Acoustical features of diphthongs in Afrikaans

Heidi Raubenheimer, M.A.

Thesis submitted in fulfillment of the requirements for the degree Philosophiae Doctor in the Department of Afrikaans and Dutch in the Faculty of Arts of the Potchefstroomse Universiteit vir Christelike Hoër Onderwys.

Promoter: Professor D.P. Wissing

Potchefstroom

1998

Acknowledgements

My promoter, Prof. Daan Wissing, for his guidance, hard work and motivation.

Dr. Wim Peeters of the RUU in the Netherlands for sharing his expertise on diphthongs.

My husband Kobie, for his continual encouragement, as well as his assistance with the mathematical and statistical aspects of the study.

My father, mother and Johan for their support and financial assistance.

The CSD, Stichting Studiefonds and Nederlandse Taalunie for bursaries for doctoral research in South Africa and in the Netherlands.

The financial assistance of the Centre for Science Development (HSRC, South Africa) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and not necessarily to be attributed to the Centre for Science Development.

Dedicated to Johan

Table of Contents

List of Figures

List of Tables

Chapter 1: INTRODUCTION

1.1 INTRODUCTION

For many years the problematical nature of diphthong research has been widely acknowledged. In this study the acoustical features of diphthongs in Afrikaans are researched. To accomplish this, the spectral aspects and the temporal aspects in so far as they are relevant to the study of the spectral aspects of natural diphthongs in production tests, are studied. The results obtained in this test are used to synthesise diphthongs for a perceptual evaluation by a group of listeners. In this chapter the statement of the problem, the objectives of the study and the method of research are portrayed.

1.2 STATEMENT OF THE PROBLEM

Acoustical phonetics is the study of the physical properties of spoken language and comprises of both spectral and temporal aspects. Information on this subject is not only of theoretical importance (deducing facts about the nature and organisation of speech production, speech perception and phonological theory (Klatt, 1974)), but also of technological importance, (text-to-speech conversion, reading aids for the blind, talking aids for the vocally handicapped (Klatt, 1987; Kent & Read, 1992), as well as of educational importance (second language training aids).

Apart from studies by Wissing and Burger (1991), Wissing (1992), Raubenheimer (1994), Wissing and Raubenheimer(1994), and Wissing and Zonneveld (1996) on the temporal aspects of vowels, and Van Wyk (1983), Taylor and Uys (1988), Van der Merwe et al. (1993) and Wissing and Coetzee (1996) on the spectral features, not much research has been done on this aspect of Afrikaans which indicates a decided lack in our knowledge.

Gay (1968), Pols (1977), Toledo and Antonanzas-Barroso (1987), and Nabelek et al. (1996) studied the spectral aspects of diphthongs of various languages. Spectral aspects comprise of fundamental frequency (F0), amplitude, formant frequency and bandwidths. The latter do not influence the phonemic quality of steady state vowels (Peeters, 1991:108), but are important as far as dynamic sounds (diphthongs) are concerned. Only Peeters (1991) presents bandwidth data for dynamic sounds. It has already been stated that very little spectral analyses have been done for Afrikaans, and none has been done on bandwidths. Research in this area can be of great value for Afrikaans, as well as for general language theory.

According to Gerrits (1995), much research has been done during the past 15 years on the acoustic-dynamic character of the diphthong. In general, diphthongs consist of an initial steady state, a transition and a terminal steady state (Lehiste & Peterson, 1961; De Manrique, 1979; Bond 1982; Gottfried ET al., 1993). This requirement that diphthong productions possess two steady state target positions appears unduly restrictive, in particular, when different speaking rates are considered (Gay, 1968). At slow and moderate speaking rates the presence of two steady state components and a glide were noted, whereas at a fast speaking rate either the first or second steady state were often found to be neglected or not present at all (Gay, 1968). Gottfried et al. (1993) state that there is generally variability found in respect to the vowel positions at which the diphthongs begin and end, but it is still maintained that the initial and final portions of diphthongs provide acoustically relevant information.

In studying the acoustic properties and auditory perception of diphthongs one finds three different points of view: **the target theory**, the **trajectory theory** as well as the **temporal formant pattern**.

According to the **target theory** the onset and offset values of the formant frequencies determine the perception of a diphthong (Bladon, 1985). Neary and Assmann (1986) present a 'dual target' hypothesis in which two explicit vowel targets are required to specify a diphthong. Bladon (1985) tested the target theory and found that the onset and offset formant frequencies are important in the perception of diphthongs. On the other hand, Bond (1982) found that a diphthong is still perceived as a diphthong when the steady state components are shortened significantly and the glide component is lengthened (cf. 2.2.2 for a detailed discussion on constructs such as steady state and glide components).

The point of departure of the **trajectory theory** is that the rate and direction of the formant transition is characteristic for diphthongs (Gay, 1968). Gay found that particular diphthongs showed little variation in the rate of F2 transition across changes in tempo and therefore stated that the duration of the transition is a primary cue in perception of a diphthong. Dolan and Mimori (1986) reported the same pattern as Gay for F2 - the rate of transition increased significantly with increase in tempo. Toledo and Antonanzas-Barroso (1987), on the other hand, found significant differences in the duration of F2 in different speaking rates.

During the past few years a shift in direction has occurred in the research being done on the acoustic properties of diphthongs. Instead of studying the separate diphthong components in the formant pattern, the **total temporal formant pattern** is now studied (Cao, 1991; Peeters, 1991; Gerrits, 1995). According to Peeters (1991), the distinctive temporal pattern of the diphthong is a combination of diphthong components.

In studies by Cao (1991), Peeters (1991) and Stollwerck (1991) the following conclusions on diphthongs are stated:

1) The articulation movement of the diphthong is a systematic movement in the time domain;
2) The temporal formant pattern of the diphthong is language specific;
3) The temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously.

Peeters (1991:100) states that the results of production tests have to be tested perceptually because "...within the speech chain perception plays the decisive part...". Acoustic patterns are complex and constantly changing. Borden and Harris (1984) ask the question whether the listener uses all the information or are there parts of the acoustic signal that are more important than other parts. Synthetic diphthongs used in listening tests reveal that gliding formants are sufficient acoustic cues for the identification of diphthongs (Borden & Harris, 1985). Natural diphthongs in production tests should be studied in Afrikaans and these tests must also be verified by means of perception tests. It would also be very important in future research to compare results obtained for Afrikaans diphthongs with those in other languages, especially those in recent studies of German and Dutch diphthongs.

The following questions have to be addressed:

1) What are the spectral features: F0, amplitude, formant frequencies and bandwidths of diphthongs in Afrikaans?

2a) What do the formant patterns of diphthongs in Afrikaans look like?

2b) If a specific pattern is found (for example, onset steady state, glide, offset steady state), would another pattern (for example, onset steady state, offglide etc.) also be acceptable to the listener?

2c) Which of the following: the target theory, the trajectory theory or the temporal formant pattern is more likely to describe diphthongs unambiguously?

1.3 OBJECTIVES OF THIS STUDY

1.3.1 GENERAL OBJECTIVE

The general objective of this research is to shed more light on the spectral and, to a lesser degree, the temporal aspects of diphthongs in Afrikaans in a production test as well as a perception test.

1.3.2 SPECIFIC OBJECTIVES

The specific objectives of this study are to determine:

1) the spectral aspects of the first three formants (F1-F3, amplitude, B1-B3, F0) of diphthongs in Afrikaans,

2a) the formant patterns of diphthongs in Afrikaans,

2b) perceptually whether, if a specific pattern is found (for example onset steady state, glide, offset steady state), another pattern (for example onset steady state, offglide etc.) would also be acceptable to the listener.

2c) which of the following, the target theory, the trajectory theory or the temporal formant pattern is more likely to unambiguously describe Afrikaans diphthongs.

1.4 HYPOTHESIS

Due to the absence of complete and systematic information on the spectral features of diphthongs in Afrikaans no specific hypothesis is given. With reference to studies of Dutch, which is related to Afrikaans, a general hypothesis is stated that the temporal formant pattern of a diphthong, rather than absolute onset and offset formant frequencies, (spectral pattern - the target theory) or the rate and direction of change (the trajectory theory), is the dominant factor which provides the language-specific cues in the perception of Afrikaans diphthongs (cf. Chapter 2).

1.5 SHORT REVIEWS OF EACH CHAPTER

This study is divided into a literature survey and a production and perception study.

In Chapter 2 the theoretical background of the study is stated. The two traditional points of view for the study of diphthongs, the target theory and the trajectory theory, are investigated. This is followed by a discussion of the temporal formant pattern of diphthongs.

In Chapter 3 the method of research of the production test is described. The stimulus material, the choice of subjects, the apparatus, the data collection and measuring procedures as well as the data analysis and statistics are discussed. Finally the results of the production test are given and a discussion and interpretation of the results follow.

In Chapter 4 the perception test is discussed. Firstly, the available literature is reviewed, whereafter the method of research follows. The stimulus material, the subjects chosen for the perception test, the data collection procedure as well as the data analysis and statistics are then given. This is followed by the results of the perception test and a discussion and interpretation of the results.

The final chapter consists of the conclusions.

Chapter 2: DIPHTHONGS: ACOUSTIC AND AUDITORY PERCEPTION RESEARCH

2.1 INTRODUCTION

In this chapter the theoretical background of the research is presented.

According to Peeters (1991), the start of electro-acoustical analysis in experimental phonetics in the twenties of this century concluded an era of approximately sixty years of physiological and physical research. He claims that researchers have been conducting studies in experimental phonetics for many years, and the same applies to studies in acoustic phonetics that is a part of experimental phonetics.

Acoustic phonetics is a part of experimental phonetics and it includes, in a broad sense, both the theory of speech as wave motion, as well as how speech waves are produced and heard. It is also concerned with the relations of sound waves to other aspects of the speech communication act (Fant, 1973; Picket, 1980).

Information on this subject is not only of theoretical importance (deducing facts about the nature and organisation of speech production, speech perception and phonological theory, (Klatt, 1974)) as well as general communication theory (Picket, 1980), but also of educational (second language training aids) and technological importance. One aim of technical speech research is to lay a foundation for techniques for producing artificial speech and of machine identification of spoken words (Fant, 1973; Clark & Yallop, 1995). Applications are: more efficient speech communication systems, synthetic speech, voice identification, automatic recognition of speech, reading aids for the blind and means of visual and tactile recording of speech for communication with the deaf (Fant, 1973; Picket, 1980; Klatt, 1987).

In the next section a description of diphthongs, in general, and Afrikaans diphthongs, in particular, precedes a discussion of the target theory, the trajectory theory as well as the temporal formant pattern.

2.2 DIPHTHONGS

2.2.1 INTRODUCTION

According to Bladon (1985:145) "...we find a clear conflict in the literature concerning the relative perceptual weight of different components of a diphthong..." and he asked the question: "Does the listener attend to a diphthong's endpoints or to its spectral rate of change?" This quote underlines the problematical nature of diphthong research.

Several researchers point out the problematical nature of diphthong research. Afrikaans diphthongs constitute an especially controversial aspect of the Afrikaans vowel system. During the past few years much research has been done on the acoustic dynamic character of diphthongs, but this aspect of Afrikaans has been neglected and there is a lack in our knowledge of Afrikaans diphthongs. Since this study researches the acoustical characteristics of diphthongs in Afrikaans, the next part of this chapter is committed to diphthongs.

Introductory remarks on diphthongs in general, as well as Afrikaans diphthongs in particular, are followed by the acoustic and auditory perception research on diphthongs. From the available literature it is clear that opinions differ greatly concerning the investigation of the acoustic properties and auditory perception of diphthongs. The three different points of view; the **target theory**, the **trajectory theory,** as well as the **temporal formant pattern** are discussed and critically evaluated.

2.2.2 DIPHTHONGS IN GENERAL AND AFRIKAANS DIPHTHONGS IN PARTICULAR

According to Gottfried (1993) and Gerrits (1995), diphthongs are not only difficult in pronouncing, but the study of diphthongs is also quite complex. This is also true for Afrikaans diphthongs. Van Rensburg (1979), Uys (1981), and Taylor and Uys (1988) claim that diphthongs constitute a controversial aspect of the Afrikaans vowel system.

Phonetically speaking, a diphthong consists of two sound segments, namely a vocalic element that is followed by an element with a semi-vocalic character (Combrink & De Stadler, 1988; Odendal, 1989). On the other hand, the traditional componential view of diphthongs is that a diphthong is a combination of two vowels with a connecting glide (Peeters, 1991). Peeters also states that the latter view cannot be upheld since acoustically we see that the second vowel-like sound is very different from its isolated counterpart.

