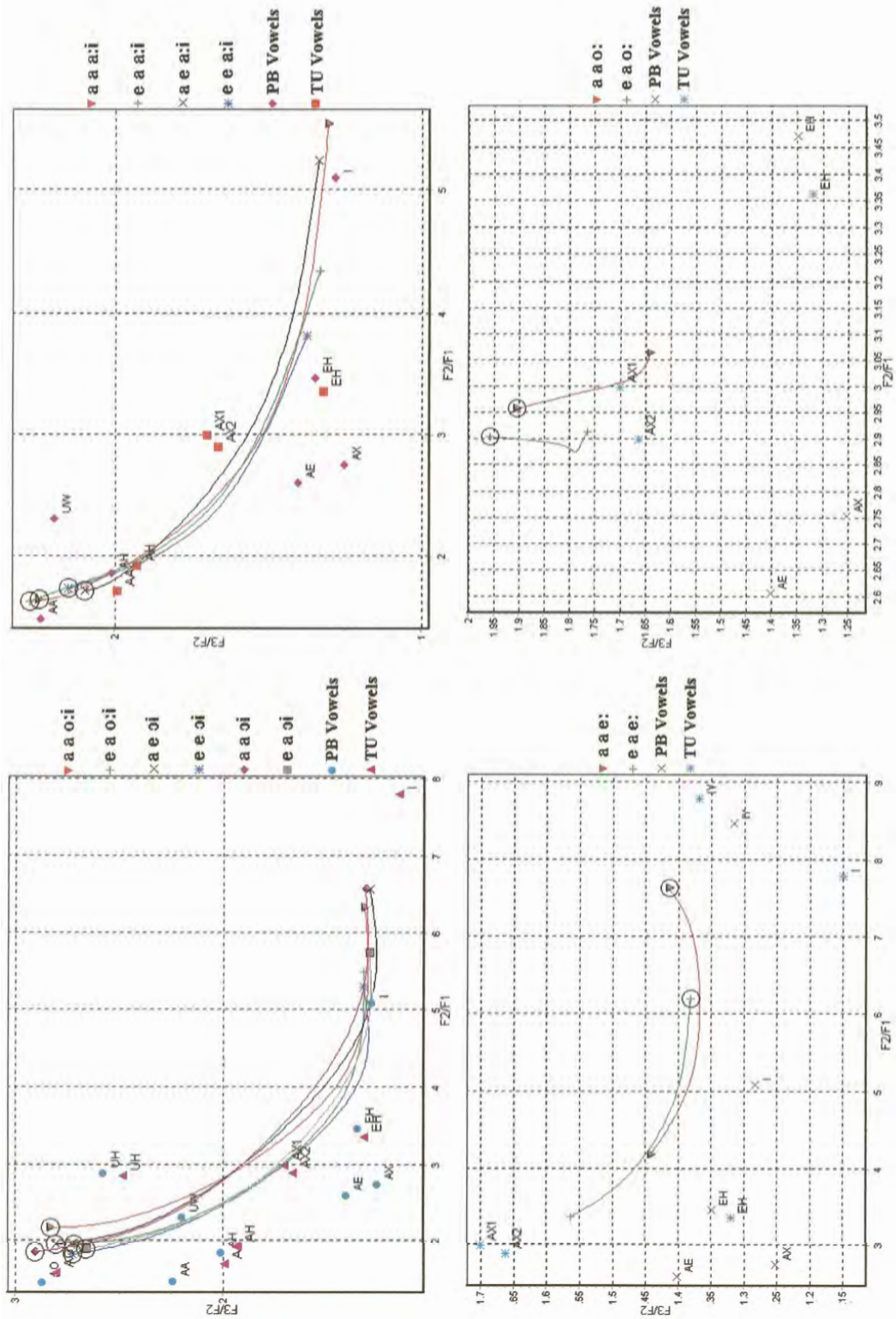



Figure 3.11: Diphthong formant ratio trajectories: [<o:i> in "*mooi*" and also <ɔi> in "*hondje*" and "boy"], [<a:i> in "*haai*" and "time"], [<e:> in "*bees*"] and [<o:> in "*kool*"].

difficulty.

The diphthong tables correlate excellently. Tables 3.7 and 3.10 only differ in one row group, namely "ei". The differences can probably largely be attributed to F3 extraction problems. The normal formant analysis results should rather be used as their analysis techniques have been accepted and are understood.

We have previously noted the controversy surrounding the "formant ratio theory". As stated, it is not entirely clear whether the formant "ratios" i.e. $\frac{F3}{F2}$ and $\frac{F2}{F1}$ have any true significance. This is primarily because we do not fully understand how the brain processes speech, and although the formant ratios do appear to have significance to the brain as pattern recogniser, there is still much scientific debate as to the validity of the theory. Formants are clearly the resonance peaks of voiced speech, and obviously have linguistic importance, but science has been unable to prove whether it is the actual locations of these formants, or merely the spacing between them which is important.

We do not attempt to speculate here as to the correctness of this theory, but for completeness and out of scientific curiosity we have calculated the formant ratios, both for the static vowels and for the dynamic diphthongs, and graphed them.

### 3.4.5 Long vowel and diphthong diphthongization results

The long vowels are considered to be quasi-stationary. It is impossible for anything but synthetic speech to have truly stationary formants. We would however like to have some measure of the level of diphthongization of voiced speech and use this as a metric for whether to label a sound as a vowel or a diphthong.

Using the cubic spline formant trajectories we have calculated for the long vowels and diphthongs, we calculate the difference between initial and terminal points of F1, F2 and F3 namely $\Delta$F1, $\Delta$F2 and $\Delta$F3, and also the cumulative absolute shift in

Vowels

| | ΔF1 | ΔF2 | ΔF3 | Σ ΔF1 | Σ ΔF2 | Σ ΔF3 | \|ΔF1\|+\|ΔF2\| | \|ΔF1\|+\|ΔF2\| +\|ΔF3\| |
|---|---|---|---|---|---|---|---|---|
| i | | | | | | | | |
| a uur | -12.70 | 27.22 | 34.87 | 12.70 | 40.41 | 35.56 | 39.92 | 74.79 |
| e uur | -7.50 | 5.48 | -6.30 | 15.48 | 16.75 | 52.45 | 12.98 | 19.28 |
| a dier | -5.21 | 13.39 | -20.31 | 5.21 | 32.84 | 23.71 | 18.60 | 38.91 |
| e dier | -7.51 | 27.76 | 10.44 | 9.06 | 27.76 | 25.28 | 35.27 | 45.71 |
| a heat | -10.60 | -0.11 | -22.43 | 10.69 | 10.00 | 28.55 | 10.71 | 33.14 |
| e heat | -8.18 | 23.72 | -25.32 | 8.18 | 23.72 | 38.10 | 31.90 | 57.22 |
| oe | | | | | | | | |
| a brue | -2.95 | -1.99 | -19.19 | 4.45 | 3.29 | 24.58 | 4.94 | 24.13 |
| e brue | 6.36 | 1.03 | -24.82 | 6.98 | 7.71 | 25.53 | 7.39 | 32.21 |
| a wie | -1.37 | -5.42 | 21.98 | 11.37 | 17.09 | 28.64 | 6.79 | 28.77 |
| e wie | 8.66 | 11.36 | -4.52 | 14.50 | 11.36 | 14.67 | 20.02 | 24.54 |
| a about | -10.43 | 1.67 | -12.72 | 12.01 | 7.95 | 17.00 | 12.10 | 24.82 |
| e about | -0.15 | 33.61 | -6.21 | 10.02 | 33.78 | 11.29 | 33.76 | 39.97 |
| ae | | | | | | | | |
| a werk | -12.92 | 5.57 | -4.91 | 13.63 | 16.21 | 50.28 | 18.49 | 23.40 |
| e werk | 8.87 | 5.86 | -18.33 | 13.28 | 7.89 | 38.77 | 14.73 | 33.06 |
| a hat | -2.34 | 21.39 | -22.34 | 11.18 | 21.39 | 57.26 | 23.73 | 46.07 |
| e hat | -4.74 | -2.31 | -15.30 | 13.17 | 22.54 | 24.46 | 7.05 | 22.35 |
| a erens | -0.91 | 25.01 | 7.79 | 11.44 | 25.01 | 32.46 | 25.92 | 33.71 |
| e erens | -2.95 | -17.66 | 4.42 | 8.88 | 20.67 | 28.57 | 20.61 | 25.03 |
| aa | | | | | | | | |
| a klaar | -8.89 | -25.77 | -15.57 | 20.28 | 25.87 | 28.49 | 34.66 | 50.23 |
| e klaar | -11.66 | -18.49 | 52.85 | 11.71 | 19.98 | 52.85 | 30.15 | 83.00 |
| a father | -22.29 | -16.79 | 8.66 | 22.29 | 20.57 | 14.67 | 39.09 | 47.74 |
| e father | -3.25 | -1.94 | -7.20 | 5.56 | 6.50 | 24.54 | 5.19 | 12.39 |
| openo | | | | | | | | |
| a dom | -8.24 | -19.97 | 13.20 | 8.66 | 19.97 | 13.30 | 28.21 | 41.41 |
| e dom | 14.52 | -27.50 | 40.99 | 32.82 | 27.51 | 51.69 | 42.02 | 83.01 |
| a bought | -14.80 | -13.06 | 21.90 | 14.80 | 18.83 | 37.05 | 27.86 | 49.76 |
| e bought | -14.14 | -13.35 | -9.38 | 14.14 | 13.35 | 30.47 | 27.49 | 36.87 |
| uu | | | | | | | | |
| a boer | -4.91 | -9.99 | 31.57 | 8.31 | 10.68 | 31.57 | 14.90 | 46.47 |
| e boer | -4.94 | -7.61 | -5.64 | 6.64 | 27.11 | 33.23 | 12.55 | 18.19 |
| a soon | -16.81 | 11.15 | 19.71 | 16.81 | 13.40 | 50.95 | 27.96 | 47.67 |
| e soon | -4.36 | -10.13 | -29.34 | 4.36 | 17.07 | 29.34 | 14.49 | 43.83 |