In this regard Gerrits (1995) declares that it is impossible to associate the beginning and end formant frequencies of a diphthong with that of the monophthongs with which they are transcribed. According to Pols (1977), none of the three genuine Dutch diphthongs reaches the vowel position indicated in its phonetic transcription. Pols also notes that the acoustic variability of these diphthongs is very large.

The phonetic properties of diphthongs change in the course of their realisation, but despite their non-homogeneous character they are felt to be unitary segments. Germanic diphthongs, of which the Afrikaans diphthongs are also part of, are unitary speech events in a physiological, acoustical, perceptual and conceptual sense (Peeters, 1991).

On a phonological level there is a distinction between **phonemic** and **non-phonemic** diphthongs. According to Wissing, (1971) and Combrink and De Stadler (1988), this distinction is also made for Afrikaans diphthongs. There are seven phonemic diphthongs in Afrikaans namely: [ɔi], [œy] [Ai], [Oi], [ui], [œu] and [Eu] (Wissing, 1971:52; Combrink & De Stadler, 1988:27).

Wissing (1971), Pols (1977), Collier et al. (1982), Combrink and De Stadler (1988), and Peeters (1991) distinguish between **genuine** ('echte/egte') and **pseudo** ('onechte/onegte') diphthongs, where the genuine diphthongs stay the same under all phonological circumstances, in contrast with the pseudo diphthongs which change.

The genuine diphthongs in Dutch are /au/, /ui/ and /ei/ (Pols, 1977; Collier et al., 1982). The results of Collier et al.'s research on Dutch diphthongs showed that genuine diphthongs behave more like unitary segments, while pseudo diphthongs behave like a sequence of two segments. They also found that the genuine diphthongs are characterised by relatively continuous and gradual changes in formant structure, whereas the pseudo diphthongs are produced with more abrupt changes in formant structure.

Taylor and Uys (1988) claim that the descriptions of Afrikaans diphthongs are probably based on accounts of Dutch. According to the available literature three genuine diphthongs in Afrikaans namely [ɔi], [œy] and [œu] can be distinguished (Wissing, 1971; Van Wyk, 1979; Coetzee, 1981; Combrink & de Stadler, 1988), as well as a number of pseudo diphthongs. In Afrikaans we also find diphthongs which are formed via diphthongisation such as [∈j] in bedjie (Combrink & De Stadler, 1988).

A third class of Afrikaans diphthongs can also be distinguished. These occur through the dipthongisation or 'breaking' of the long vowels [E], [O] and [Ø] (Combrink & De Stadler, 1988). This results in [E] becoming [iɔ] as in 'nee', [O] becoming [uɔ] as in 'boom' and [Ø] becoming [yɔ] as in 'steun'.

Lehiste and Peterson (1961:277) define a diphthong as follows "...a diphthong is a vocalic syllable nucleus containing two **target** positions...". The extent of the vowel 'target' is the time interval within the syllable nucleus where the formants are parallel to the time axis. Parameters, which are considered important in the so-called 'targets', are **rate of formant change** and **slope of transition**. The rate of formant change is the frequency range in cycles per second through which the formant moves in a given time interval (Lehiste & Peterson, 1961:273). The slope of transition is seen as criteria for distinguishing between diphthongs and glides (Lehiste &

Peterson, 1961:274). For years these parameters dominated acoustical and perceptual research (Peeters, 1991).

It is evident from the available literature that diphthongs have been described and defined in numerous, often contradictory ways and the study of diphthongs has been approached from various angles (Stollwerck, 1991). Lehiste and Peterson (1961) describe two types of complex syllable nuclei or diphthongs; **single-target** diphthongs (**non-phonemic**) which consist of only one component and **double-target** diphthongs (true or **phonemic**).

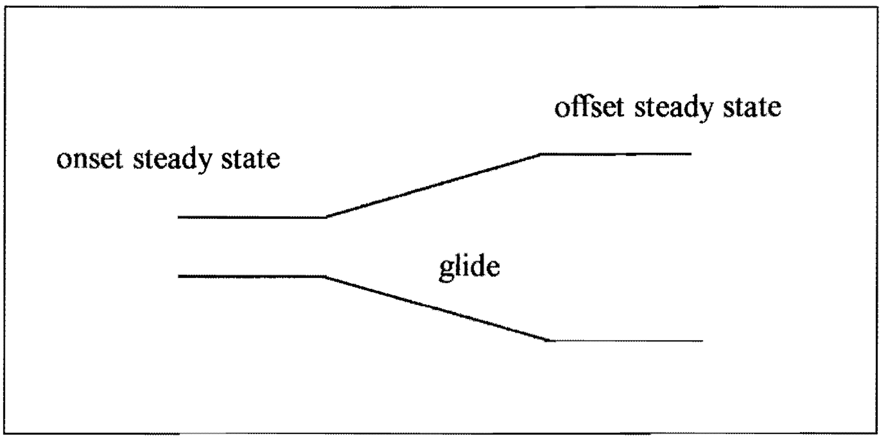


Figure 1: The three components of formants 1 and 2 of a diphthong

Bond (1982) mention that **non-phonemic** diphthongs have one component, while **phonemic** diphthongs consist of three components, and initial and a final steady state portion and a glide portion (cf. Figure 1).

The **steady state** component is the portion where the formant frequency stays relatively constant (Lehiste & Peterson, 1961; Bond, 1982; Gottfried et al., 1993). Pols (1977) states that a diphthong can be described as quite a long steady state onset part followed by a fast specific transition to an offset area where no steady state part is necessary.

Gay (1968) found that, dependent on the speaking rate, these components can vary. At a slow speaking rate the two steady state components are present, the initial steady state and the final steady state, but at a fast speaking rate either the first or the last steady state can be neglected (Gay, 1968). This is also supported by Pols' (1977) results.

Peeters (1991) concludes that a diphthong consists of the following combinations:

1. steady state + transition + steady state
2. steady state + transition
3. transition
4. steady state + steady state

Since the pioneering vowel study by Peterson and Barney (1952), it has been a widely held view that the main acoustic determinants of vowel quality are the frequencies of the two lowest formants. This is the result of the different shapes of the vocal tract. The results of numerous matching experiments have confirmed this notion's perceptual validity (Aaltonen, 1985). F1 and F2 are also of vital importance in determining the acoustic quality of diphthongs. This is significant for this investigation, especially as far as the perception test is concerned.

Traditionally, the descriptive study of diphthongs has focused on "...articulatory-acoustic impressionistic characterisations, grouping diphthongs into vowel triangles or quadrangles..." (Stollwerck, 1991:2) which can be described as static in the sense that they give the onset and offset values, but do not provide specification of the intrinsic dynamic properties of the diphthong.

In the following paragraphs the target theory is discussed and critically evaluated, whereafter the trajectory theory is reviewed. A discussion and evaluation of the temporal formant pattern of diphthongs follows.

2.2.3 THE TARGET THEORY

"Some investigators have sought to describe diphthongs with respect to sections isolated from a particular production, which correspond to vowel targets" (Gottfried et al., 1993:206). These targets are essentially the steady state portions of the diphthongs. From this point of view the diphthong is characterised by an initial steady state, a glide and a terminal steady state (Lehiste & Peterson, 1961). They found that the diphthongs [ɔi], [ai] and [au] in American English usually contain both initial and terminal steady states. According to the target theory, the initial (onset) and final (offset) values of the formant frequencies determine the perception of a diphthong (Gerrits, 1995).

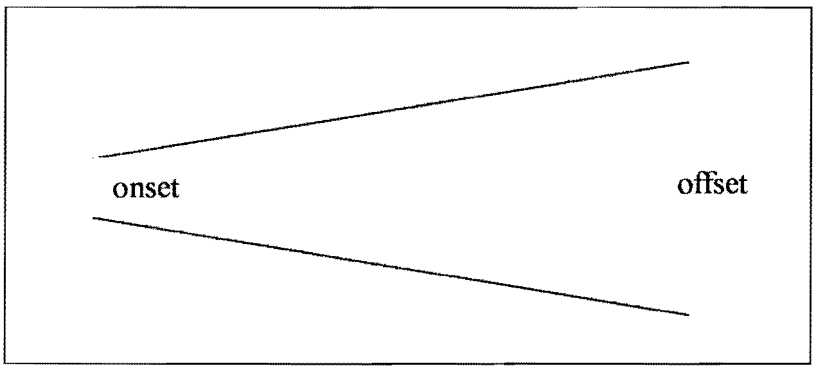


Figure 2: Graphic presentation of the target theory

Gottfried et al. (1993) claim that the practice of transcribing diphthongs as a sequence of two monophthongs suggest that the diphthongs may in part be characterised in terms of formant values which identify these monophthongal segments. However, it appears that there is variability in respect to the vowel positions at which the various diphthongs begin and end. They further state that one can hypothesise that diphthongs are distinguished in terms of initial and final steady states which need not coincide with any monophthong. They call this the 'dual target' hypothesis.

Slis and Katwijk (1963) conducted a perceptual study on Dutch diphthongs and found that perfectly identifiable diphthongs can be synthesised without any transitions. If the duration and amplitude of the two steady state segments are properly dimensioned, the identity of the diphthong is fully determined by the quality of their initial and final steady state parts, which have to be within specific tolerance regions. They maintain that if the formant transitions are not necessary for the identification of a diphthong, they still might have perceptual relevance with regard to its naturalness and acceptability. Collier and 't Hart claim that the target theory was confirmed by Slis and Katwijk's results.

Gerber (1971) studied diphthongs in various languages and found that analyses of diphthongs in these different languages showed no variation in the final frequencies of the formants. This means that the end formant frequency is not a distinctive characteristic of the diphthong.

Bond (1978, 1982) tested the validity of the target theory. Bond (1982) studied the effects of steady state and glide duration on the identification of diphthongs. He varied the durations of the steady states and glides in his experiments and found that although the duration of the components can vary considerably the diphthongs were still recognised with great ease. The stimuli in Bond's study consisted of a very short transition (10 ms) with two relatively long steady state components. He found that when the glide was short and the two steady states were long, the majority of the tokens were identified as diphthongs. Because these diphthongs were well identified by listeners he concluded that the initial and final formant frequencies are important in the identification of diphthongs.

On the other hand, Bond (1982) found that when he increased the duration of the transition component in the stimulus words and the duration of the steady state components were relatively short, the diphthongs were still recognised by listeners.

Bond (1982), therefore, came to the conclusion that in order to identify vocalic nuclei as diphthongs, listeners need two targets: either a glide beginning and ending at those targets, or alternatively, the targets without a detectable glide proving to be sufficient. This is in accordance with Pols' (1977) results, where he found that the absolute values of the formant frequencies of diphthongs could vary considerably.

Peeters criticised Bond saying that due to his "...implicit violation of the language-specific relationship of intrinsic inner-component length categories ...only a deformed diphthong definition could emerge" (Peeters, 1991:90). A diphthong is resistant to manipulations and when diphthong components are lengthened or shortened all components are involved. Since Bond (1982) did not take this into account it seems that Peeters' criticism is valid. Another point of criticism is the very short glide of 10 ms that Bond used. It is not physiologically possible for a human being to produce such a short glide.

The Bladon (1985) study's first objective was to clarify the issue 'target' versus 'trajectory' in the perception of diphthongs. In his experiments he explicitly tested the target theory. From the results of the first experiment it was evident that the initial and final formant frequencies are very important for the perception of the diphthong.

In his second experiment he found that a diphthong can remain 100% recognisable when the transition segment was removed from the initial steady state/ transition/ final steady state combination. In this experiment the transitionless diphthongs sounded remarkably natural.

In the third experiment Bladon's results showed that when the steady state components were removed and only a transition was presented, confusion occurred when listeners tried to identify diphthongs from their transitions alone. Only 46% of the stimuli were recognised by the listeners.

Bladon (1985:153) came to the conclusion that, "...what determines the perceived diphthong identity are the endpoints attained and not the trajectory through the auditory space..." and that the absence of the transitional material in a diphthong left its identity totally unimpaired.

The results of the experiments, yielding a preference for the target theory over the trajectory theory, must be doubted according to Peeters (1991), since there are a number of problems with

Bladon's experiments. In his first experiment Bladon used vowel combinations which do not represent English diphthongs and, therefore, the results cannot simply be applied to genuine diphthongs. Peeters (1991) regarded the design of his second experiment, where Bladon presented his listeners "transitionless" or "glide-only" stimuli as likewise defective due to the incorrect application of the segmentation technique.