Diphthongs

| | ΔF1 | ΔF2 | ΔF3 | Σ ΔF1 | Σ ΔF2 | Σ ΔF3 | \|ΔF1\|+\|ΔF2\| | \|ΔF1\|+\|ΔF2\| +\|ΔF3\| |
|---|---|---|---|---|---|---|---|---|
| ei | | | | | | | | |
| a ryk | -283.67 | 498.08 | 355.56 | 283.67 | 498.08 | 355.56 | 781.75 | 1137.31 |
| e ryk | -241.67 | 461.64 | 174.15 | 241.67 | 461.64 | 174.15 | 703.31 | 877.46 |
| a play | -266.93 | 413.98 | 281.54 | 266.93 | 413.98 | 281.54 | 680.91 | 962.45 |
| a play | -232.79 | 382.23 | 146.19 | 232.79 | 382.23 | 146.19 | 615.02 | 761.21 |
| a bly | -277.19 | 459.08 | 299.89 | 277.19 | 459.08 | 299.89 | 736.27 | 1036.16 |
| a bly | -227.82 | 444.96 | 137.49 | 227.82 | 444.96 | 137.49 | 672.78 | 810.27 |
| oey | | | | | | | | |
| a trui | -199.18 | 754.05 | 307.28 | 199.18 | 754.05 | 328.76 | 953.23 | 1260.51 |
| e trui | -184.32 | 536.24 | 138.45 | 184.32 | 536.24 | 187.11 | 720.56 | 859.01 |
| ou | | | | | | | | |
| a home | -179.17 | -80.93 | 5.99 | 179.17 | 80.93 | 14.71 | 260.10 | 266.09 |
| e home | -173.65 | 10.08 | -100.30 | 173.65 | 22.73 | 124.85 | 183.73 | 284.03 |
| a blou | -221.82 | -104.27 | 17.88 | 221.82 | 104.27 | 72.79 | 326.09 | 343.97 |
| e blou | -175.06 | -25.19 | -120.32 | 175.06 | 35.78 | 137.27 | 200.25 | 320.57 |
| a gou | -246.20 | -156.74 | -7.77 | 246.20 | 156.74 | 36.31 | 402.94 | 410.71 |
| e gou | -184.88 | 7.23 | -102.55 | 184.88 | 14.79 | 116.39 | 192.11 | 294.66 |
| oei | | | | | | | | |
| a mooi | -66.98 | 1157.96 | 313.55 | 130.88 | 1157.96 | 428.25 | 1224.94 | 1538.49 |
| e mooi | -79.03 | 1071.53 | 257.18 | 122.82 | 1071.53 | 375.30 | 1150.56 | 1407.74 |
| a boy | -125.46 | 1152.61 | 228.86 | 135.53 | 1152.61 | 399.95 | 1278.07 | 1506.93 |
| e boy | -104.67 | 1029.09 | 186.53 | 120.03 | 1029.09 | 281.17 | 1133.76 | 1320.29 |
| a hondje | -135.59 | 1167.89 | 252.15 | 135.59 | 1167.89 | 470.64 | 1303.48 | 1555.63 |
| e hondje | -107.42 | 1092.70 | 231.83 | 123.32 | 1092.70 | 376.76 | 1200.12 | 1431.95 |
| aai | | | | | | | | |
| a haai | -285.45 | 921.28 | 153.48 | 292.09 | 921.28 | 289.17 | 1206.73 | 1360.21 |
| e haai | -229.64 | 769.91 | -17.61 | 231.40 | 769.91 | 125.05 | 999.55 | 1017.16 |
| a time | -289.05 | 783.90 | 148.10 | 289.05 | 783.90 | 187.55 | 1072.95 | 1221.05 |
| e time | -188.12 | 661.14 | -9.12 | 202.42 | 661.14 | 111.90 | 849.26 | 858.38 |
| ee | | | | | | | | |
| a bees | 155.37 | -311.14 | -396.41 | 155.37 | 311.14 | 396.41 | 466.51 | 862.92 |
| e bees | 159.44 | -361.62 | -224.89 | 159.44 | 361.62 | 230.44 | 521.06 | 745.95 |
| oo | | | | | | | | |
| a kool | 60.26 | 197.07 | 23.85 | 60.26 | 197.07 | 40.49 | 257.33 | 281.18 |
| e kool | 53.24 | 153.71 | 69.66 | 53.24 | 153.71 | 109.17 | 206.95 | 276.61 |

Table 3.11: A table indicating the level of diphthongization of the long vowels and diphthongs.

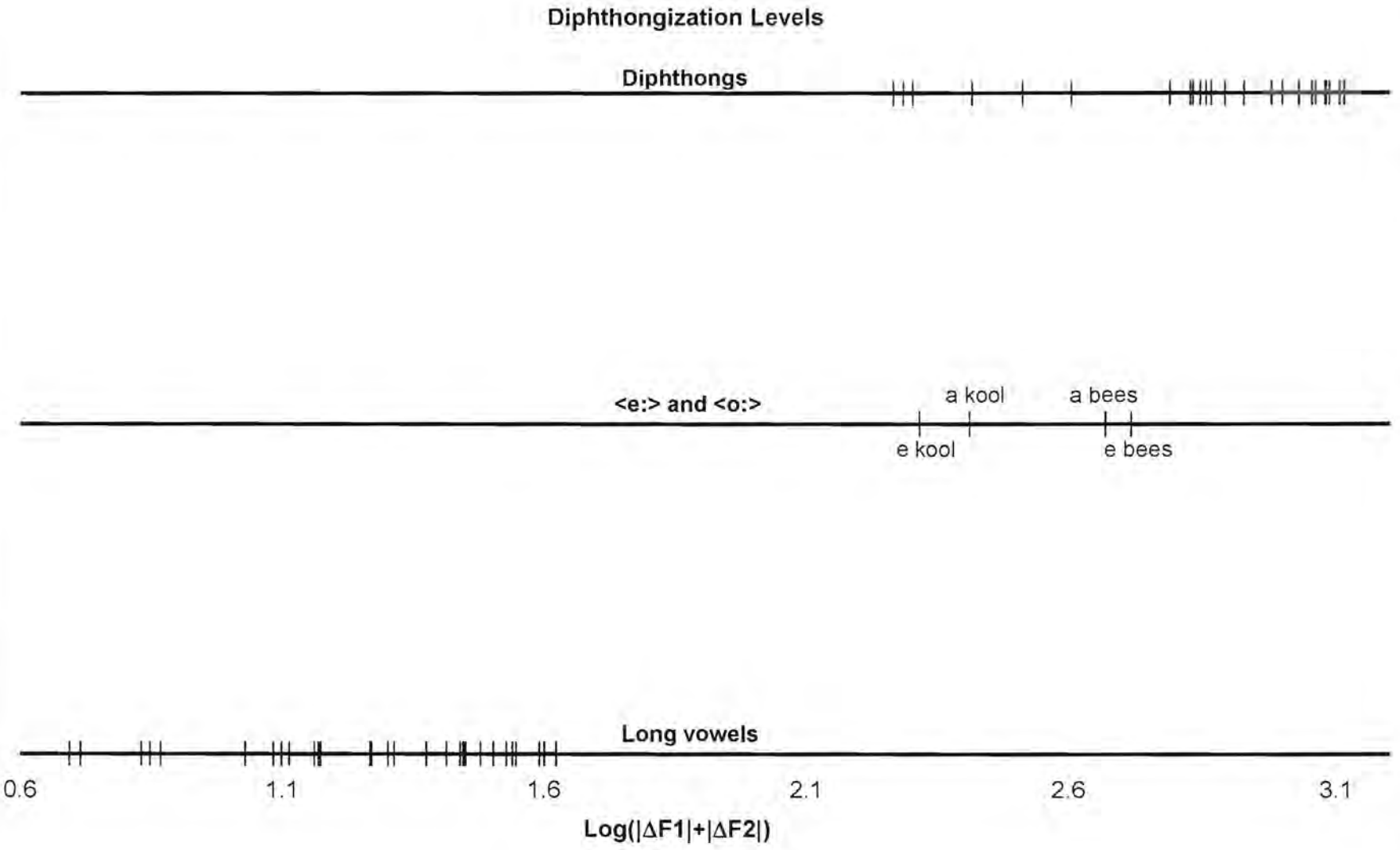



Figure 3.12: A figure giving a graphical representation of the data in Table 3.11 with the level of diphthongization of the long vowels and diphthongs indicated as well as <e:> and <o:> which is clearly seen to lie in the range of the diphthongs.

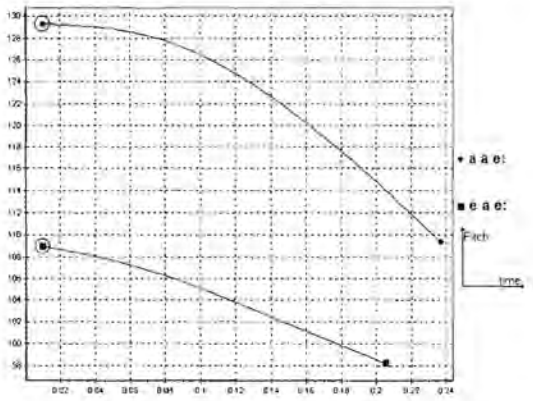



Figure 3.13: Vowel pitch trajectory: [<e:> in "*bees*"].

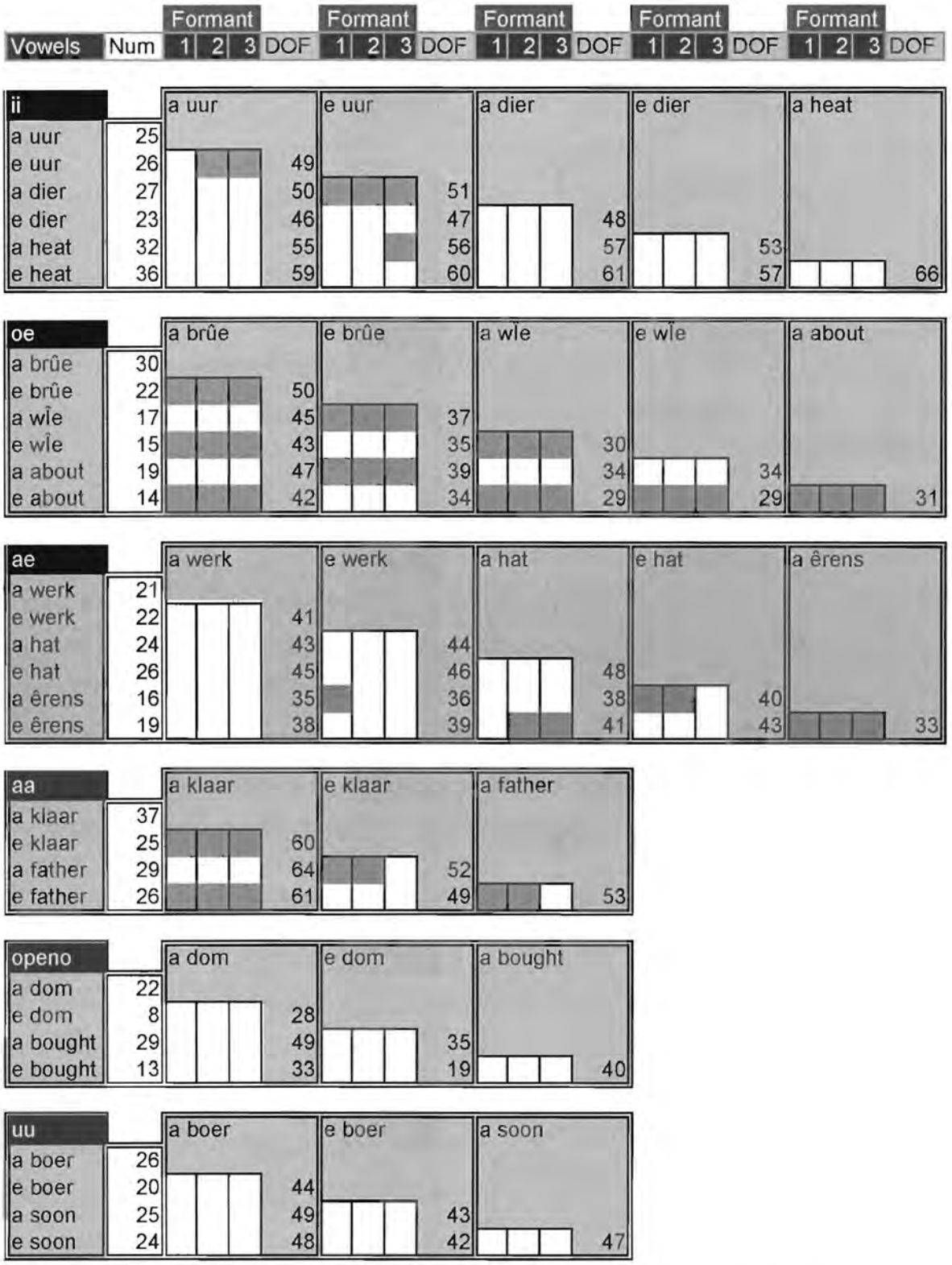
formant values ΣF1, ΣF2 and ΣF3, as demonstrated in Figure 2.11. The results are given in Table 3.11 where we have included a measure of diphthongization, namely, $|\Delta F1| + |\Delta F2|$ (and also $|\Delta F1| + |\Delta F2| + |\Delta F3|$). The results are also represented graphically in Figure 3.12 where we have plotted the logarithm of $|\Delta F1| + |\Delta F2|$ to scale the data for plotting clarity. We can see from Table 3.11 that by simply stating the condition that if the measure $|\Delta F1| + |\Delta F2|$ exceeds about 200Hz then we can consider the sound to be a diphthong or conversely, if the measure is less than 40Hz then it is a vowel. It is of special importance to note that this is also true of the much argued over "potential" diphthongs <e:> and <o:>. This adds further credibility to the notion that these sounds should be classified as diphthongs and not vowels, in spite of their short duration. This has been emphasised in Figure 3.12.