Bladon's findings were confirmed in the research of Gottfried et al. (1993). They tested the target theory (they called it the **onset + offset hypothesis**) and found that classification performance for the onset + offset hypothesis remained very high (more than 90%).

It is evident in the literature that different researchers have studied the defining of diphthongs according to the target theory. But although various researchers' results confirmed the validity of the target theory, just as many contradicting results showed that it is not possible to define a diphthong completely by only using the target theory. The trajectory theory is now discussed.

2.2.4 THE TRAJECTORY THEORY

Contrary to the target theory, where steady state components are important in defining diphthongs, the trajectory theory departs from the point of view that the **rate** (Figure 4) and **direction** (Figure 3) of the **formant transition** is essential in the perception of a diphthong (Gerrits, 1995).

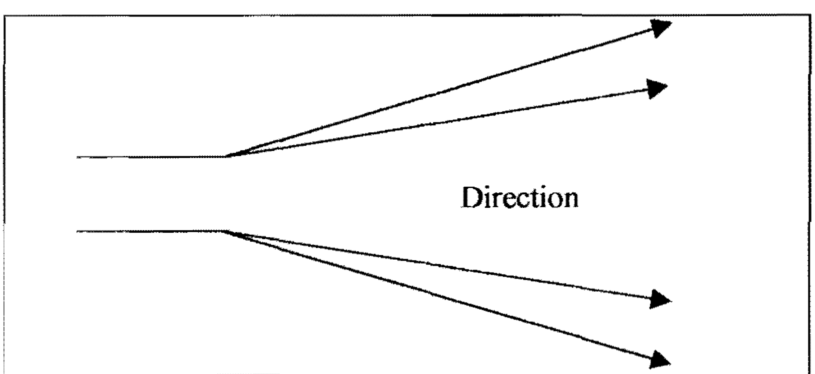


Figure 3: Graphic presentation of the trajectory theory – direction of change

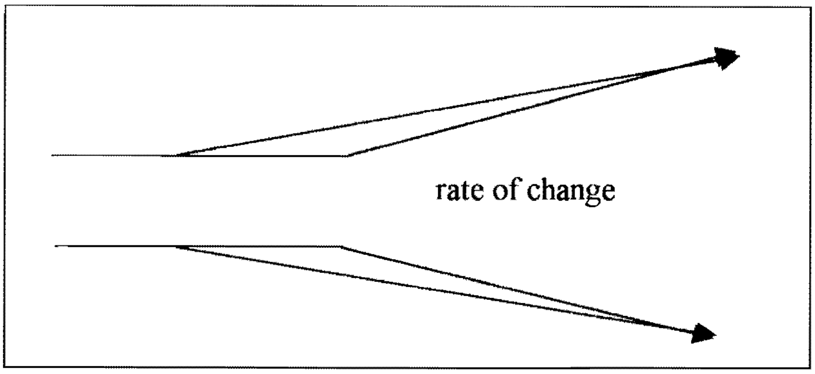


Figure 4: Graphic presentation of the trajectory theory – rate of change

According to Bladon (1985), the best known 'advocate' for the trajectory theory is Thomas Gay. Gay (1967; 1968; 1970) conducted several studies to research the effect of the direction and the rate of change of the glide components on the perception of American English diphthongs.

Gay (1967; 1968; 1970) maintained that the primary feature of American English diphthongs is a gliding movement, which in itself is sufficient for providing diphthongal quality. Borden and Harris (1984) also state that synthesised diphthongs used in listening tests reveal that gliding formants are sufficient acoustic cues for identification. Usually these gliding movements are described primarily in terms of onset and offset frequencies.

Gay (1967) conducted two experiments to analyse the effects of formant frequency movement on the perception of American English diphthongs as well as the effect of overall glide duration. From these results Gay deduced that transition duration rather than change in frequency of F2 was of primary importance for diphthong identification, leading him to conclude that the rate of formant change was a fixed feature of the diphthong trajectory.

In Gay (1968) the influence of the speaking rate on the different components of the diphthong was researched. Gay systematically varied the duration of the F2 glide. His results showed that the rate of change of the transition component of the second formant (F2) varied slightly under the influence of the speaking rate. He came to the conclusion that the duration of the transition is a primary cue that distinguishes the diphthong from other speech sounds. He also found that the rate of change of the F2 is a fixed feature in the diphthong formant movement, while the offset target may or may not be reached, depending on the speaking rate.

He considered Gay's (1967) **transition duration** as a primary cue to distinguish between vowels and diphthongs and the rate of change as the most important feature for differentiation of the various diphthongs among themselves.

The purpose of Gay's (1970) second experiment was to determine whether the phonetic identity of the targets, or the absolute course of the F2 transition serves as primary identifying cue in diphthongs. He maintains that diphthongs show a gliding movement along a particular path in the vowel space between zones appropriate to two different vowels (Gay, 1970:65). His results indicate that the rate of formant frequency change is a fixed feature of the diphthong movement and that the data show that the specific course of the glide, rather than the locations of the targets, serve as primary distinguishing cue.
He further claimed that the "non-essential characteristics of such steady states for diphthong identification..." (Gay, 1970:76) were underlined in this study. He found, however, that some form of steady state is usually present in real speech.

Peeters (1991) detected several shortcomings in Gay's test set-up and criticised the fact that in eliminating either the initial or final portion of the transition the structure of the diphthong as a perceptual unit was violated.

Nooteboom (1972) also studied the direction of the formant transition of Dutch diphthongs. His results indicated the following:

1. The F1 changes during the whole of the duration of the diphthong in one specific direction.
2. The direction of the change of the formants (the trajectory theory) of the diphthong is more important to distinguish between diphthongs than the frequencies of the end point (target theory).

Therefore it can be stated that Nooteboom's results favour the trajectory theory above the target theory.

It has been suggested that the rate of change rather than the absolute F2 frequency is the primary acoustic cue for diphthong recognition (Gay, 1970). De Manrique (1979) obtained similar results. De Manrique analysed 14 Spanish diphthongs under two different speaking rates and the rate of change of the F2 transitions were obtained. Results show that the formant pattern, rate of change and temporal relations between both steady states contribute to the characterisation of Spanish diphthongs.

It was also found that the frequency position of the steady states of Spanish diphthongs undergoes a considerable shift from the target values. Furthermore, either one or both vowel segments may not reach a steady state. This depends on the speaking rate. In general, De Manrique's results are consistent with those obtained by Gay (1968), but both the steady states and the directions and rate of F2 transition appear to be relevant cues for the recognition of Spanish diphthongs. It, therefore, seems that diphthongs cannot be described according to only the target theory or only the trajectory theory.

Quite recently, Gottfried et al. (1993) also tested the trajectory theory according to the **onset + slope hypothesis** (rate of change) and **onset and direction hypothesis** (direction of transition). Concerning the onset + slope hypothesis they found that F2 rate of change is clearly an effective parameter in the classification of American English diphthongs. The onset + direction hypothesis was only slightly less effective than the others in classifying diphthong tokens (the average classification was 94%). On the other hand, Pols (1977) found that the direction of change in the formants of Dutch diphthongs was a more important cue for diphthong identification than the rate of change.

Though various researchers found grounds to support the trajectory theory, Bladon (1985) states that there are 'uneasy' aspects concerning the Gay (1968) study. For example, the subjects indeed successfully identified the diphthongs which contained no initial or final steady state 'target' for the diphthongs, but they were not offered any stimuli with steady states at all and "...we therefore do not know how they would have performed with steady state information..." (Bladon, 1985:147).

This shortcoming in Gay's study came close to being rectified by Bond (1982) who offered his subjects stimuli with steady state components (Bladon, 1985). Once the diphthongs had a steady state of 20 ms or more it was found that the rate of change had a negligible effect on diphthong identification (Bond, 1982). This finding would appear to directly refute Gay's claim that rate of change is the primary feature cueing a diphthong. Bladon (1985) also claims that the transitional rate of change can be a candidate for perceptual cueing, but it cannot be accepted that its status is that of "primary feature" which Gay attributes to it.

Collier and 't Hart (1983) studied Dutch diphthongs and conducted an experiment to find answers to the question whether there is a perceptually preferred rate of change and a preferred onset moment of transition. Their findings show that there is "...no clear perceptually preferred rate of change for the formant trajectories..." (Collier & 't Hart, 1983:45) and that there is no need for a steady state final part.

Toledo and Antonanzas-Barroso (1987) researched the invariance in F2 onset frequency and the rate of change of the F2 transition in spite of differences in speaking rate. They found that results obtained from Spanish data indicate that different speech rates result in significant statistical differences in the F2 rate of change. According to them the production of Argentinean Spanish diphthongs show a language-specific trend rather than a universal-specific one previously suggested by Gay (1968) and De Manrique (1979). In supporting their point of view Toledo and Antonanzas-Barroso (1987) quoted Dolan and Mimori (1986) who found that changes in speech rate influenced the F2 slope in English as well as in Japanese diphthongs, though the influence was smaller in Japanese.

Peeters (1991) also criticises the trajectory theory. According to him the strongly postulated F2 rate of change considered a cueing factor in diphthong identification turned out to be inconsistent even in identical data, as in the case of the study of Gay (1967; 1968). Nabelek et al. (1994) found that the clear identification of synthesised diphthong stimuli is possible for a large range of durations and rates of change in F1 and F2 transitions. In the study of Nabelek et al. (1996) the intensity of F1 and F2 transitions was attenuated and they found that in noise and reverberation fewer errors occurred for diphthong tokens characterised by high intensity F2 transitions.

In discussing the trajectory theory it is evident that researchers like Gay (1967; 1968; 1970), for American English, and De Manrique (1979), for Spanish, found evidence 'proving' that the rate of change and direction of the formant transitions are essential in the classification of a diphthong. Other researchers (e.g. Bladon, 1985; Peeters, 1991) experience difficulties in defining diphthongs according to the trajectory theory. Gottfried et al. (1993) found that the formant patterns at the onset and offset of diphthong tokens provide acoustically relevant parameters for classification of the tokens (target theory) as well as the rate of transition and the direction of the formant movement (trajectory theory).

In recent studies on diphthongs (Peeters, 1991; Stollwerck, 1991; Gerrits, 1995) there has been a moving away from the traditional target theory and trajectory theory and these two theories are now more or less both incorporated in studying **the temporal formant pattern** of diphthongs. The relevant literature on the temporal formant pattern of diphthongs is now identified and evaluated.

2.2.5 THE TEMPORAL FORMANT PATTERN

"In treating diphthongs like static particles in an articulatory and acoustic space, the important information which is conveyed by diphthongs namely their spectral development in the time domain and the perceptual handling of this dynamic complex is suppressed." (Stollwerck, 1991:2). In recent literature many different researchers find that diphthongs cannot be described properly through the beginning and end formant frequencies (target theory) or by the means of the direction or rate of formant change (trajectory theory) (cf. 2.2.3 and 2.2.4). These findings have to be tested for Afrikaans.

During the past few years a significant shift can be seen in the research conducted on the acoustic characteristics of diphthongs (Peeters, 1991; Stollwerck, 1991; Gerrits, 1995). The most important feature of this shift is the moving away from the importance of the individual components of the formant pattern. Researchers currently seem to be focussing on the **total temporal formant pattern**. This new approach is beginning to show up language-specific differences in the dynamics of the formant trajectories of the diphthongs which has important implications for understanding the diphthong as an entity in phonetic research (Stollwerck, 1991). Research in this area can be of great value for Afrikaans as well as for general language theory.

The Germanic diphthongs, of which the Afrikaans diphthongs are also part, are in a physiological, acoustical, perceptual and conceptual sense unitary speech events (Peeters, 1991). It has been shown extensively in the available literature that the onset and offset frequencies of diphthongs in Germanic languages such as Dutch, British English and German overlap in production and, therefore, cannot supply the language specific diphthong cues (Peeters, 1991). However, the possibility of various temporal patterns for the same diphthong was acknowledged in the literature. These various temporal patterns were not regarded as language-specific, but as free productional variants.

Although it has been shown that onset and offset frequencies of diphthongs in Germanic languages can overlap in production, the opposite is also found when, for example, onset and offset frequencies of identical diphthongs differ. Narahara et al.'s (1977) results show clear differences between onsets and offsets in identical diphthongs among speakers of German. Pols (1977) also found clear differences between onsets and offsets and glide directions in the three genuine Dutch diphthongs. Gerrits (1995) claims that in studies on the improvement of synthetic speech it was found that the exact formant values are not necessary for the synthesis of diphthongs.

Peeters (1991), abandoning the traditional segmental analysis techniques in favour of a perceptual approach, hypothesises that the durational relationship of the diphthong pattern components, rather than the absolute onset and offset formant frequencies, is the dominant factor, which elicits a recognisable timbre for the listener.

Stimuli for three different languages were devised with a fixed overall duration (240 ms), fixed onset and offset formant frequencies, fundamental frequencies and bandwidths. Peeters showed that it is possible to synthesise acceptable Dutch, German and British English diphthongs while the total duration and the beginning and end formant frequencies stay the same for all diphthongs. Only the temporal formant pattern varied. (For graphic presentations of the various temporal patterns cf. 4.3.6.7)

It was found, all things being equal, that for the three above mentioned languages, specific durational relations between onset steady state, glide and offset steady state were present. Since significant language-specific temporal preferences are found for English, German and Dutch, Peeters claims that the main language-specific characteristic of Germanic diphthongs is the temporal pattern. These temporal patterns are the result of the combination of a number of diphthong components, on the one hand, and the durational relationships between these components, on the other hand (Peeters, 1991:25).

The experiments conducted by Peeters (1991) identified two important diphthong pattern types, namely a tripartite type, showing a steady state/ glide/ steady state structure, and a bipartite type, showing a steady state/ offglide structure. The tripartite structure of German diphthong trajectories, which differs from the American English patterns of the formant contours, was also reported by Narahara et al. (1977).

Cao (1991) investigated the durational ratio among the parts of onset, offset and the transitional glide for Standard Chinese. He found that the dominant influence of temporal structure upon the timbre discrimination of the diphthongs is remarkably strong and it is a sufficient acoustic cue for listeners to identify diphthongs correctly. Cao's results also indicate that the articulatory movement from one target to another in a diphthong is not casual, but well planned in the time domain and it is language specific. He claimed that the formant trajectory can neither be represented by "...a simple straight line nor a casual glide but by a proper language dependent curve." (Cao, 1991:47). The question now arises whether this is true for all languages and in this case specifically for Afrikaans.

Cao finally came to the conclusion that one can argue that temporal structure is a dominant cue not only for the language-specific characteristics of diphthongs, but also for certain subtle distinctions of diphthongs within a language. It is important to study Afrikaans diphthongs to see whether the temporal structure is indeed the dominant cue for the language-specific characteristics of diphthongs. Cao's finding that the temporal formant structure is also important in differentiating between diphthongs within a language must also be examined for Afrikaans.

The aim of the Stollwerck (1991) research was to determine whether there are significant language differences in proportional durations of onset steady state, glide and offset steady state in the English and German diphthongs [ai] and [au]. In accordance with Peeters' study (1991) her results lend support to the idea that there are definite language-specific trajectories for diphthongs.

The most recent research conducted on the temporal formant pattern of diphthongs is that of Ellen Gerrits (1995). She compared the Dutch diphthongs /au/, /ui/ and /ei/ uttered by deaf speakers, speech therapists and naïve speakers. The duration and the formants of the diphthongs were analysed and compared. The results of the production test indicate that the formant patterns of the deaf speakers (especially of F2) differed from those of the speech therapists and naïve speakers in that a fast frequency increase during the trajectory of the F2 is absent in the diphthongs of deaf speakers. In the second part of this study listeners in two perception experiments judged these diphthongs. Results show that listeners very seldom chose the diphthongs from deaf speakers (Gerrits' study is discussed in greater detail in Chapter 4). These results also indicate the importance of the temporal formant pattern.

The results of the research conducted by Cao (1991), Peeters (1991) and Stollwerck (1991) seem to indicate that the temporal formant pattern embodies the features with which diphthongs can be described unambiguously.

Since Peeters (1991) and Stollwerck (1991) (Germanic languages) and Cao (1991) (Standard Chinese) found that the temporal formant pattern of a diphthong is language specific. It is of great importance to determine whether such patterns exist for Afrikaans diphthongs, and if they do exist, what they look like.

Afrikaans diphthongs will have to be analysed in a production test to see whether a specific pattern emerges. If a specific pattern is found, a perception test is necessary to determine whether this pattern is acceptable to the listener and whether an alternative pattern would also be acceptable to the listener (cf. Chapter 4).

2.2.6 CONCLUSION

The problematic nature of diphthong research was underlined throughout this section. In order to find a way to be able to give an adequate description of diphthongs acoustically the target theory, the trajectory theory as well as the temporal formant pattern were discussed and critically evaluated.

The available literature indicates that there has been a moving away from the traditional ways of studying diphthongs (the target and trajectory theories) to a new approach, which takes the dynamic nature of diphthongs into account (Stollwerck, 1991; Gerrits, 1995).

Whether there are language specific trajectories for diphthongs, was studied by several researchers (Cao, 1991; Peeters, 1991; Stollwerck, 1991; Gerrits, 1995) and their results all indicate the presence of language specific temporal formant patterns for the Germanic diphthongs as well as Standard Chinese diphthongs.

According to Peeters (1991) it is now possible to give a more adequate description of Germanic diphthongs. "A diphthong is an inherently dynamic speech sound characterised by an acoustically and perceptually coherent sequence of steady state and glide portions, either in tripartite or bipartite form. These portions show language-specific mutual durational relationships, constituting specific spectro-temporal patterns." (Peeters, 1991:213).

In studies by Cao (1991), Peeters (1991) and Stollwerck (1991) the following conclusions regarding diphthongs are stated:

1. The temporal formant pattern of a diphthong is language specific.

2. The temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously.

In the following chapter the production test is described: Firstly, the experiment (the stimulus material, subjects, apparatus, the data collection and measuring procedures) is discussed where after the method of data analysis is represented, secondly the results of the production test are given, interpreted and discussed.

Chapter 3: THE PRODUCTION TEST

3.1 INTRODUCTION TO THE EXPERIMENT

The general objective of this research is to shed more light on the acoustical features of diphthongs in Afrikaans in a production test as well as a perception test. In this chapter the production test is presented. The choice of subjects, stimulus material, apparatus, the data collection and measuring procedures as well as the data analysis and statistics are given. Finally the results of the production test are presented and a discussion and interpretation of the results follow.

3.2 THE EXPERIMENT

3.2.1 SUBJECTS

The primary focus of acoustic analyses during the past four decades was the normal male speaker (Van der Merwe et al., 1993). The reason for this is the lower fundamental frequency of the male voice, which makes analyses easier and more reliable than the analyses of the voices of women and children. Therefore, five male, native speakers of Standard Afrikaans, with no known speech or hearing disorders took part in this experiment. They were either post-graduate students or lecturers at the Potchefstroom University and their ages ranged between 25 and 45 years. They originally came from different parts of South Africa, but had lived in Potchefstroom for more than five years preceding the experiment and did not speak a regional dialect. They were not paid for their participation in the experiment.

When the measuring procedure started at the Phonetic Institute of the University of Utrecht, the Netherlands, it was found that a distortion occurred on the DAT recording of one subject.

Since many Afrikaans-speaking students and lecturers were present in Utrecht at that stage, a decision was made to record one of them, a male subject who complied to the above criteria.

3.2.2 THE STIMULUS MATERIAL

The main objective of this study was to research the acoustical features of the genuine diphthongs in Afrikaans. Three genuine diphthongs can be distinguished in Afrikaans namely: [ɔi], [œy] and [œu]. For the sake of convenience these diphthongs are from now on presented as /ei/, /ou/ and /ui/. In order to be able to compare these diphthongs in future studies with the three genuine diphthongs /ui/, /ei/ and /au/ in Dutch, the stimulus material was devised by dr. Wim Peeters of the Phonetic Institute of the University of Utrecht, the Netherlands. The Dutch text was then translated into Afrikaans. The Afrikaans text did not differ much from the original text since most Dutch and Afrikaans words are similar, for example, the Dutch word "buiten" is translated as "buite" in Afrikaans. The directly translated text was fully understandable to the Afrikaans subjects (cf. Appendix A).

The stimulus material consisted of a word list containing single and multi-syllabic words, as well as open and closed syllabic words. This was followed by a paragraph, containing words with a specific diphthong, for example /ui/. The other two diphthongs were presented in the same way. There were 74 words containing the /ui/ sound, 67 words the /ei/ sound and 51 the /ou/ sound.

Despite potential shortcomings, (not all phonetic contexts were taken into account, as well as an imbalance with regard to the number of open and closed syllables) it was nevertheless decided to use the translated text, since Peeters was of opinion that it would not have a significant influence on the results of the production test.

3.2.3 DATA COLLECTION PROCEDURE

Tape recordings were made in a professionally equipped studio. The apparatus used was a Philips DAT (Digital Audio Tape – ZA5ES) recorder and a Shure dynamic (SM48) microphone. The microphone was kept at a distance of between 20 and 30 centimetres from the speakers' lips. Instructions on how to read the material were given by the investigator. The subjects had the opportunity to warm up for a few minutes and were asked to read the first part of the task while the investigator set the recording levels. They were then asked to read the material as naturally as possible at an easy tempo. The subjects were also instructed that they could interrupt and re-read a token if they made a mistake. The script was read twice and it was ensured that the signal did not overload.

3.2.4 MEASURING PROCEDURE

In order to analyse the speech material it was read into the computer. The speech analysis programme GIPOS (IPO Eindhoven) was used to, through visual and auditive inspection, isolate the different diphthongs. The total duration in milliseconds of each diphthong was determined and then the segmented diphthongs were copied to new files and stored.

The speech analysis program then divided the signal into frames of 10 ms. A spectral analysis was made per frame of the first five formants, their bandwidths, the amplitude and the F0 of the signal. The Wiber program was used to determine the beginning and end frequencies of the formants, the F0 and the amplitude and the frequencies on four time equidistant measuring points. Six measuring points for each measuring pattern were saved. The reason for this was to reach a time normalisation of the differing total duration of the diphthongs. The number of values thus became equal for each diphthong and the transition in the formant pattern stayed recognisable (Gerrits, 1995). In this way a relatively fast discrete temporal pattern of the diphthong was found.

3.2.5 DATA ANALYSES

No data analyses were performed for the total duration of the diphthongs, since the temporal aspects of diphthongs were only studied in so far as it was relevant to the study of the spectral aspects. However, for the sake of completeness the durational results of the production test are presented in the appendix B.
The F0 results of the production test indicate that, in all cases, the F0 curve progresses linearly through the time domain with a slight increase or decrease in ending value, depending on the contour spoken by the subject. No further analyses are done for the F0's, but for the sake of completeness the F0 results of the production test are presented in the appendix B.

Gerrits (1995) performed MANOVA's (Multiple Analysis of Variance) with the help of the SPSSX program, while Stollwerck (1991) used a mixed model analysis of variance in analysing her data. Since both of these studies researched the temporal formant pattern it seems inadequate to make use of different methods of analysis of variance where only specific points in the formant patterns can be compared. In order to rectify this, a way of analysing the whole pattern was pursued. For this purpose Jandel's Scientific TableCurve was employed. TableCurve is statistical computer software used to perform curve fits on two-dimensional data sets.

A set of data points was read into the computer and a curve fit was performed. The TableCurve curve fit is fully automated for linear equations. The review process began with a graph of the equation having the best fit criteria with an ordered selection list of all valid equations. The main curve fit graph is the central focus of the review process. The review process is both graphical and numeric.

An example of a curve fit performed on the F1 and F2 of a subject's diphthong can be seen in Figure 5 and Figure 6. In the curve fit graph, the equation is the solid line and the table points are plotted. The r^2 coefficient of determination, as well as the terms of the equation, are also visible (cf. Figure 5 and Figure 6).