### 3.4.6 Pitch results

Tables 3.12 and 3.13 summarise the analysis of variance comparisons between the pitch trajectories of the vowels and diphthongs respectively. We have also included a single plot of pitch trajectories for the vowel/diphthong <e:> in Figure 3.13. The rest of the plots are available in Appendix A.3.

It is important to note that, while we determine significant differences between the means of the English and Afrikaans pitch trajectories, this appears to be more a speaker

***Vowel Pitch Analysis of Variance***



| Vowels | Num | Formant 1 | Formant 2 | Formant 3 | DOF |
|---|---|---|---|---|---|
| **ii** | | | | | |
| a uur | 25 | | | | |
| e uur | 26 | | | | |
| a dier | 27 | | | | |
| e dier | 23 | | | | |
| a heat | 32 | | | | |
| e heat | 36 | | | | |
| a uur | | 25 | 26 | 49 | |
| e uur | | 50 | 51 | 47 | |
| a dier | | 46 | 55 | 56 | |
| e dier | | 60 | 59 | 48 | |
| a heat | | 57 | 61 | 53 | |
| e heat | | 57 | 66 | | |
| **oe** | | | | | |
| a brûe | 30 | | | | |
| e brûe | 22 | | | | |
| a wĺe | 17 | | | | |
| e wĺe | 15 | | | | |
| a about | 19 | | | | |
| e about | 14 | | | | |
| a brûe | | 50 | 45 | 43 | |
| e brûe | | 47 | 42 | 37 | |
| a wĺe | | 35 | 39 | 34 | |
| e wĺe | | 30 | 34 | 29 | |
| a about | | 34 | 29 | 31 | |
| **ae** | | | | | |
| a werk | 21 | | | | |
| e werk | 22 | | | | |
| a hat | 24 | | | | |
| e hat | 26 | | | | |
| a êrens | 16 | | | | |
| e êrens | 19 | | | | |
| a werk | | 41 | 43 | 45 | |
| e werk | | 44 | 46 | 35 | |
| a hat | | 36 | 38 | 39 | |
| e hat | | 48 | 40 | 43 | |
| a êrens | | 41 | 33 | | |
| **aa** | | | | | |
| a klaar | 37 | | | | |
| e klaar | 25 | | | | |
| a father | 29 | | | | |
| e father | 26 | | | | |
| a klaar | | 60 | 64 | 61 | |
| e klaar | | 52 | 49 | 53 | |
| **openo** | | | | | |
| a dom | 22 | | | | |
| e dom | 8 | | | | |
| a bought | 29 | | | | |
| e bought | 13 | | | | |
| a dom | | 28 | 49 | 33 | |
| e dom | | 35 | 19 | 40 | |
| **uu** | | | | | |
| a boer | 26 | | | | |
| e boer | 20 | | | | |
| a soon | 25 | | | | |
| e soon | 24 | | | | |
| a boer | | 44 | 49 | 48 | |
| e boer | | 43 | 42 | 47 | |

Table 3.12: An analysis of variance table of the long-vowel pitches.

***Diphthong Pitch Analysis of Variance***

| Diphthong | Num | Formant 1 | Formant 2 | Formant 3 | DOF | Formant 1 | Formant 2 | Formant 3 | DOF | Formant 1 | Formant 2 | Formant 3 | DOF | Formant 1 | Formant 2 | Formant 3 | DOF | Formant 1 | Formant 2 | Formant 3 | DOF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ei** | | a ryk | | | | e ryk | | | | a play | | | | e play | | | | a bly | | | |
| a ryk | 37 | | | | | | | | | | | | | | | | | | | | |
| e ryk | 35 | | | | 70 | | | | | | | | | | | | | | | | |
| a play | 37 | | | | 72 | | | | 70 | | | | | | | | | | | | |
| e play | 37 | | | | 72 | | | | 70 | | | | 72 | | | | | | | | |
| a bly | 32 | | | | 67 | | | | 65 | | | | 67 | | | | 67 | | | | |
| e bly | 32 | | | | 67 | | | | 65 | | | | 67 | | | | 67 | | | | 62 |
| **oey** | | a trui | | | | | | | | | | | | | | | | | | | |
| a trui | 38 | | | | | | | | | | | | | | | | | | | | |
| e trui | 32 | | | | 68 | | | | | | | | | | | | | | | | |
| **ou** | | a home | | | | e home | | | | a blou | | | | e blou | | | | a gou | | | |
| a home | 36 | | | | | | | | | | | | | | | | | | | | |
| e home | 33 | | | | 67 | | | | | | | | | | | | | | | | |
| a blou | 44 | | | | 78 | | | | 75 | | | | | | | | | | | | |
| e blou | 30 | | | | 64 | | | | 61 | | | | 72 | | | | | | | | |
| a gou | 37 | | | | 71 | | | | 68 | | | | 79 | | | | 65 | | | | |
| e gou | 30 | | | | 64 | | | | 61 | | | | 72 | | | | 58 | | | | 65 |
| **ooi** | | a mooi | | | | e mooi | | | | a boy | | | | e boy | | | | a hondjie | | | |
| a mooi | 35 | | | | | | | | | | | | | | | | | | | | |
| e mooi | 19 | | | | 52 | | | | | | | | | | | | | | | | |
| a boy | 46 | | | | 79 | | | | 63 | | | | | | | | | | | | |
| e boy | 24 | | | | 57 | | | | 41 | | | | 68 | | | | | | | | |
| a hondjie | 35 | | | | 68 | | | | 52 | | | | 79 | | | | 57 | | | | |
| e hondjie | 23 | | | | 56 | | | | 40 | | | | 67 | | | | 45 | | | | 56 |
| **aai** | | a haai | | | | e haai | | | | a time | | | | | | | | | | | |
| a haai | 35 | | | | | | | | | | | | | | | | | | | | |
| e haai | 31 | | | | 64 | | | | | | | | | | | | | | | | |
| a time | 31 | | | | 64 | | | | 60 | | | | | | | | | | | | |
| e time | 31 | | | | 64 | | | | 60 | | | | 60 | | | | | | | | |
| **ee** | | a bees | | | | | | | | | | | | | | | | | | | |
| a bees | 21 | | | | | | | | | | | | | | | | | | | | |
| e bees | 25 | | | | 44 | | | | | | | | | | | | | | | | |
| **oo** | | a kool | | | | | | | | | | | | | | | | | | | |
| a kool | 27 | | | | | | | | | | | | | | | | | | | | |
| e kool | 15 | | | | 40 | | | | | | | | | | | | | | | | |

Table 3.13: An analysis of variance table of the diphthong pitches.

dependent influence than a language or accent group influence. This means that, because we have relatively few speakers, it is quite probable that the difference in pitch trajectories is purely due to the fact that a few of the speakers in the Afrikaans group spoke with a slightly higher pitched voice. We doubt that this is a general trend observable across the language groups.

It is also important to note that if we assume that this is true, and then adjust all the pitch trajectories to begin at the same pitch (i.e. introduce an offset), then we find no significantly observable differences between the two groups. In other words, there appears to be no difference in the intonation (change in pitch over time) of the two groups even though there are observable differences in pitch. It is unlikely therefore that we can make use of intonation as a means of distinguishing between the two language/accent groups.

There are a few interesting features which we can deduce from the pitch trajectory plots in Appendix A.3 and from Table 3.14 which shows mean durations.

Firstly, the diphthongs have noticeably longer duration than the vowels. This is true for all the diphthongs, except the potential diphthongs or centring diphthongs <e:> and <o:> which are called vowels by some phonologists. Perhaps it is this relatively short duration that has led to them being labelled as vowels in the past. Although the centring diphthongs have short durations similar to vowels (as can be seen at the bottom right of Table 3.14) they are clearly diphthongized (as is reflected in Table 3.11 and Figure 3.12). If we perform an analysis of variance between the long vowels, diphthongs and potential diphthongs we find that there is no statistically measurable difference between the mean durations of the long vowels and <e:> and <o:>. Between the long vowels and diphthongs there is though (as expected), and between the diphthongs and <e:> and <o:> there is too (which is also expected). This, with $F$ ratio values is summarised in Table 3.15.

Another interesting feature is that the initial pitch of the diphthongs appears to be held

| Vowels | µDuration (s) | Average µDuration (s) |
|---|---|---|
| ii | | |
| a uur | 0.20 | |
| e uur | 0.21 | |
| a dier | 0.13 | |
| e dier | 0.14 | |
| a heat | 0.16 | |
| e heat | 0.15 | 0.17 |
| oe | | |
| a brue | 0.15 | |
| e brue | 0.15 | |
| a wie | 0.17 | |
| e wie | 0.17 | |
| a about | 0.15 | |
| e about | 0.11 | 0.15 |
| ae | | |
| a werk | 0.14 | |
| e werk | 0.17 | |
| a hat | 0.12 | |
| e hat | 0.13 | |
| a erens | 0.19 | |
| e erens | 0.20 | 0.16 |
| aa | | |
| a klaar | 0.18 | |
| e klaar | 0.16 | |
| a father | 0.19 | |
| e father | 0.15 | 0.17 |
| openo | | |
| a dom | 0.13 | |
| e dom | 0.12 | |
| a bought | 0.17 | |
| e bought | 0.12 | 0.13 |
| uu | | |
| a boer | 0.17 | |
| e boer | 0.17 | |
| a soon | 0.19 | |
| e soon | 0.17 | 0.18 |
| Vowel average average | | 0.16 |

| Diphthongs | µDuration (s) | Average µDuration (s) |
|---|---|---|
| ei | | |
| a ryk | 0.28 | |
| e ryk | 0.30 | |
| a play | 0.32 | |
| e play | 0.31 | |
| a bly | 0.29 | |
| e bly | 0.29 | 0.30 |
| oey | | |
| a trui | 0.35 | |
| e trui | 0.29 | 0.32 |
| ou | | |
| a home | 0.28 | |
| e home | 0.28 | |
| a blou | 0.30 | |
| e blou | 0.29 | |
| a gou | 0.30 | |
| e gou | 0.27 | 0.29 |
| ooi | | |
| a mooi | 0.36 | |
| e mooi | 0.30 | |
| a boy | 0.34 | |
| e boy | 0.28 | |
| a hondjie | 0.32 | |
| e hondjie | 0.29 | 0.31 |
| aai | | |
| a haai | 0.32 | |
| e haai | 0.35 | |
| a time | 0.32 | |
| e time | 0.32 | 0.33 |
| Diphthong average average | | 0.31 |
| ee | | |
| a bees | 0.23 | |
| e bees | 0.21 | 0.22 |
| oo | | |
| a kool | 0.17 | |
| e kool | 0.15 | 0.16 |
| <e:> <o:> average average | | 0.19 |

Table 3.14: A table showing the mean duration of the long-vowels and diphthongs.

| First Set | Second Set | $F$ ratio |
|---|---|---|
| Vowels | <e:> and <o:> | 1.00 |
| Diphthongs | <e:> and <o:> | **61.05** |
| Vowels | Diphthongs | **84.54** |

Table 3.15: Analysis of variance of the long vowels, diphthongs and potential diphthongs' mean durations as given in Table 3.14.

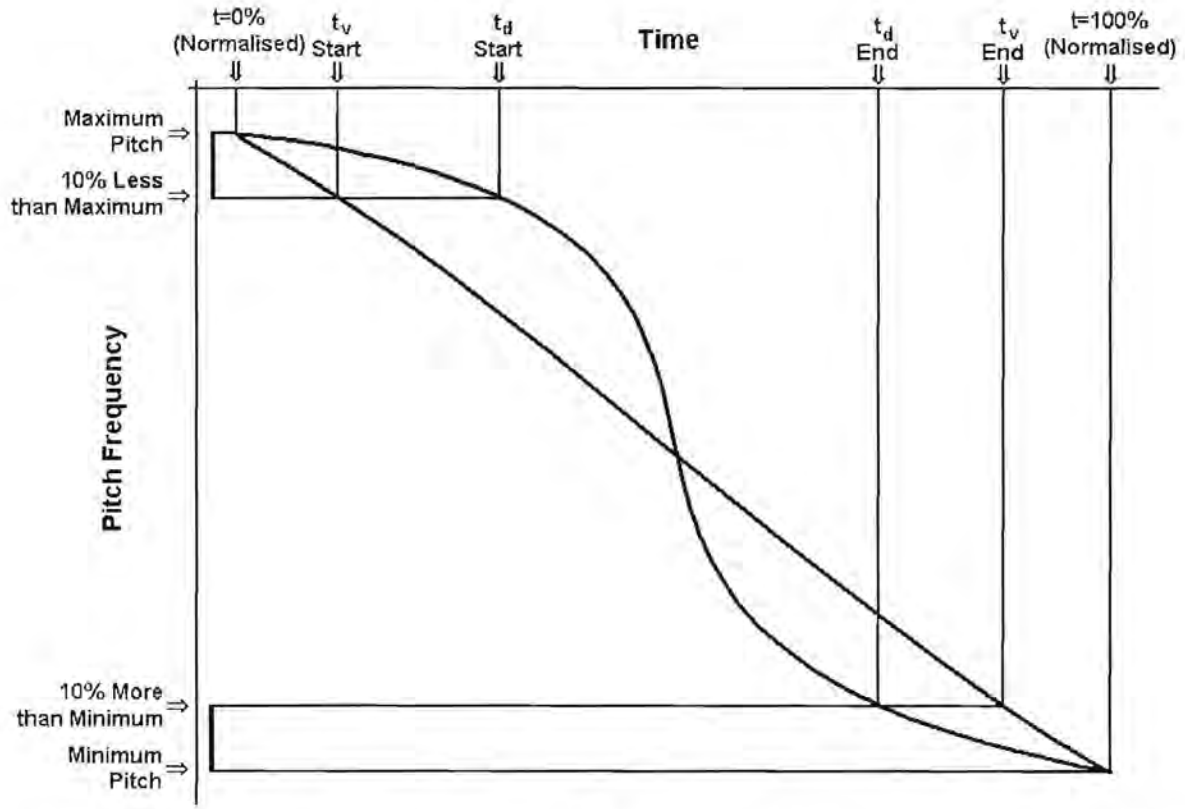



Figure 3.14: This graph demonstrates how we measured the change of pitch from the initial point to final point for the long vowels and diphthongs.

**Vowels**

| | $t_v$ Start | $t_v$ End | $\mu t_v$ Start | $\mu t_v$ End |
|---|---|---|---|---|
| ii | | | | |
| a uur | 0.38 | 0.95 | | |
| e uur | 0.29 | 0.92 | | |
| a dier | 0.14 | 0.93 | | |
| e dier | 0.13 | 0.94 | | |
| a heat | 0.55 | 0.95 | | |
| e heat | 0.13 | 0.93 | 0.27 | 0.94 |
| oe | | | | |
| a brue | 0.36 | 0.94 | | |
| e brue | 0.18 | 0.95 | | |
| a wie | 0.45 | 0.94 | | |
| e wie | 0.24 | 0.94 | | |
| a about | 0.24 | 0.94 | | |
| e about | 0.19 | 0.91 | 0.28 | 0.94 |
| ae | | | | |
| a werk | 0.15 | 0.92 | | |
| e werk | 0.40 | 0.96 | | |
| a hat | 0.11 | 0.96 | | |
| e hat | 0.29 | 0.94 | | |
| a erens | 0.27 | 0.93 | | |
| e erens | 0.38 | 0.95 | 0.27 | 0.94 |
| aa | | | | |
| a klaar | 0.23 | 0.94 | | |
| e klaar | 0.20 | 0.93 | | |
| a father | 0.44 | 0.91 | | |
| e father | 0.27 | 0.94 | 0.28 | 0.93 |
| openo | | | | |
| a dom | 0.20 | 0.90 | | |
| e dom | 0.18 | 0.83 | | |
| a bought | 0.21 | 0.94 | | |
| e bought | 0.22 | 0.87 | 0.20 | 0.88 |
| uu | | | | |
| a boer | 0.25 | 0.95 | | |
| e boer | 0.57 | 0.95 | | |
| a soon | 0.28 | 0.94 | | |
| e soon | 0.27 | 0.94 | 0.34 | 0.94 |
| Average average vowel pitch onset time | | | 0.27 | 0.93 |

**Diphthongs**

| | $t_d$ Start | $t_d$ End | $\mu t_d$ Start | $\mu t_d$ End |
|---|---|---|---|---|
| ei | | | | |
| a ryk | 0.20 | 0.88 | | |
| e ryk | 0.39 | 0.92 | | |
| a play | 0.34 | 0.89 | | |
| e play | 0.36 | 0.89 | | |
| a bly | 0.34 | 0.92 | | |
| e bly | 0.35 | 0.91 | 0.33 | 0.90 |
| oey | | | | |
| a trui | 0.25 | 0.88 | | |
| e trui | 0.24 | 0.80 | 0.24 | 0.84 |
| ou | | | | |
| a home | 0.36 | 0.91 | | |
| e home | 0.31 | 0.89 | | |
| a blou | 0.16 | 0.84 | | |
| e blou | 0.18 | 0.88 | | |
| a gou | 0.40 | 0.94 | | |
| e gou | 0.18 | 0.86 | 0.27 | 0.89 |
| ooi | | | | |
| a mooi | 0.36 | 0.78 | | |
| e mooi | 0.22 | 0.92 | | |
| a boy | 0.23 | 0.60 | | |
| e boy | 0.24 | 0.95 | | |
| a hondje | 0.41 | 0.90 | | |
| e hondje | 0.32 | 0.95 | 0.30 | 0.85 |
| aai | | | | |
| a haai | 0.19 | 0.76 | | |
| e haai | 0.35 | 0.93 | | |
| a time | 0.41 | 0.91 | | |
| e time | 0.43 | 0.92 | 0.35 | 0.88 |
| Average average diphthong pitch onset time | | | 0.30 | 0.87 |
| ee | | | | |
| a bees | 0.27 | 0.93 | | |
| e bees | 0.21 | 0.92 | 0.24 | 0.92 |
| oo | | | | |
| a kool | 0.18 | 0.90 | | |
| e kool | 0.20 | 0.93 | 0.19 | 0.91 |
| Average average <e:> <o:> pitch onset time | | | 0.22 | 0.92 |

Table 3.16: The fraction of the normalised length of the long vowels and diphthongs at which the pitch has dropped by 10% from the maximum pitch and still has 10% to drop to the minimum pitch. The last line in the table reflects the fact that for diphthongs, the pitch "spends more time" at the initial and final values.

| First Set | Second Set | $F$ ratio Start | $F$ ratio End |
|---|---|---|---|
| Vowels | <e:> and <o:> | 0.88 | 0.88 |
| Diphthongs | <e:> and <o:> | 3.78 | 1.13 |
| Vowels | Diphthongs | 0.98 | **13.27** |

Table 3.17: Analysis of variance of the long vowels, diphthongs and potential diphthongs mean pitch onset times, for $t_{v/d}Start$ and $t_{v/d}End$ as shown in Figure 3.14 and Table 3.16.

for a while before shifting to the lower pitch, and reaches the lower pitch sooner than the long vowels do (This concept is demonstrated in Figure 3.14). In the case of the long vowels the pitch shift is a relatively smooth transition. A table with measurements that confirm this are given in Table 3.16. This may be a side-effect of the hyper-correction induced by the recording of non-continuous speech. This warrants further research as it may have a substantial influence on the realism of synthetic speech generated with prosodic influences added to improve naturalness.

If we submit these starting and ending threshold times to an analysis of variance (ANOVA) test between the long vowels, diphthongs and potential diphthongs we yield Table 3.17. The results are a bit inconclusive due to the low degree of freedom introduced by <e:> and <o:>, but clearly, by looking at the means and the ANOVA results, we can see that the vowels and diphthongs have similar initial pitch slopes (intonations), but have dissimilar final slopes, with the diphthongs reaching their minimum pitch sooner than the vowels. This can be seen by the bold **13.27** in Table 3.17 which indicates a large $F$ ratio and hence a statistically measurable difference.

# Chapter 4

# Summary and conclusion

This dissertation has presented the motivation, background theory, technique and results on an acoustical modelling of the long vowels and diphthongs of Afrikaans and South African English.

We believe such a study was justifiably motivated by:

- A need for a further study of the acoustic phonetics of Afrikaans and South African English.
- With the use of text to speech(TTS) systems, a thorough understanding of the pronunciation of phonemes and their uniqueness in an accent is required for natural and realistic sounding speech.
- With the likely large-scale roll-out of Automatic Speech Recognition technologies in the near future, a need for compensating for "foreign accents".