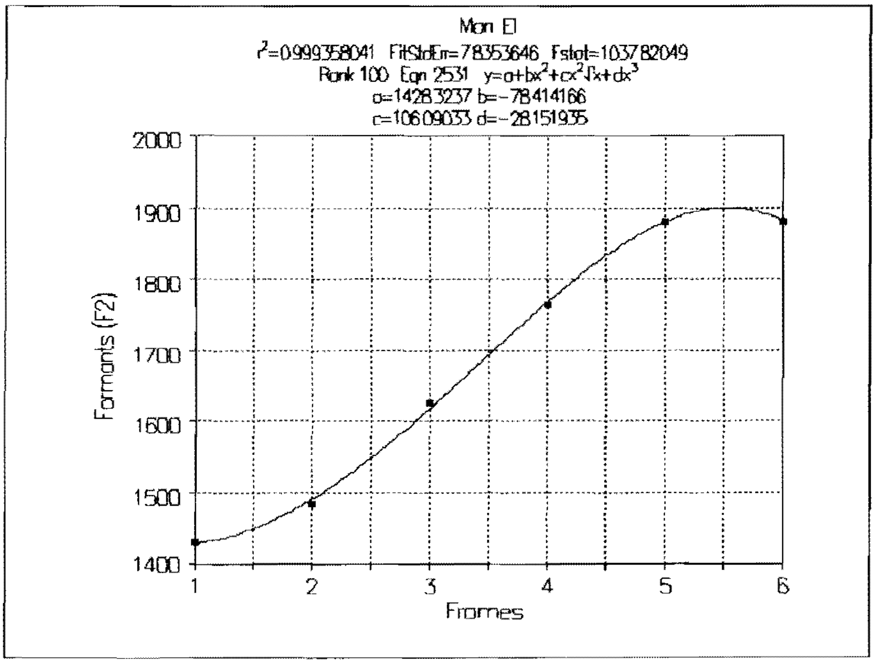


Figure 5: Curve fit on a subject's diphthong (F2)

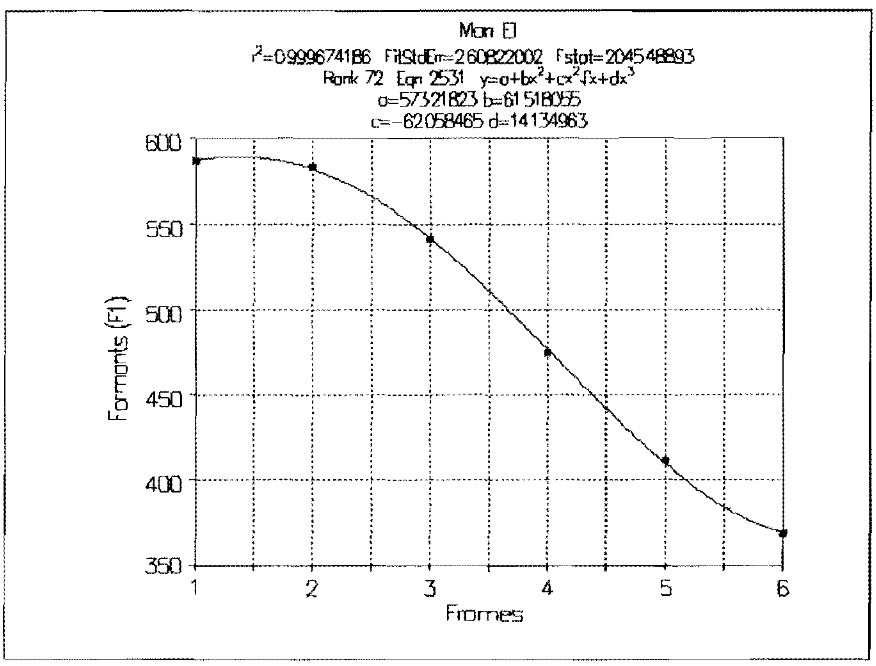


Figure 6: Curve fit on a subject's diphthong (F1)

3.2.6 RESULTS AND DISCUSSION

The general objective of the study is to shed more light on the acoustical features, especially the spectral features, of the diphthongs in Afrikaans. In the following paragraphs the results and discussion of F1 - F3, B1 - B3 and the amplitude are given. One of the specific objectives of the study is to determine which of the following; the target theory, the trajectory theory or the temporal formant pattern is more likely to describe diphthongs unambiguously. The results concerning the different theories are also presented and discussed.

3.2.6.1 F1 - F3, B1 - B3 and Amplitude

All the data points of F1 - F3, B1 - B3 and the amplitude for the different diphthongs were read into the computer and saved in separate files. Then a curve fit was performed for each set of data points. Different graphs, having the best curve fit criteria, were shown and inspected by the researcher. The better curve fits had a r^2 coefficient of determination of close to one (for example **0,999**) and in those cases the chosen equation described the data points of the five subjects accurately.

Moving down a list of selected curve possibilities, curves were chosen on the basis of r^2 and the standard deviation. After screening the ten best curve fits, the equation yielding the best fit for a specific component was chosen. This equation was then used to mathematically represent the selected components.

For example, for F1 the following complex third degree polynomial was found accurate for all the data sets tested:

$$\mathbf{y = a + bx^2 + cx^2.x^{1/2} + dx^3}$$

a = term 1 (T1), **b** = term 2 (T2), **c** = term 3 (T3) and **d** = term 4 (T4).

T1-T4 determines the shape of the curve. T1, for example, determines the origin and position of the curve on the x-y axis, while the second degree terms (T2-T3) of the polynomial reflect the change in curve gradient and the third degree term (T4) influences sudden curve deflections.

3.2.6.1.1 FORMANT 1: RESULTS AND DISCUSSION

For F1 the following complex third degree polynomial was found sufficiently accurate for all the data sets tested:

$$\mathbf{y = a + bx^2 + cx^2.x^{1/2} + dx^3}$$

All the curve fits are good fits since the r^2 coefficients of **/ui/** vary between **0.997** and **0.999** for the five subjects. For **/ei/**, the r^2 coefficients vary between **0.995** and **0.999,** and for **/ou/** the r^2 coefficients vary between **0.993** and **0.999**. Therefore, it can be stated that the chosen equation describes the data points of the five subjects accurately.

It is important to notice that the average values are not relevant, since in all cases the minimum and maximum values of a specific property (such as a-e, minimum, maximum and mean frequency, as well as frequency range) define that property adequately. Only the boundaries (maximum and minimum values) of the properties are required for differentiation and not the averages.

When looking at the results it is evident that in most cases the minimum and maximum constant values (a-e), onset and offset, and frequency (minimum, maximum, mean and range) values of the different diphthongs overlap. In order to determine the percentage overlap of two diphthongs the lowest minimum value was subtracted from the highest maximum value to get the total working range (100%). To determine the overlapping range, the second highest minimum value was subtracted from the second highest maximum value. The percentage overlap was then determined by dividing the overlap by the total working range.

Example: (apropos constant a: values of /ei/ and /ou/)

(553 - 536) / (592 - 491) = 17/101 = 0,168 × 100% = 16.8% (17%)

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of formant 1 (F1) are represented in **Table 1.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 1: F1 -- Minimum and maximum values of constant 'a'

Constant 'a'	**/ui/**	**/ei/**	**/ou/**
Minimum value	490	536	491
Maximum value	532	592	553

The first degree term, 'a' (or T1) determines the starting point and thus the position of the curve on the x-y axis (x = 0). The starting point of the curve and the onset value of the diphthong is not the same since the starting point of the curve is determined at x = 0, while the onset value of the diphthong is determined at x = 1 (the value at the first frame).

The difference between the minimum and maximum 'a' values in identical diphthongs variesbetween **42** for /ui/ and **62** for /ou. The values of the three different diphthongs, therefore, overlap. The overlap for /ui/ and /ou/ is **65%** and for /ei/ and /ou/, **17%**. There is, however, no overlap for /ui and /ei/.

These results, therefore, indicate that it is possible to differentiate between /ei/ and /ui/ with the 'a' value, while it is not possible to differentiate between /ui/ and /ou/, as well as between /ei/ and /ou/ with this value.

In the selected equation, for F1, $\mathbf{y = a + bx^2 + cx^2.x^{1/2} + dx^3}$, if x = 1 then y = a+b+c+d. This is the onset of the specific diphthong. If, for example, one replaces the values 'a-d' of diphthong /ui/ when x = 1 (y = 506 + 77 + (-67) + 18 = 534), y will equal the onset frequency of the subject, namely **534 Hz**. In the same way the offset frequency (x = 6) can be attained, namely **324 Hz**.

It was already stated that F1 and F2 are of vital importance in determining the acoustic quality of diphthongs (cf. 2.2.2). Therefore, in the cases of F1 and F2 not only are the results of the Tablecurve fits (constants 'a'-'d', as well as the minimum frequency, the maximum frequency, the mean frequency and the frequency range) discussed, but also the onset and offset values of the three diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of the onset of F1 are represented in **Table 2.** These values are given in Hertz (Hz).

Table 2: F1 -- Minimum and maximum values of the Onset

Onset F1	/ui/	/ei/	/ou/
Minimum value:	519	562	511
Maximum value:	574	606	584

The minimum and maximum /ui/, /ei/ and /ou/ values of the offset of F1 are represented in **Table 3.** These values are given in Hertz (Hz).

Table 3: F1 -- Minimum and maximum values of the Offset

Offset F1	/ui/	/ei/	/ou/
Minimum value:	291	317	288
Maximum value:	351	409	412

The difference between the minimum and maximum onset and offset formant frequencies in identical diphthongs varies between **44 Hz** (/ei/) and **73 Hz** (/ou/) for the onset and between **60 Hz** (/ui/) and **124 Hz** (/ou/) for the offset. (It is also important to notice that in all the cases the maximum and minimum values are merely averages and that the minimum and maximum values of each individually spoken diphthong are likely to vary more exceedingly).

This is in accordance with Narahara et al., (1977) and Pols' (1977) findings for German and Dutch diphthongs. They found clear differences between onset and offset values (as well as glide directions) in identical diphthongs.

The onset values of the three different diphthongs overlap. For /ui/ and /ei/ the onset overlap is **14%**, for /ui/ and /ou/ **75%** and for /ei/ and /ou/ **23%.** The offset overlap for /ui/ and /ei/ is **29%**, for /ui/ and /ou/ **51%** and **74%** for /ei/ and /ou/.

These findings are in accordance with Peeters (1991) who states that onset and offset values for diphthongs overlap in production and, therefore, cannot supply the language specific diphthong cues.

On the grounds of the variation in the onset and offset values in identical diphthongs, as well as the overlap of onset and offset values of the three diphthongs, it is clear that onset and offset information alone is insufficient to describe the first formant of /ui/, /ei/ and /ou/ unambiguously. Thus, the target theory's demand that the starting points and endpoints (onsets and offsets) are significant in diphthong identification is refuted by these results.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of F1 are represented in **Table 4**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 4: F1 -- Minimum and maximum values of constant 'b'

Constant 'b'	/ui/	/ei/	/ou/
Minimum value	74	30	58
Maximum value	148	107	128

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of F1 are represented in **Table 5**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 5: F1 -- Minimum and maximum values of constant 'c'

Constant 'c'	/ui/	/ei/	/ou/
Minimum value	-135	-100	-125
Maximum value	-62	-33	-61

The second degree terms, T2 and T3 ('b' and 'c') of the polynomial determine the change in curve gradient.

The difference between the minimum and maximum 'b' values in identical diphthongs varies between **70** for /ou/ and **77** for /ei/. The difference between the minimum and maximum values of 'c' in identical diphthongs varies between **64** for /ou/ and **73** for /ui/. However, the values of the three different diphthongs overlap. As far as 'b' is concerned the overlap for /ui/ and /ei/ is **28%** , for /ui/ and /ou/ **60%** and for /ei/ and /ou/ **50%**. As far as 'c' is concerned the overlap for /ui/ and /ei/ is **37%** , for /ui/ and /ou/ **85%** and for /ei/ and /ou/ **42%**.

On the grounds of the variation in the values of 'b' and 'c' in identical diphthongs, as well as the constants' overlap of the three different diphthongs, one can deduce that the change in curve gradient ('b' and 'c') is not sufficient to distinguish between the three diphthongs. As a result of these findings it seems that the trajectory theory has to be rejected.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of F1 are represented in **Table 6.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 6: F1 -- Minimum and maximum values of constant 'd'

Constant 'd'	/ui/	/ei/	/ou/
Minimum value	12	8	14
Maximum value	29	23	29

The third degree term, T4, ('d') of the polynomial reflects sudden curve deflections.
The difference between the minimum and maximum 'd' values in identical diphthongs varies between **15** for /ei/ as well as for /ou/ and **17** for /ui/. The values of the three different diphthongs overlap. The overlap for /ui/ and /ei/ is **52%, 88%** for /ui/ and /ou/ and **43%**. for /ei/ and /ou/

On the grounds of the variation in the values of 'd' in identical diphthongs, as well as the overlap of the three diphthongs it can be deduced that the different curve deflections alone cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

In the following tables minimum frequency is abbreviated as Min. Frequency, while maximum frequency is abbreviated as Max. Frequency.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of F1 are represented in **Table** 7. These values are given in Hertz.

Table 7: F1 -- Minimum and maximum values of the minimum frequency

Min. frequency	/ui/	/ei/	/ou/
Minimum value	291	317	259
Maximum value	351	409	412

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of F1 are represented in **Table 8**. These values are given in Hertz.

Table 8: F1 -- Minimum and maximum values of the maximum frequency

Max. frequency:	**/ui/**	**/ei/**	**/ou/**
Minimum value	529	562	518
Maximum value	596	616	596

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of F1 are represented in **Table 9**. These values are given in Hertz.