## 4.1 Summary of results

Using a multiple stage recording technique we collected long-vowels and diphthongs from Afrikaans and South African English first language speakers and also recorded them speaking their second languages. We recorded the long vowels and diphthongs in three ways:

- Isolated form: For example, just the <a:> in f**a**ther.
- Contextual form: For example, the complete word "f**a**ther".
- Pseudo-word form: Using consonants which have minimal influence on the vowels and diphthongs, for example, "h-**a**-t" ([ha:t]).

The data was verified (by listening), segmented and labelled (using time and spectrogram representations). The primary analysis/modelling technique consisted of formant plotting. The formants are the resonant peaks of voiced speech. We utilised linear prediction techniques to extract the formants. This extraction was then verified by superimposing the extracted formants on the spectrograms of the speech segments from which they came and visual inspection. Any obvious extraction mistakes were manually corrected.

Each of the vowels and diphthongs have been discussed in detail in Section 3.4. It is important however not to "miss the forest for the trees". We have not noticed any general trends between the two language groups' formant structures in terms of global features. For example, some researchers have noted that Afrikaans vowels appear to be more centred around <ə> than British English vowels (for example, compare Ward[20] and Coetzee[23]). This may be true, but no such trend between Afrikaans and South African English has been observed by us. This would suggest that South African English has been noticeably influenced by Afrikaans and vice-versa. Some of the vowels demonstrate distinct differences and other not. We can therefore not apply

a single linear transformation to all vowels or diphthongs to adapt the one formant space to the other, however, knowing which vowels differ, and in which way, is an important result, especially in context of the justification for this study(as mentioned at the beginning of this chapter).

Table 4.1 and table 4.2 summarise the results that were discussed in Chapter 3 "Experiments". The black blocks represent that particular set of vowels or diphthongs (from a particular language group) that has been found to be statistically similar (at the 0.99 significance level) to other vowel and diphthong sets from the same or the other accent group. So, for example, we see in Table 4.1 that for the group of vowels usually transcribed as <u:> ("uu"), the set of English utterances of the vowel <u:> as in the word "soon" form their own cluster (i.e. are dissimilar to the other sets) and the sets of Afrikaans utterances of <u:> as in "*boer*" (farmer) and "soon" and the set of English utterances of <u:> as in "*boer*" form their own cluster. We define a cluster as being a unique row in a row group. Discussions of this clustering and other phenomena were discussed in detail in Chapter 3.

We have developed a new measure of diphthongization and used it to cluster voiced speech segments as either vowels (having low diphthongization) or diphthongs (having high diphthongization). Using this metric we were able to justify the claim by some phoneticians that <e:> and <o:> are in fact diphthongs and not long vowels.

The pitch trajectories were also analysed for the vowels and diphthongs, and even though the mean trajectories were found to be different, a simple logical transformation (i.e. mean normalisation) results in the pitch trajectories generally being statistically identical. We therefore suggest that the differences are purely a speaker dependent phenomenon and not accent dependent.

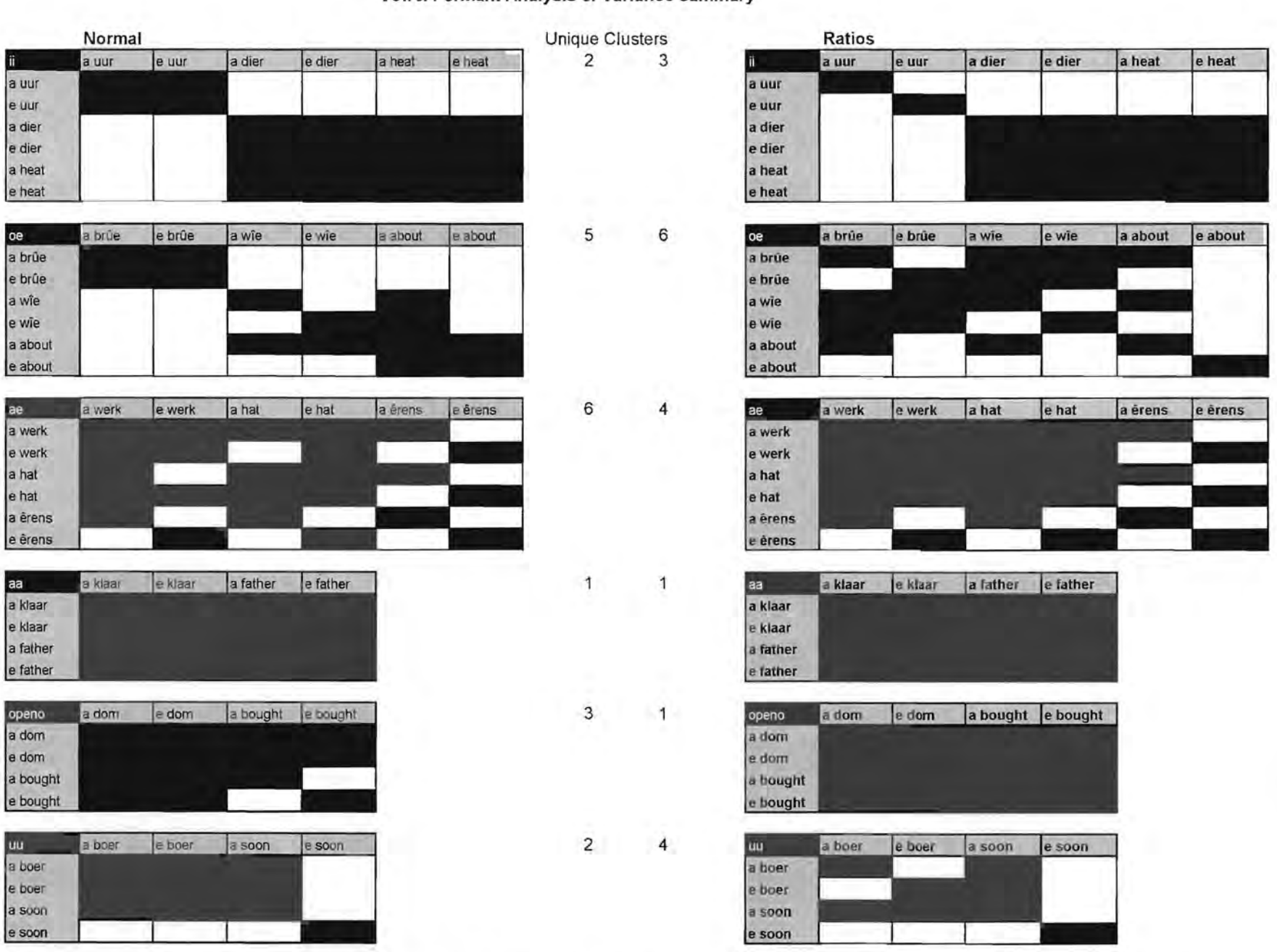



Table 4.1: A statistical similarity cluster table for the long-vowel formants (normal[left] and ratios[right]).

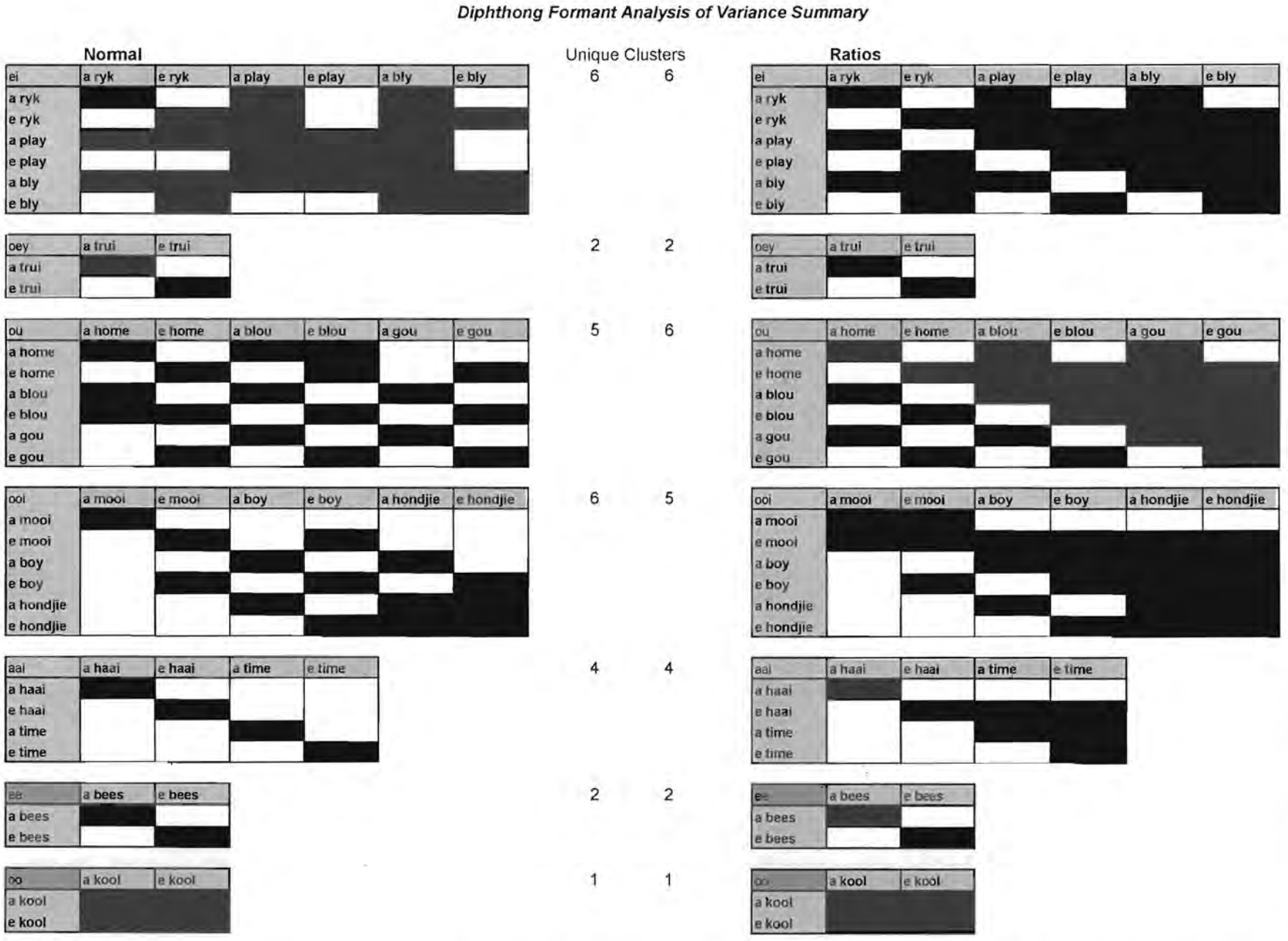



Table 4.2: A statistical similarity cluster table for the diphthong formant trajectories (normal[left] and ratios[right]).

## 4.2 Shortcomings and future work

Due to a mistake in the initial data collection planning the long vowel <ɛ:> was incorrectly replaced with the long vowel <æ:>. This was as a result of an alternative pronunciation of the word "*êrens*" (somewhere) which is used in certain parts of South Africa, namely [ɛ:rəns] as opposed to [æ:rəns]. As a result, to complete the study a thorough analysis of <ɛ:> would have to be undertaken to complete this study. This problem clearly demonstrates the need for an accurate pronunciation dictionary for the South African languages, one of the reasons this study was undertaken in the first place!