Table 9: F1 -- Minimum and maximum values of the mean frequency

Mean frequency:	**/ui/**	**/ei/**	**/ou/**
Minimum value	436	451	419
Maximum value	487	518	490

The minimum and maximum /ui/, /ei/ and /ou/ values of the frequency range of F1 are represented in **Table 10**. These values are given in Hertz.

Table 10: F1 -- Minimum and maximum values of the frequency range

Frequency range	**/ui/**	**/ei/**	**/ou/**
Minimum value	187	186	152
Maximum value	252	273	253

The difference between the minimum and maximum values of the minimum frequency, the maximum frequency, the mean frequency, as well as the frequency range in identical diphthongs varies in all the cases between **51** for /ui/ and **153** for /ou/. However, the values of the three different diphthongs overlap. In all four cases the overlap for /ui/ and /ei/ varies between **29%**

and **76%**, for /ui/ and /ou/, between **48%** and **86%** and, for /ei/ and /ou/ between **35%** and **60%**.

On the grounds of the variation in frequency in identical diphthongs, as well as the overlap in frequency between the three diphthongs it can be deduced that the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.1.1 CONCLUSIONS

The results of F1 indicate that none of the different components (except for constant 'a' with which there can be distinguished between /ui/ and /ei/) of the formant pattern can **individually** describe diphthongs unambiguously. Therefore, the target theory's demand that the onset and offset values are significant in diphthong identification are contradicted, as well as the trajectory theory's claim that the direction and rate of change of the formant transitions are essential in distinguishing between different diphthongs.

According to Peeters (1991), the distinctive temporal pattern of a diphthong is a combination of the diphthong components. The possibility that such a description lies in a combination of the different components (the temporal formant pattern – in this case the above mentioned parameters) has to be tested perceptually (cf. Chapter 4). It is also possible that a description lies in a combination of the different components of **F1** and **F2**.

3.2.6.1.2 FORMANT 2: RESULTS AND DISCUSSION

For F2, as for F1 the following complex third degree polynomial was found sufficiently accurate for F2 for all the data sets tested:

$$\mathbf{y = a + bx^2 + cx^2.x^{1/2} + dx^3}$$

The curve fits for /ui/ and /ei/ are good fits since the r^2 coefficients of /ui/ vary between **0.998** and **0.999** for the five subjects. For /ei/ the r^2 coefficients vary between **0.995** and **0.999,** while for /ou/ the r^2 coefficients vary between **0.896** and **0.994.** The latter indicates that the curve fits for /ou/ were not as good as for /ui/ and /ei/.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of formant 2 (F2) are represented in **Table 11**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 11: F2 -- Minimum and maximum values of constant 'a'

Constant 'a':	/ui/	/ei/	/ou/
Minimum value	1324	1324	1262
Maximum value	1436	1505	1424

The difference between minimum and maximum 'a' values in identical diphthongs varies between **112** for /ui/ and **181** for /ei/. However, the values of the three different diphthongs overlap. The overlap for /ui/ and /ei/ is **62%**, for /ui/ and /ou/ **58%** and for /ei/ and /ou/, **26%.**

On the grounds of the variation of the values of 'a' in identical diphthongs, as well as the overlap between the three diphthongs it can be deduced that the 'a' value of F2 cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of the onset of F2 are represented in **Table 12**. These values are given in Hertz.

Table 12: F2 -- Minimum and maximum values of the Onset

Onset F2:	/ui/	/ei/	/ou/
Minimum value	1258	1306	1327
Maximum value	1390	1537	1441

The minimum and maximum /ui/, /ei/ and /ou/ values of the offset of F2 are represented in **Table 13**. These values are given in Hertz.

Table 13: F2 -- Minimum and maximum values of the Offset

Offset F2	/ui/	/ei/	/ou/
Minimum value	1732	1791	961
Maximum value	1953	1900	1324

The difference between the minimum and maximum onset and offset formant frequencies in identical diphthongs varies between **114 Hz** (/ou/) and **231 Hz** (/ei/) for the onset and between **109 Hz** (/ei/) and **363 Hz** (/ou/) for the offset.

This is also in accordance with Narahara et al., (1977) and Pols' (1977) findings for German and Dutch diphthongs. They found clear differences between onset and offset values (as well as glide directions) in identical diphthongs.

The onset values of the three different diphthongs overlap. The overlap for /ui/ and /ei/ is **30%**, for /ui/ and /ou/ **34%** and for /ei/ and /ou/ **49%.** These findings are in accordance with those of Peeters (1991) who states that the onset values for diphthongs overlap. The offset overlap for /ui/ and /ei/ is **49%**, but there was no overlap for /ui/ and /ou/ or for /ei/ and /ou/.

From these results it is clear that the onset information of F2 alone is insufficient to describe the three diphthongs unambiguously. The offset information for F2 of /ui/ and /ei/ is also not sufficient to distinguish between these two diphthongs, while the endpoints seem to be important in distinguishing between /ui/ and /ou/, and /ei/ and /ou/. According to these results it is evident that the target theory's claim, that the onset information is important in diphthong identification should be rejected. The importance of the offset in distinguishing between /ui/ and /ei/ also has to be rejected. However, it is possible to distinguishing between /ou/ and the other two diphthongs according to the target theory.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of F2 are represented in **Table 14.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 14: F2 -- Minimum and maximum values of constant 'b'

Constant 'b':	/ui/	/ei/	/ou/
Minimum value	-402	-191	83
Maximum value	-104	-37	281

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of F2 are represented in **Table 15**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 15: F2 -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	119	4	-290
Maximum value	394	212	-88

The difference between the minimum and maximum 'b' values in identical diphthongs varies between **154** for /ei/ and **298** for /ui/. The difference between the minimum and maximum 'c' values in identical diphthongs varies between **202** for /ou/ and **275** for /ui/. However, the values of the three different diphthongs overlap. As far as 'b' and 'c' are concerned the overlap for /ui/ and /ei/ is **24%** in both cases, but the values for /ou/ do not overlap with the values of either /ui/ or /ei/.

On the grounds of the variation in identical diphthongs (/ui/ and /ei/) as well as the overlap between them, it can be deduced that the change in curve gradient in itself is not sufficient in distinguishing between the two diphthongs. It is evident though that the values for /ou/ never overlap with those values for the other two sounds and it can, therefore, be deduced that the change in curve gradient can provide the differentiating cue for /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of F2 are represented in **Table 16**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 16: F2 -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	-92	-52	21
Maximum value	-29	-3	72

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **49** for /ei/ and **63** for /ui/. The values of the diphthongs /ui/ and /ei/ overlap and the overlap is **26%**, while the values never overlap for /ou/.

On the grounds of the variation in identical diphthongs (/ui/ and /ei/) as well as the overlap between them, it can be deduced that the different curve deflections in itself cannot sufficiently distinguish between the two diphthongs. However, it is evident that the values for /ou/ never overlap with the values of the other two diphthongs and it can, therefore, be deduced that the change in curve gradient can provide the differentiating cue for /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of F2 are represented in **Table 17**. These values are given in Hertz.

Table 17: F2 -- Minimum and maximum values of the minimum frequency

Min. frequency:	/ui/	/ei/	/ou/
Minimum value	1258	1326	961
Maximum value	1380	1537	1276

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of F2 are represented in **Table 18**. These values are given in Hertz.

Table 18: F2 -- Minimum and maximum values of the maximum frequency

Max. frequency:	/ui/	/ei/	/ou/
Minimum value	1819	1845	1327
Maximum value	1953	2005	1441

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of F2 are represented in **Table 19**. These values are given in Hertz.

Table 19: F2 -- Minimum and maximum values of the mean frequency

Mean frequency:	/ui/	/ei/	/ou/
Minimum value	1521 Hz	1605 Hz	1182 Hz
Maximum value	1646 Hz	1725 Hz	1357 Hz

The minimum and maximum /ui/, /ei/ and /ou/ values of the frequency range of F2 are represented in **Table 20**. These values are given in Hertz.

Table 20: F2 -- Minimum and maximum values of the frequency range

Frequency range:	/ui/	/ei/	/ou/
Minimum value	524	339	165
Maximum value	601	591	394

The difference between the minimum and maximum values of the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range in identical diphthongs varies in all the cases between 77 **Hz** for /ui/ and **315 Hz** for /ou/.

However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ varies between **19%** and **58%** in all the cases. It can be deduced from these results that the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range cannot provide the differentiating cue between the diphthongs /ui/ and /ei/.

For /ui/ and /ou/ the values only overlap in one case, that of the minimum frequency (**4%**) and for /ei/ and /ou/ the values also only overlap in one case, that of the frequency range (**13%**). From these results it can be deduced that the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range can be differentiating factors of /ou/.

3.2.6.1.2.1 CONCLUSIONS

The results of F2 indicate that none of the different components of the formant pattern can **individually** describe diphthongs unambiguously. Therefore, the target theory's demand that the onset and offset values are significant in diphthong identification are contradicted, as well as the trajectory theory's claim that the direction and rate of change of the formant transitions are essential in distinguishing between different diphthongs.

The distinctive temporal pattern of a diphthong is a combination of the diphthong components according to Peeters (1991), The possibility that such a description lies in a combination of the different components (the temporal formant pattern – in this case the above mentioned parameters) has to be tested perceptually (cf. Chapter 4). It is also possible that the description lies in a combination of the different components of **F1** and **F2**.

It is possible though, on the grounds of the offset (target theory), the change in curve gradient (trajectory theory), the curve deflection as well as the minimum frequency (not in the case of ei/), the maximum frequency, the mean frequency and the frequency range (not in the case of /ui/) to distinguish between /ou/ and the other two diphthongs. Since /ei/ and /ui/ sound so much alike in Afrikaans, it is expected that it should be easy to discriminate between /ou/ and the other two diphthongs.

3.2.6.1.3 FORMANT 3: RESULTS AND DISCUSSION

For F3 the following standard third degree polynomial was found sufficiently accurate for the data sets tested:

$$\mathbf{y = a + bx + cx^2 + dx^3}$$

The curve fits for /ui/ and /ei/ are good fits since the r^2 coefficients of /ui/ varies between **0.980** and **0.997** for the five subjects. For /ei/ the r^2 coefficients vary between **0.994** and **0.998**, while for /ou/ the r^2 coefficients vary between **0.890** and **0.993**. The latter indicates that the curve fits for /ou/ are not all as good as in the case of /ui/ and /ei/.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of F3 are represented in **Table 21**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 21: F3 -- Minimum and maximum values of constant 'a'

Constant 'a':	/ui/	/ei/	/ou/
Minimum value	2230	2402	2297
Maximum value	2548	2600	2493

The difference between the minimum and maximum 'a' values in identical diphthongs varies between **196** for /ou/ and **318** for /ui/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ou/ is **40%**, for /ei/ and /ou/, **62%** and for /ei/ and /ou/, **30%** .

On the grounds of the variation in values of 'a' in identical diphthongs, as well as the overlap between the three diphthongs it can be deduced that the 'a' value cannot be a differentiating cue for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of F3 are represented in **Table 22**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 22: F3 -- Minimum and maximum values of constant 'b'

Constant 'b':	/ui/	/ei/	/ou/
Minimum value	-291	-760	-141
Maximum value	49	-105	-10

The minimum and maximum /ui/, ei/ and /ou/ values of constant c of F3 are represented in **Table 23**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 23: F3 -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	-10	21	-19
Maximum value	74	87	31

The difference between the minimum and maximum 'b' values in identical diphthongs varies between **131** for /ou/ and **655** for /ei/, while the difference between the minimum and maximum values of 'c' in identical diphthongs varies between **66** for /ei/ and **84** for /ui/ However, the values of the different diphthongs overlap. As far as 'b' is concerned the overlap for /ui/ and /ei/ is **23%**, for /ui/ and /ou/, **44%** and for /ei/ and /ou/, **5%**. Concerning constant 'c' the overlap for /ui/ and /ei/ is **55%** for /ui/ and /ou/, **44%** and for /ei/ and /ou/, **9%**.

On the grounds of the variation in values of 'b' and 'c' in identical diphthongs, as well as the overlap between the three diphthongs, it can be deduced that the change in curve gradient cannot be a differentiating factor for the three diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of F3 are represented in **Table 24**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 24: F3 -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	-3	-6	-2
Maximum value	4	1	4

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **6** for /ou/ and **7** for /ui/ and /ei/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **40%**, **86%** for /ui/ and /ei/ and **30%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'd' in identical diphthongs as well as the overlap of the three diphthongs it can be deduced that the different curve deflections cannot be the differentiating factor for the three diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of F3 are represented in **Table 25**. The values are given in Hertz.