We reiterate that we are aware the the research only holds true for a particular group of speakers in South Africa. There are a couple of L1 accents for both Afrikaans and South African English, and this study focuses on L1 and L2 common to well educated white males on the Gauteng Province.

The temporal nature of the diphthongs has largely been down-played in this study. The diphthong formant graphs clearly display the mean path followed by the formants during articulation of the diphthongs, but the rate at which they do this is not visible. We suggest that there may be importance in the temporal shift from one "vowel" to another during diphthong articulation. This should be studied in future work.

Important future work includes the use of the models developed here in ASR and TTS systems. Although fairly basic, the models have the potential to increase recognition rates of "foreign" accents in automatic speech recognition systems and make more natural and familiar sounding text-to-speech systems.

# Appendix A

# Appendix

## A.1 Formant extraction using LPC - Matlab

### A.1.1 Autocorrelation

From Rabiner[1] we have:

If we have a windowed frame $s$ of size $N$ samples then the autocorrelation(with order $P$) is defined as:

$$R(i) = \sum_{n=0}^{N-1-i} s(n)s(n+i) \qquad i = 0, 1, ..., P. \tag{A.1}$$

In Matlab this can be coded as:

```
%       [R] = autocorr(s,P)
%       where s is the input vector, and P is the order of prediction.
%       Function to compute the autocorrelation of the data
%       computes autocorrelation R(i) for i=1, .. ,P+1.
```

```
function [R] = autocorr(s,P)

N=max(size(s));
for i=0:P
 R(i+1,1)=sum(s(1:N-i).*s(i+1:N));
end
```

### A.1.2 Durbin recursion

Durbin recursion (where we have $L$ frames) is defined in Rabiner[1] as:

*Solve recursively for* $i = 1, 2, ..., P$ :

$$E(0) = R(0) \tag{A.2}$$

$$k_i = \frac{\{R(i) - \sum_{j=1}^{L-1} a_j^{(i-1)} R(\mid i-j \mid)\}}{E(i-1)} \qquad 1 \leq i \leq P \tag{A.3}$$

$$a_i(i) = k_i \tag{A.4}$$

$$a_j(i) = a_j(i-1) - k_i a_{i-j}(i-1) \tag{A.5}$$

$$E(i) = (1 - k_i^2)E(i-1) \tag{A.6}$$

In Matlab this can be coded as:

```
%  [a]=durbin(R);
%  Function to calculate the linear predictive coefficients a, from
%  autocorrelation lags R.

function [a] = durbin(R)
P = max(size(R))-1;
a = ones(P,1);
E(1)=R(1);
for i=1:P
 for j=1:i-1
  a_past(j)=a(j);
 end
 sum_term=0;
 for j=1:i-1
```

```
 sum_term = sum_term + a_past(j)*R(i-j+1);
end
k(i) = (R(i+1) - sum_term) / E(i);
a(i) = k(i);
for j=1:i-1
 a(j) = a_past(j) - k(i)*a_past(i-j);
end

E(i+1) = (1-k(i)^2)*E(i);
end
```

### A.1.3 Formant extraction

Utilising the functions above we can determine the formants for a frame of speech. The program simply utilises the LP coefficients (determined with the above functions) and a root finding algorithm to determine the resonance frequencies(formants) of the speech segment.

```
% [f] = formants(x,RO,NUM_FORMANTS,LPC_ORDER)
%   Function to estimate the NUM_FORMANTS formants of voiced speech x,
%   with LPC_ORDER order LPC analysis and peak picking. RO is a
%   parameter that varies between 0 and 1 and it is multiplied by each
%   LP coefficient to make the peaks clearer. It is usually 0.6.

function [f] = formants(x,ro,num_formants,LPC_ORDER,SAMP_FREQ);
 x=filter([1 -1],1,x);

 lpc=ro*durbin(autocorr(x,LPC_ORDER));
 f=roots([1 -lpc']);
 b=abs(SAMP_FREQ/2/pi*log10(abs(f)));
 f=SAMP_FREQ/2/pi*angle(f);
 f=f.*(f>200);
 index=find(f);
 f=f(index);
 b=b(index);
 [b,ind]=sort(b);
 f=f(ind);
 f=sort(f(1:num_formants));
end
```

## A.2 Pitch extraction using autocorrelation

- Step 1. Preprocessing: to remove the side-lobe of the Fourier transform of the Hanning window for signal components near the Nyquist frequency, a soft up-sampling is performed as follows: an FFT is performed on the whole signal; filtering is done by multiplication in the frequency domain linearly to zero from 95% of the Nyquist frequency to 100% of the Nyquist frequency; an inverse FFT of order one higher than the first FFT is then performed.

- Step 2. The global absolute peak value of the signal is computed(see Step 3.3).

- Step 3. Because the method is a short-term analysis method, the analysis is performed for a number of small segments (frames) that are taken from the signal in steps given by the TimeStep parameter (default is 0.01 seconds). For every frame at most MaximumNumberOfCandidatesPerFrame (default is 4) lag-height pairs are found that are good candidates for the periodicity of this frame. This number includes the unvoiced candidate, which is always present. The following steps are taken for each frame:

  Step 3.1. A segment is taken from the signal. The length of this segment (the window length) is determined by the MinimumPitch parameter, which stands for the lowest fundamental frequency that you want to detect. The window should be just long enough to contain three periods (for pitch detection) of MinimumPitch. E.g. if MinimumPitch is 75 Hz, the window length is 40 ms.

  Step 3.2. The local average is subtracted.

  Step 3.3. The first candidate is the unvoiced candidate, which is always present. The strength of this candidate is computed with two soft threshold parameters. E.g., if VoicingThreshold is 0.4 and SilenceThreshold is 0.05, this frame bears a good chance of being analysed as voiceless (in step 4) if there are no autocorrelation peaks above approximately 0.4 or if the local absolute peak value is less than approximately 0.05 times the global absolute peak value, which was computed in step 2.

Step 3.4. The segment is multiplied by a window function (e.g. Hanning).

Step 3.5. Half a window length of zeroes is appended (because autocorrelation values up to half a window length are needed).

Step 3.6. Zeroes are appended until the number of samples is a power of two.

Step 3.7. A Fast Fourier Transform is performed.

Step 3.8. The samples are squared in the frequency domain.

Step 3.9. A Fast Fourier Transform is performed. This gives a sampled version of $r_a(\tau)$.

Step 3.10. This is then divided by the autocorrelation of the window, which must be computed once with steps 3.5 through 3.9. This gives a sampled version of $r_x(\tau)$.

Step 3.11. The locations and heights of the maxima of the continuous version of $r_x(\tau)$ are then found. The only locations considered for the maxima are those that yield a pitch between MinimumPitch and MaximumPitch. The MaximumPitch parameter should be between MinimumPitch and the Nyquist frequency. The only candidates that are remembered, are the unvoiced candidate which has a local strength equal to

$$R \equiv VoicingThreshold + max\left(0.2 - \frac{\frac{(localabsolutepeak)}{(globalabsolutepeak)}}{\frac{(SilenceThreshold)}{(1+VoicingTheshold)}}\right) \tag{A.7}$$

and the voiced candidates with the highest local strength

$$R \equiv r(\tau_{max}) - OctaveCost \cdot log_2(MinimumPitch \cdot \tau_{max}). \tag{A.8}$$

The OctaveCost parameter favours higher fundamental frequencies. One of the reasons for the existence of this parameter is that for a perfectly periodic signal

all the peaks are equally high and we should choose the one with the lowest lag. Another reason for this parameter is unwanted local downward octave jumps caused by additive noise.

After performing step 3 for every frame, a number of frequency-strength pairs ($F_{ni}$,$R_{ni}$) are left, where the index $n$ runs from 1 to the number of frames, and i is between 1 and the number of candidates in each frame. The locally best candidate in each frame is the one with the highest $R$. But as several approximately equally strong candidates can exist in any frame, a global path finder is utilised, the aim of which is to minimise the number of incidental voiced-unvoiced decisions and large frequency jumps.

- Step 4. For every frame $n$, $p_n$ is a number between 1 and the number of candidates for that frame. The values $p_n|1 \leq n \leq numberofframes$ define a path through the candidates: $(F_{np_n}, R_{np_n})|1 \leq n \leq numberofframes$. With every possible path a cost

$$cost(\{P_n\}) = \sum_{n=2}^{numberOfFrames} transitionCost(F_{n-1,p_{n-1}}, F_{np_n}) - \sum_{n-1}^{numberOfFrames} R_{np_n} \tag{A.9}$$

is associated, where the $transitionCost$ function is defined by

$$transitionCost(F1, F2) = \begin{cases} 0 & if\ F1\ unvoiced\ and\ F2\ unvoiced \\ VoicedUnvoicedCost & if\ F1\ unvoiced\ xor\ F2\ unvoiced \\ OctaveJumpCost \cdot |log_2 \frac{F1}{F2}| & if\ F1\ voiced\ and\ F2\ voiced \end{cases} \tag{A.10}$$

where the $VoicedUnvoicedCost$ and $OctaveJumpCost$ parameters could both be 0.2. The globally best path is the path with the lowest cost. This path might contain some candidates that are locally second-choice. The cheapest path can

be found with the aid of dynamic programming, e.g., using the Viterbi algorithm described for Hidden Markov Models by Van Alphen and Van Bergem[44]. For stationary signals, the global path finder can easily remove all local octave errors, even if they comprise as many as 40% of all the locally best candidates. This is because the correct candidates will be almost as strong as the incorrectly chosen candidates. For most dynamically changing signals, the global path finder can still cope easily with 10% local octave errors.

## A.3 Pitch trajectories

### A.3.1 Vowel pitch trajectories

The figures in this section are the complete graphs of the pitch trajectories determined for the long vowels studied.

### A.3.2 Diphthong pitch trajectories

The figures in this section are the complete graphs of the pitch trajectories determined for the diphthongs studied.

## A.4 Expanded formant plots

### A.4.1 Expanded vowel formant plots

The graphs given in this section are the complete versions of the graphs shown in Figures 3.4 and 3.5. The individual utterance means are shown in addition to the

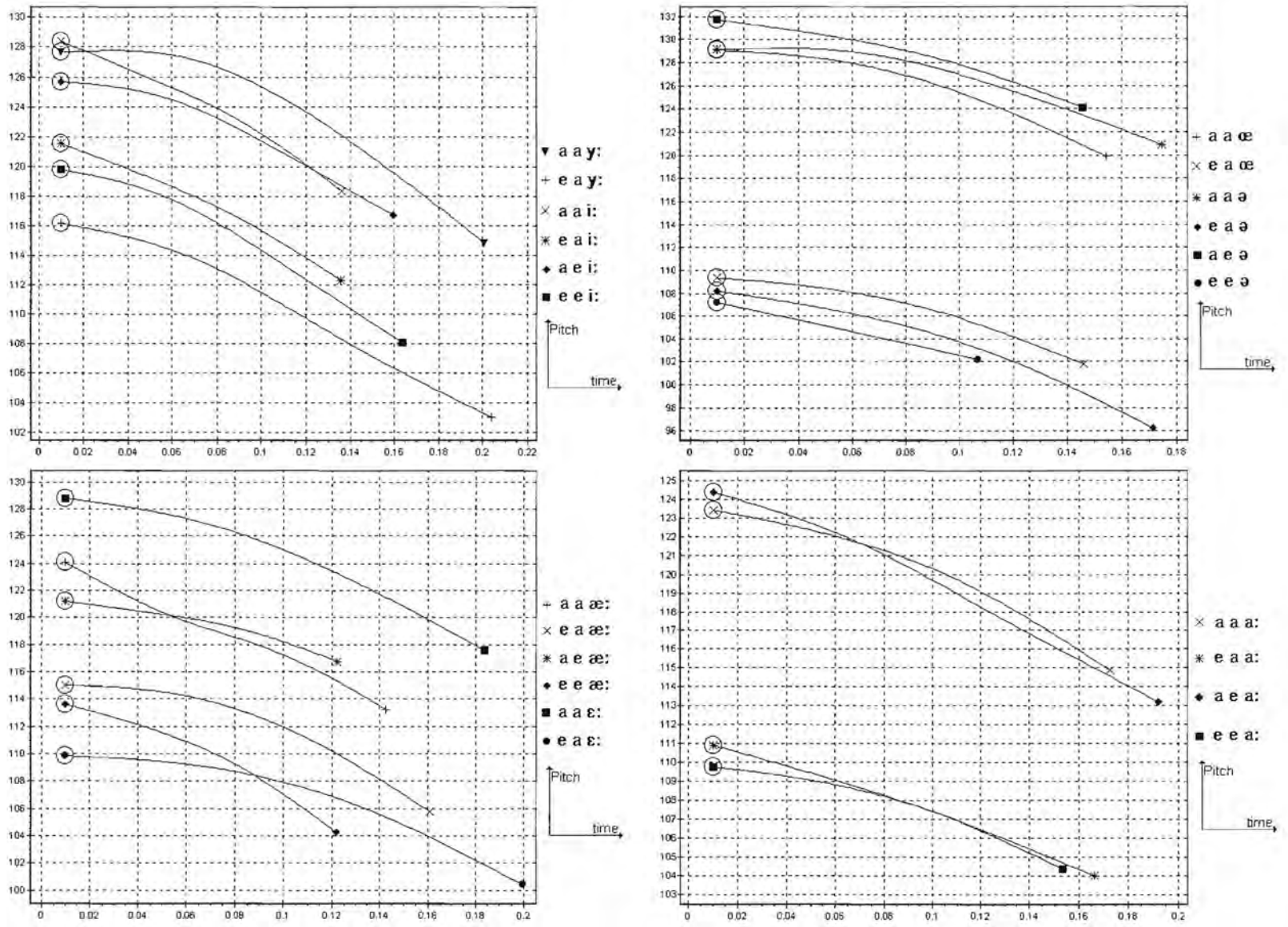



Figure A.1: Vowel pitch trajectories: [<y:> in "*uur*" and also <i:> in "*dier*" and "heat"], [<œ> in "*brûe*" and also <ə> in "*wîe*" and "about"], [<æ:> in "*werk*" and "hat" and also <ɛ:> in "*êrens*"] and [<a:> in "*klaar*" and "father"]. The first $a/e$ indicates the mother-tongue of the speakers and the second $a/e$ indicates from which language the vowel was indicted as coming from.

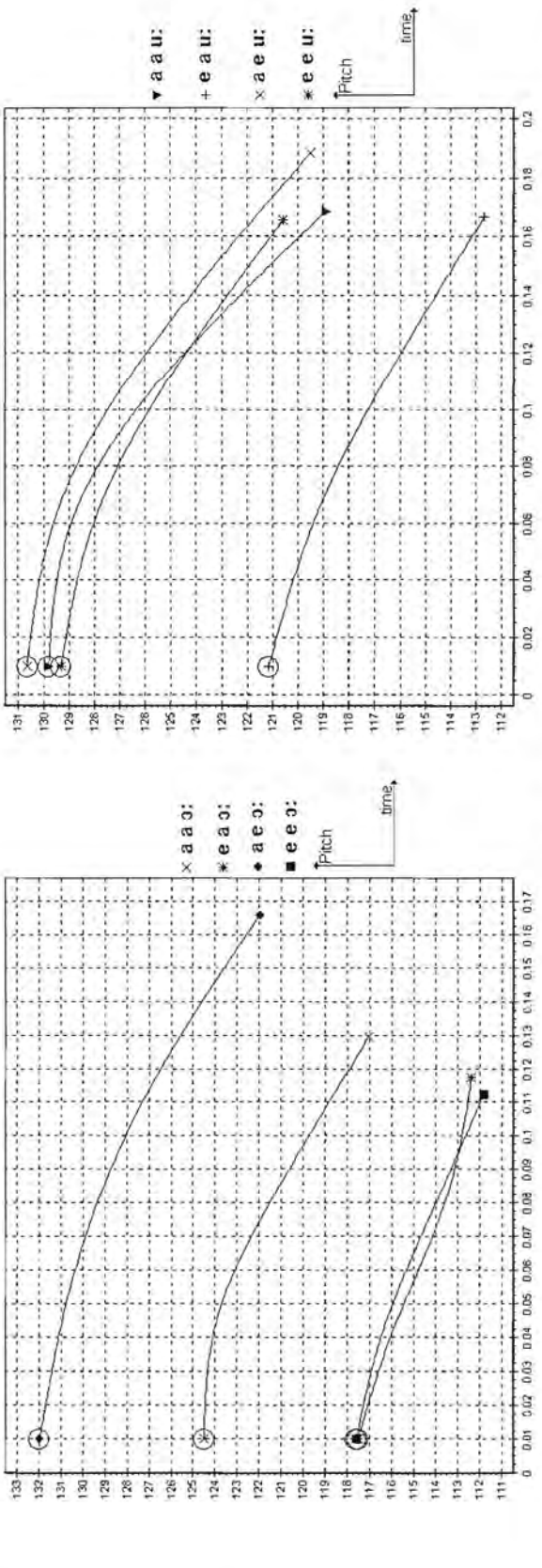



Figure A.2: Vowel pitch trajectories: [<ɔ:> in "*dom*" and in "bought"] and [<u:> in "*boer*" and "soon"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from.

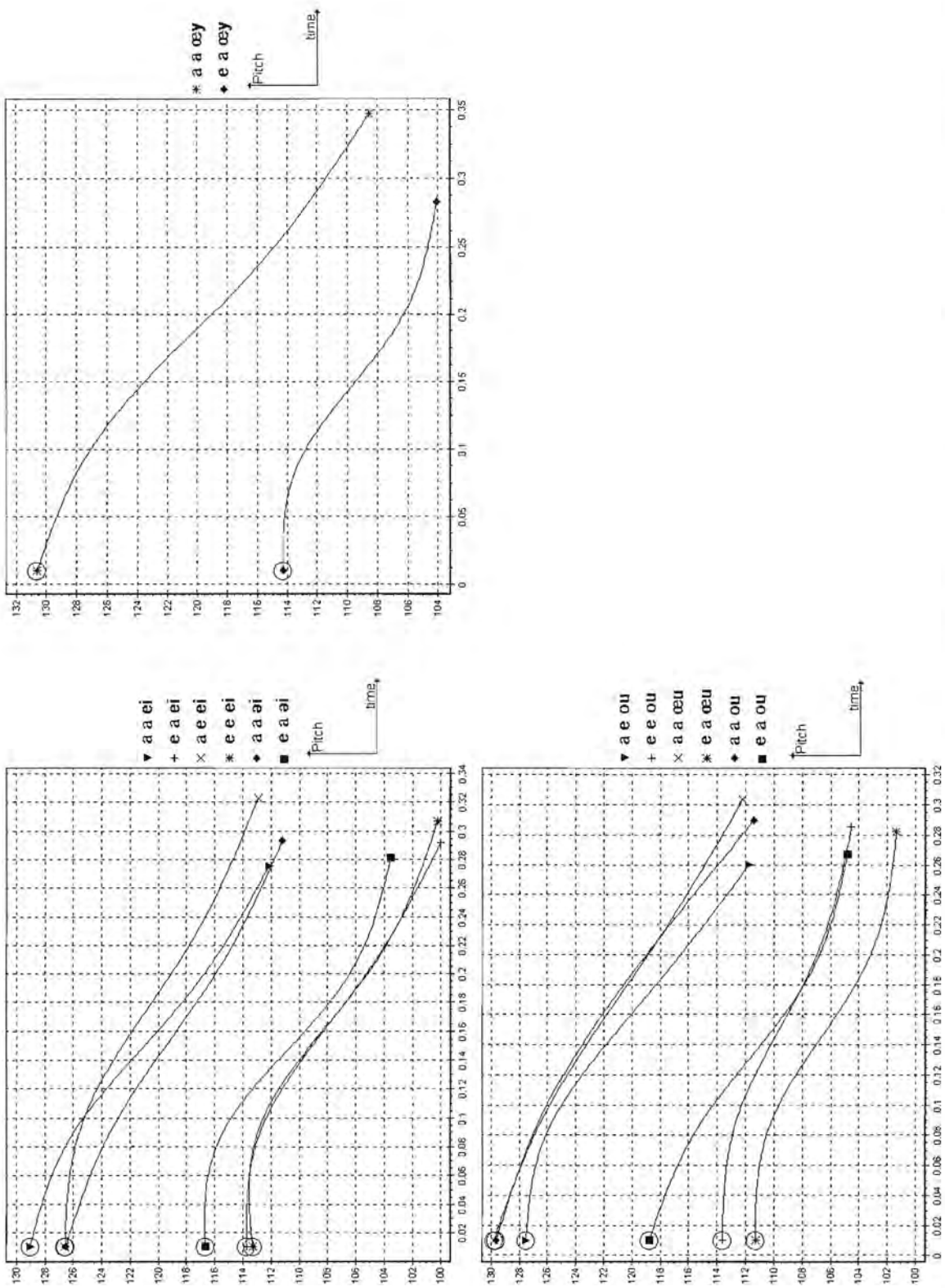



Figure A.3: Diphthong pitch trajectories: [<ei> in "*ryk*" and "play" and also <əi> in "*bly*"], [<œy> in "*trui*" ] and [<ou> in "*gou*" and "home" and also <œu> in "*blou*"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from.