Table 25: F3 -- Minimum and maximum values of the minimum frequency

Min. frequency:	/ui/	/ei/	/ou/
Minimum value	2126	2241	2042
Maximum value	2349	2438	2403

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of F3 are represented in **Table 26**. The values are given in Hertz.

Table 26: F3 -- Minimum and maximum values of the maximum frequency

Max. frequency:	/ui/	/ei/	/ou/
Minimum value	2470	2489	2298
Maximum value	2588	2545	2512

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of F3 are represented in **Table 27**. The values are given in Hertz.

Table 27: F3 -- Minimum and maximum values of the mean frequency

Mean frequency:	/ui/	/ei/	/ou/
Minimum value	2276	2337	2136
Maximum value	2396	2473	2391

The minimum and maximum /ui/, /ei/ and /ou/ values of the frequency range of F3 are represented in **Table 28**. The values are given in Hertz.

Table 28: F3 -- Minimum and maximum values of the frequency range

Frequency range:	/ui/	/ei/	/ou/
Minimum value	139	79	82
Maximum value	462	250	280

The difference between the minimum and maximum values of the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range in identical diphthongs varies in all the cases between **56** for /ei/ and **361** /ou/. However, the values for the different diphthongs overlap. In all four cases the overlap for /ui/ and /ei/ varies between **29%** and **48%**, for /ui/ and /ou/ the overlap varies between **15%** and **62%** and for /ei/ and /ou/ between **9%** and **84%**.

On the grounds of the variation in frequency in identical diphthongs, as well as the overlap in frequency between the three diphthongs, it can be deduced that the minimum frequency, the maximum frequency, the mean frequency as well as the frequency range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.3.1 CONCLUSIONS

The results of F3 indicate that none of the different components of the formant pattern can **individually** describe diphthongs unambiguously. Therefore, the target theory's claim that the onset and offset values are significant in diphthong identification are contradicted, as well as the trajectory theory's claim that the direction and rate of change of the formant transitions are essential in distinguishing between different diphthongs.

The distinctive temporal pattern of a diphthong is a combination of the diphthong components (Peeters (1991), The possibility that such a description lies in a combination of the different components (the temporal formant pattern – in this case the above mentioned parameters) has to be tested perceptually (cf. Chapter 4)

3.2.6.1.4 AMPLITUDE: RESULTS AND DISCUSSION

For the amplitude the following complex third degree polynomial was found accurate for the data sets tested:

$$\mathbf{y = a + bx.x^{1/2} + cx^2 + dx^3}$$

All the curve fits are reasonably good fits since the r^2 coefficients of **/ui/** vary between **0.972** and **0.997** for the five subjects. For **/ei/** the r^2 coefficients vary between **0.974** and **0.999** and for **/ou/** the r^2 coefficients vary between **0.991** and **0.998**.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of the amplitude are represented in **Table 29.** Since constants are mathematical function parameters no units such as decibel are given because it is irrelevant.

Table 29: Amplitude -- Minimum and maximum values of constant 'a'

Constant 'a':	/ui/	/ei/	/ou/
Minimum value	2041	2704	2227
Maximum value	6408	7590	9151

The difference between the minimum and maximum 'a' values in identical diphthongs varies between **4367** for /ui/ and **6924** for /ou/. The values of the different diphthongs overlap and the overlap for /ui/ and /ei/ is **67%**, **34%** for /ui/ and /ei/ and **83%** for /ei/ and /ou/.

On the grounds of the variation in values of 'a' in identical diphthongs, as well as the overlap between the three diphthongs, it can be deduced that the 'a' value cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of the amplitude are represented in **Table 30.** Since constants are mathematical function parameters no units such as decibel are given because it is irrelevant.

Table 30: Amplitude -- Minimum and maximum values of constant 'b'

Constant 'b':	/ui/	/ei/	/ou/
Minimum value	1820	2726	5361
Maximum value	7982	9310	10022

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of the amplitude are represented in **Table 31.** Since constants are mathematical function parameters no units such as decibel are given because it is irrelevant.

Table 31: Amplitude -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	-4743	-5200	-6684
Maximum value	-2071	-1745	-4039

The difference between the minimum and maximum values of 'b' in identical diphthongs varies between **4661** for /ou/ and **6584** for /ei/. The difference between the minimum and maximum values of 'c' in identical diphthongs varies between **2645** for /ou/ and **3455** for /ei/. However, the values of the different diphthongs overlap. As far as 'b' is concerned the overlap for /ui/ and /ei/ is **70%**, for /ui/ and /ou, **32%** and for /ei/ and /ou/ **83%**. As far as 'c' is concerned the overlap for /ui/ and /ei/ is 77%, for /ui/ and /ou/, **15%** and for /ei/ and /ou/, **24%**.

On the grounds of the variation in values of 'b' and 'c' in identical diphthongs as well as the overlap between the three diphthongs it can be deduced that the change in curve gradient cannot be a differentiating factor for the three diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of the amplitude are represented in **Table 32.** Since constants are mathematical function parameters no units such as decibel are given because it is irrelevant.

Table 32: Amplitude -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	-72	108	279
Maximum value	244	259	426

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **151** for /ei/ and **316** for /ui/. The values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **41%** and **7%** for /ui/ and /ou/. There is no overlap for /ei/ and /ou/.

On the grounds of the variation in identical diphthongs, as well as the overlap between them, it can be deduced that the different curve deflections cannot sufficiently distinguish between the diphthongs /ui/ and /ei/ as well as /ui/ and /ou/. However, it is clear that the values for /ei/ and /ou/ never overlap and it can, therefore, be deduced that the sudden curve deflections can differentiate between /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum amplitude are represented in **Table 33.** The values for the amplitude are logarithmic values and, therefore, the values of the following parameters are not given in decibel.

Table 33: Amplitude -- Minimum and maximum values of minimum amplitude

Min. amplitude:	**/ui/**	**/ei/**	**/ou/**
Minimum value	2455	3091	2286
Maximum value	6780	7117	3977

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum amplitude are represented in **Table 34.** The values for the amplitude are logarithmic values and, therefore, the values of the following parameters are not given in decibel.

Table 34: Amplitude -- Minimum and maximum values of maximum amplitude

Max. amplitude:	**/ui/**	**/ei/**	**/ou/**
Minimum value	4637	6063	7794
Maximum value	11141	11451	10661

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean amplitude are represented in **Table 35,** The values for the amplitude are logarithmic values and therefore the values of the following parameters are not given in decibel.

Table 35: Amplitude -- Minimum and maximum values of the mean amplitude

Mean amplitude:	/ui/	/ei/	/ou/
Minimum value	3654	4769	4907
Maximum value	8805	9457	6685

The minimum and maximum /ui/, /ei/ and /ou/ values of the amplitude range are represented in **Table 36.** The values for the amplitude are logarithmic values and therefore the values of the following parameters are not given in decibel.

Table 36: Amplitude -- Minimum and maximum values of the amplitude range

Amplitude range:	/ui/	/ei/	/ou/
Minimum value	2189	1190	5119
Maximum value	6346	6439	8071

The difference between the minimum and maximum values of the minimum amplitude, the maximum amplitude, the mean amplitude as well as the amplitude range in identical diphthongs varies between **1691** for /ou/ and **6504** for /ui/. However, the values for the different diphthongs overlap. In all four cases the overlap for /ui/ and /ei/ varies between **70%** and **79%**, for /ui/ and /ou/, between **21%** and **93%**, and for /ei/ and /ou/ between **18%** and **53%**.

On the grounds of the variation in amplitude in identical diphthongs as well as the overlap in amplitude of the three diphthongs it can be deduced that the minimum amplitude, the maximum amplitude, the mean amplitude as well as the amplitude range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

It is also important to notice that there are large differences among the amplitude values of the five subjects for /ei/ and /ui/.

3.2.6.1.4.1 CONCLUSIONS

Due to the variation in amplitude in identical diphthongs, as well as the overlap in bandwidth of the three different diphthongs, it can be concluded that none of the above-mentioned parameters provide specific cues to distinguish between the three diphthongs unambiguously. However, the values of /ei/ and /ou/ never overlap and it can, therefore, be deduced that the sudden curve deflections can differentiate between /ei/ and /ou/.

3.2.6.1.5 BANDWIDTH 1: RESULTS AND DISCUSSION

For the bandwidth the following standard third degree polynomial was found the most accurate for the data sets tested:

$$\mathbf{y = a + bx^3 + cexpx + d/x^2}$$

All the curve fits are reasonably good fits since the r^2 coefficients of **/ui/** vary between **0.954** and **0.995** for the five subjects. For **/ei/** the r^2 coefficients vary between **0.952** and **0.998,** and for **/ou/** the r^2 coefficients vary between **0.956** and **0.998**.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of Bandwidth 1 (B1) are represented in **Table 37.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 37: B1 -- Minimum and maximum values of constant 'a'

Constant 'a':	/ui/	/ei/	/ou/
Minimum value	59	54	51
Maximum value	192	199	223

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **133** for /ui/ and **172** for /ou/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **92%, 77%** for /ui/ and /ei/ and **84%** for /ei/ and /ou/.

On the grounds of the variation in values of 'a' in identical diphthongs, as well as the overlap between the three diphthongs, it can be deduced that the 'a' value cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of B1 are represented in **Table 38.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 38: B1 -- Minimum and maximum values of constant 'b'

Constant 'b':	/ui/	/ei/	/ou/
Minimum value	-3	-2	-4
Maximum value	1	1	1

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of B1 are represented in **Table 39.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 39: B1 -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	2	0	3
Maximum value	0	1	0

The difference between the minimum and maximum values of 'b' in identical diphthongs varies between **3** for /ei/ and **5** for /ou/. The difference between the minimum and maximum values of 'c' in identical diphthongs varies between **1** for /ei/ and **3** for /ou/. The values of the different diphthongs overlap. As far as 'b' is concerned the overlap for /ui/ and /ei/ is **75%,** for /ui/ and /ou/, **80%** and for /ei/ and /ou/, **60%**. As far as 'c' is concerned the overlap for /ui/ and /ei/ is **50%**, for /ui/ and /ou/, **67%** and for /ei/ and /ou/, **33%**.

On the grounds of the constants' overlap of the three diphthongs it is evident that it is not possible to differentiate between the diphthongs on the grounds of differences in changes in the gradient of the bandwidths.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of B1 are represented in **Table 40.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 40: B1 -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	45	21	-48
Maximum value	241	180	155

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **159** for /ei/ and **203** for /ou/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **61%, 38%** for /ui/ and /ei/ and **40%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'd' in identical diphthongs as well as the overlap of the three diphthongs it can be deduced that the different curve deflections cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of B1 are represented in **Table 41.** These values are given in Hertz.

Table 41: B1 -- Minimum and maximum values of the minimum frequency

Min. frequency :	/ui/	/ei/	/ou/
Minimum value	42	21	48
Maximum value	230	210	222

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of B1 are represented in **Table 42**. These values are given in Hertz.

Table 42: B1 -- Minimum and maximum values of the maximum frequency

Max. frequency:	/ui/	/ei/	/ou/
Minimum value	121	114	167
Maximum value	428	316	619

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of B1 are represented in **Table 43.** These values are given in Hertz.

Table 43: B1 -- Minimum and maximum values of the mean frequency

Mean frequency	/ui/	/ei/	/ou/
Minimum value	72	77	78
Maximum value	301	199	328

The minimum and maximum /ui/, /ei/ and /ou/ values of the bandwidth range of B1 are represented in **Table 44.** These values are given in Hertz.

Table 44: B1 -- Minimum and maximum values of the bandwidth range

Bandwidth range:	/ui/	/ei/	/ou/
Minimum value	79	59	119
Maximum value	198	164	519

The difference between the minimum and maximum values of the minimum bandwidth, the maximum bandwidth, the mean bandwidth as well as the bandwidth range in identical diphthongs varies in all the cases between **105 Hz** for /ei/ and **452 Hz** for /ou/. However, the values of the different diphthongs overlap. In all four cases the overlap for /ui/ and /ei/ varies between **53%** and **80%**, for /ui/ and /ou/ between **18%** and **93%** and for /ei/ and /ou/ between **10%** and **81%**.