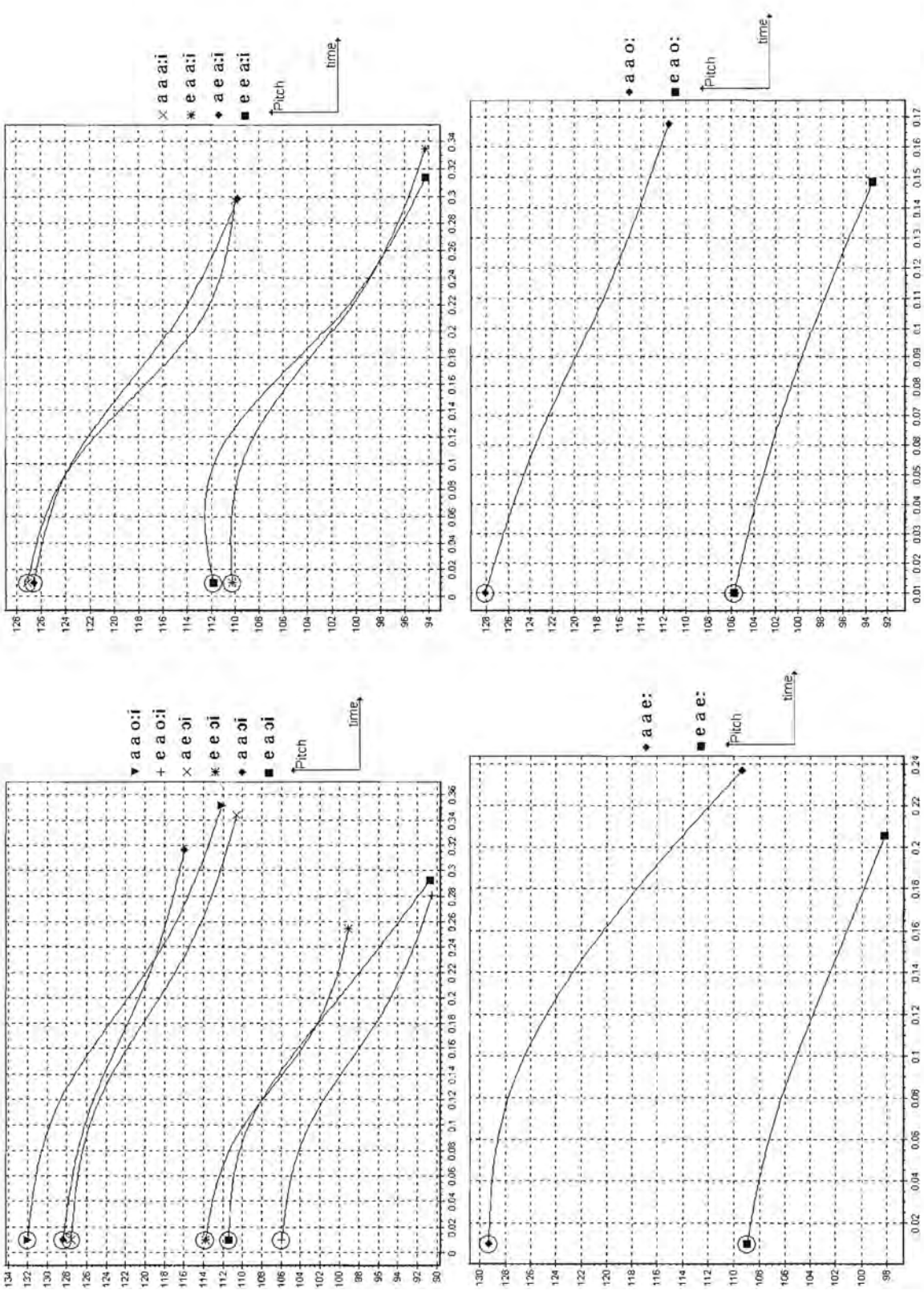



Figure A.4: Diphthong pitch trajectories: [<o:i> in "*moot*" and also <ɔi> in "*hondjie*" and "boy"], [<a:i> in "*haai*" and "time"], [<e:> in "*bees*"] and [<o:> in "*kool*"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from.

global mean and variance as in the the simpler figures.

## A.5 Compact Disk Contents

The attached compact disk contains the following:

- The data recorded, labelled and used in the study.
- This dissertation in GZipped PostScript form.
- C Programmes

  Wyre: The programme used to segment and label the data.

  DataPlay: The programme used to play back the segmented sections for audio verification.

  DataSort: The programme used to split the data from speakers into language groups.

  Pitch: The programme used to convert Praat style pitch trajectory files into files suitable for GPlot.

  GPlot: The programme used to plot the mean vowel locations, variance bubbles, diphthong trajectories and perform analysis of variance comparisons.

- Matlab Programmes

  General: A number of programmes used to plot the results from research done in previous studies.

  SPTool: The programme used to verify that the extracted formants are correct when compared to the spectrograms.

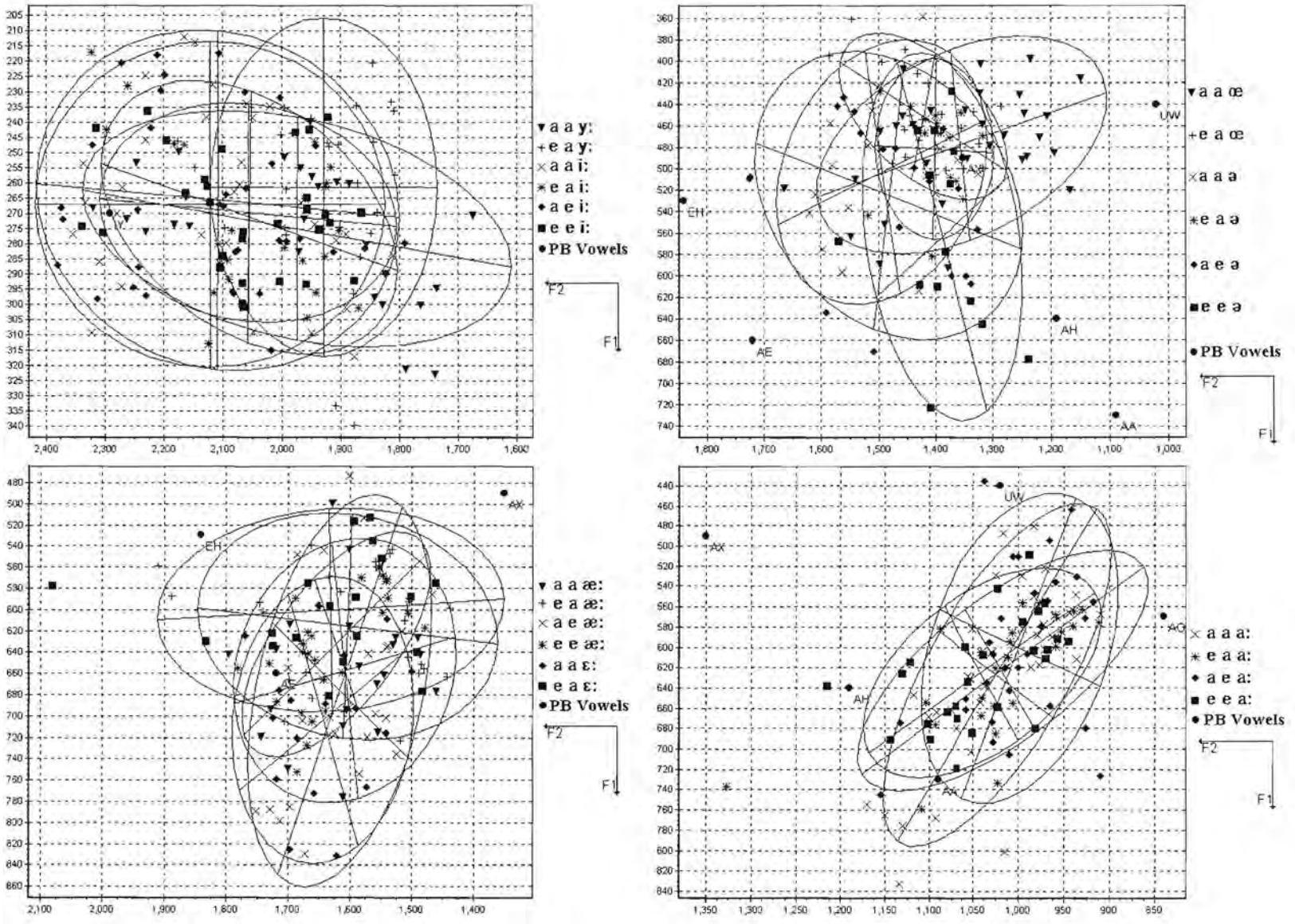



Figure A.5: Vowel formant clusters: [<y:> in "*uur*" and also <i:> in "*dier*" and "heat"], [<œ> in "*brûe*" and also <ə> in "*wîe*" and "about"], [<æ:> in "*werk*" and "hat" and also the incorrectly used <ɛ:> in "*êrens*"] and [<a:> in "*klaar*" and "father"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from.

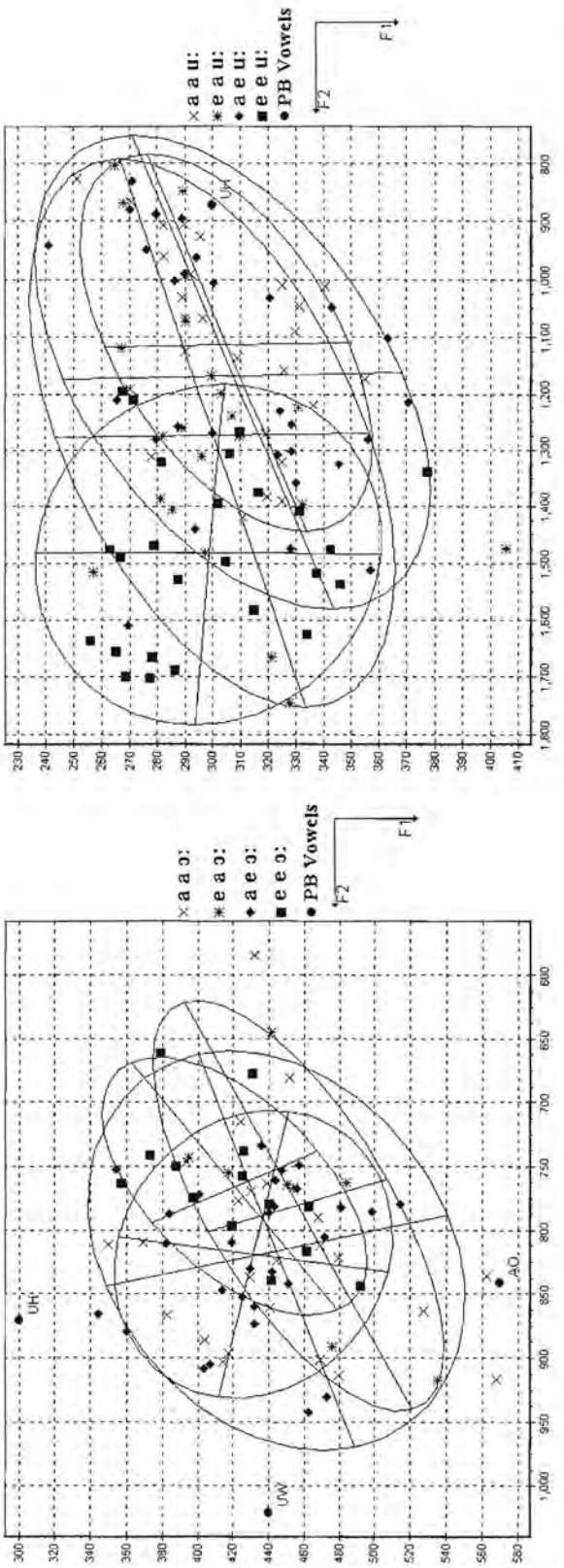



Figure A.6: Vowel formant clusters: [<ɔ:> in "*dom*" and in "bought"] and [<u:> in "*boer*" and "soon"]. The first *a/e* indicates the mother-tongue of the speakers and the second *a/e* indicates from which language the vowel was indicted as coming from.

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