On the grounds of the variation in bandwidth in identical diphthongs as well as the overlap in the bandwidth of the three diphthongs it can be deduced the minimum bandwidth, the maximum bandwidth, the mean bandwidth as well as the bandwidth range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.5.1 CONCLUSIONS

Due to the variation in bandwidth in identical diphthongs, as well as the overlap in bandwidth of the three different diphthongs, it can be concluded that none of the above-mentioned parameters provide specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.6 BANDWIDTH 2: RESULTS AND DISCUSSION

Since the values for Bandwidth 2 varied greatly, no standard or complex third degree polynomial could describe the data points accurately and a standard fourth degree polynomial had to be found. For B2 the following standard fourth degree polynomial was found the be the most accurate for the data sets tested:

$$\mathbf{y = a + bx + cx^2 + dx^3 + ex^4}$$

All the curve fits are reasonably good fits since the r^2 coefficients of **/ui/** vary between **0.993** and **0.999** for the five subjects. For **/ei/**, the r^2 coefficients vary between **0.985** and **0.999** and for **/ou/** the r^2 coefficients vary between **0.981** and **0.999.**

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of bandwidth 2 (B2) are represented in **Table 45.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 45: B2 -- Minimum and maximum values of constant 'a'

Constant 'a':	/ui/	/ei/	/ou/
Minimum value	529	80	463
Maximum value	994	880	1055

The difference between the minimum and maximum 'a' values in identical diphthongs varies between **465** for /ui/ and **800** for /ei/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **35%, 79%** for /ui/ and /ei/ and **43%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'a' in identical diphthongs, as well as the overlap of the three diphthongs, it can be deduced the 'a' value cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of B2 are represented in **Table 46.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 46: B2 -- Minimum and maximum values of constant 'b'

Constant 'b':	/ui/	/ei/	/ou/
Minimum value	-1125	-960	-1310
Maximum value	-320	400	-198

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of B2 are represented in **Table 47.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 47: B2 -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	142	-235	64
Maximum value	600	450	676

The difference between the minimum and maximum values of 'b' in identical diphthongs varies between **560** for /ei/ and **1112** for /ou/. The difference between the minimum and maximum values of 'c' in identical diphthongs varies between **458** for /ui/ and **685** for /ei/.

As far as 'b' is concerned the overlap for /ui/ and /ei/ is **42%**, for /ui/ and /ou/, **72%** and /ei/ and /ou/, **45%**. As far as 'c' is concerned the overlap for /ui/ and /ei/ is **37%**, for /ui/ and /ou/, **75%** and for /ei/ and /ou/, **42%**.

On the grounds of the variation in the values of 'b' and 'c' in identical diphthongs as well as the overlap of the three diphthongs it can be deduced that the change in curve gradient cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of B2 are represented in **Table 48.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 48: B2 -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	-136	-97	-150
Maximum value	-12	47	-7

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **144** for /ei/ and **148** for /ui/). However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **46%**, **47%** for /ui/ and /ei/ and **94%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'd' in identical diphthongs, as well as the overlap of the three diphthongs, it can be deduced that the different curve deflections cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant e of B2 are represented in **Table 49.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 49: B2 -- Minimum and maximum values of constant 'e'

Constant 'e':	/ui/	/ei/	/ou/
Minimum value	0	-3	4
Maximum value	11	7	12

The difference between the minimum and maximum 'e' values in identical diphthongs varies between **8** for /ou/ and **11** for /ui/. The overlap for /ui/ and /ei/ is **50%, 58%** for /ui/ and /ei/ and **20%** for /ei/ and /ou/.

On the grounds of the overlap in the constant 'e' values of the three diphthongs it can be deduced that they cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of B2 are represented in **Table 50.** These values are given in Hertz.

Table 50: B2 -- Minimum and maximum values of the minimum frequency

Min frequency:	/ui/	/ei/	/ou/
Minimum value	150	197	123
Maximum value	226	359	294

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of B2 are represented in **Table 51.** These values are given in Hertz.

Table 51: B2 -- Minimum and maximum values of the maximum frequency

Max. frequency:	/ui/	/ei/	/ou/
Minimum value	299	288	579
Maximum value	632	566	696

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of B2 are represented in **Table 52.** These values are given in Hertz.

Table 52: B2 -- Minimum and maximum values of the mean frequency

Mean frequency:	/ui/	/ei/	/ou/
Minimum value	215	193	262
Maximum value	377	488	388

The minimum and maximum /ui/, /ei/ and /ou/ values of the frequency range of B2 are represented in **Table 53.** These values are given in Hertz.

Table 53: B2 -- Minimum and maximum values of the frequency range

Frequency range	/ui/	/ei/	/ou/
Minimum value	131	157	258
Maximum value	467	330	573

The difference between the minimum and maximum values of the minimum bandwidth, the maximum bandwidth, the mean bandwidth, as well as the bandwidth range in identical diphthongs varies in all the cases between **76** for /ui/ and **333** for /ui/.

In all four cases the overlap for /ui/ and /ei/ varies between **47%** and **78%**, for /ui/ and /ou/ between **11%** and **67%** and for /ei/ and /ou/ between **17%** and **43%**, except for the maximum frequency which does not overlap.

On the grounds of the variation in bandwidth in identical diphthongs, as well as the overlap in bandwidth of the three diphthongs, it can be deduced the minimum bandwidth, the maximum bandwidth, the mean bandwidth as well as the bandwidth range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.6.1 CONCLUSIONS

Due to the variation in bandwidth in identical diphthongs, as well as the overlap in bandwidth of the three different diphthongs, it can be concluded that none of the above-mentioned parameters provide specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.7 BANDWIDTH 3: RESULTS AND DISCUSSION

Since the values for Bandwidth 3 varied greatly, no standard or complex third degree polynomial could describe the data points accurately and a standard fourth degree polynomial had to be found. For the B3 the following standard fourth degree polynomial was found to be the most accurate for the data sets tested:

$$\mathbf{y = a + bx + cx^2 + dx^3 + ex^4}$$

All the curve fits are reasonably good fits since the r^2 coefficients of **/ui/** vary between **0.829** and **0.997** for the five subjects. For **/ei/**, the r^2 coefficients vary between **0.973** and **0.999** and for **/ou/** the r^2 coefficients vary between **0.993** and **0.998**.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'a' of Bandwidth 3 (B3) are represented in **Table 54.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant

Table 54: B3 -- Minimum and maximum values of constant 'a'

Constant 'a'	/ui/	/ei/	/ou/
Minimum value	319	197	345
Maximum value	904	1229	1298

The difference between the minimum and maximum 'a' values in identical diphthongs varies between **585** for /ui/ and **1032** for /ei/. However, the values of the different diphthongs overlap. The overlap for /ui/ and /ei/ is **57%, 57%** for /ui/ and /ei/ and **80%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'a' in identical diphthongs as well as the overlap of the three diphthongs it can be deduced the 'a' value cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant b of B3 are represented in **Table 55.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 55: B3 -- Minimum and maximum values of constant 'b'

Constant 'b'	/ui/	/ei/	/ou/
Minimum value	-916	-1292	-1738
Maximum value	-125	86	-189

The minimum and maximum /ui/, /ei/ and /ou/ values of constant c of B3 are represented in **Table 56.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 56: B3 -- Minimum and maximum values of constant 'c'

Constant 'c':	/ui/	/ei/	/ou/
Minimum value	39	-41	94
Maximum value	463	529	937

The difference between the minimum and maximum values of 'b' in identical diphthongs varies between **791** for /ui/ and **1549** for /ou/. The difference between the values of 'c' in identical diphthongs varies between **424** for /ui/ and **843** for /ou/. However, the values of the different diphthongs overlap. As far as 'b' is concerned the overlap for /ui/ and /ei/ is **57%,** for /ui/ and /ou/, **45%** and for /ei/ and /ou/ **61%**. As far as 'c' is concerned the overlap for /ui/ and /ei/ is **74%** for /ui/ and /ou/, **41%** and for /ei/ and /ou/, **45%**.

On the grounds of the variation in the values of 'b' and 'c' in identical diphthongs as well as the overlap of the three diphthongs it can be deduced that the change in curve gradient of the bandwidths cannot be a differentiating factor for the different diphthongs.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant d of B3 are represented in **Table 57**. Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 57: B3 -- Minimum and maximum values of constant 'd'

Constant 'd':	/ui/	/ei/	/ou/
Minimum value	-96	-81	-209
Maximum value	-4	7	-23

The difference between the minimum and maximum 'd' values in identical diphthongs varies between **88** for /ei/ and **186** for /ou/. On the other hand the values for the different diphthongs overlap. The overlap for /ui/ and /ei/ is **75%**, **36%** for /ui/ and /ei/ and **27%** for /ei/ and /ou/.

On the grounds of the variation in the values of 'd' in identical diphthongs, as well as the overlap of the three diphthongs, it can be deduced that the different curve deflections cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of constant 'e' of B3 are represented in **Table 58.** Since constants are mathematical function parameters no units such as Hertz are given because it is irrelevant.

Table 58: B3 -- Minimum and maximum values of constant 'e'

Constant 'e':	/ui/	/ei/	/ou/
Minimum value	1	-1	2
Maximum value	7	8	17

The difference between minimum and maximum values in identical diphthongs varies between **6** for /ou/ and **15** for /ui/. The overlap for /ui/ and /ei/ is **78%**,. **31%** for /ui/ and /ei/ and **33%** for /ei/ and /ou/.

On the grounds of the overlap of the three diphthongs it can be deduced that the different 'e' values cannot indicate differences between the diphthongs /ui/ and /ei/ and /ou/.

The minimum and maximum /ui/, /ei/ and /ou/ values of the minimum frequency of B3 are represented in **Table 59.** These values are given in Hertz.

Table 59: B3 -- Minimum and maximum values of the minimum frequency

Min. frequency:	/ui/	/ei/	/ou/
Minimum value	139	198	167
Maximum value	370	359	381

The minimum and maximum /ui/, /ei/ and /ou/ values of the maximum frequency of B3 are represented in **Table 60.** These values are given in Hertz.

Table 60: B3 -- Minimum and maximum values of the maximum frequency

Max. frequency:	/ui/	/ei/	/ou/
Minimum value	227	255	167
Maximum value	511	623	968

The minimum and maximum /ui/, /ei/ and /ou/ values of the mean frequency of B3 are represented in **Table 61.** These values are given in Hertz.

Table 61: B3 -- Minimum and maximum values of the mean frequency

Mean frequency:	/ui/	/ei/	/ou/
Minimum value	195	225	253
Maximum value	440	446	502

The minimum and maximum /ui/, /ei/ and /ou/ values of the frequency range of B3 are represented in **Table 62.** These values are given in Hertz.

Table 62: B3 -- Minimum and maximum values of the frequency range

Frequency range:	/ui/	/ei/	/ou/
Minimum value	46	57	277
Maximum value	293	423	776

The difference between the minimum and maximum values of the minimum bandwidth, the maximum bandwidth, the mean bandwidth as well as the bandwidth range in identical diphthongs varies in all the cases between **161** for /ei/ and **801** for /ou/. However, the values of the different diphthongs overlap. In all four cases the overlap for /ui/ and /ei/ varies between **63%** and **86%**, for /ui/ and /ou/ between **2%** and **84%** and for /ei/ and /ou/ between **20%** and **75%**, except for the maximum frequency which does not overlap.

On the grounds of the variation in bandwidth in identical diphthongs, as well as the overlap in the bandwidth of the three diphthongs, it can be deduced the minimum bandwidth, the maximum bandwidth, the mean bandwidth as well as the bandwidth range do not provide the specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.1.7.1 CONCLUSIONS

Due to the variation in bandwidth in identical diphthongs, as well as the overlap in bandwidth of the three different diphthongs, it can be concluded that none of the above-mentioned parameters provide specific cues to distinguish between the three diphthongs unambiguously.

3.2.6.2 Summary and conclusions

In the production test the acoustical features of Afrikaans diphthongs were studied. A way of analysing the whole diphthong pattern was pursued and curve fits were performed on the F1-F3, amplitude and B1-B3.

For all the above mentioned parameters it was found that the minimum and maximum values of the different constants (a-e) as well as the minimum, maximum and mean frequencies and the frequency range for identical diphthongs varied greatly in most cases. It was also found that the minimum and maximum values of the different constants (a-e) as well as the minimum, maximum and mean frequencies and the frequency range of the different diphthongs overlapped in most cases.

The results of F1 indicated that none of the components (except for constant 'a' with which it is possible to distinguish between /ui/ and /ei/) of the formant pattern (neither the target theory nor the trajectory theory) could individually describe diphthongs unambiguously.

The results of F2 indicated that none of the individual components of the formant pattern (neither the target theory nor the trajectory theory) could describe the diphthongs /ui/ and /ei/

unambiguously. The possibility that such a description lies in a combination of the different components has to be tested perceptually.

It was possible though, on the grounds of the offset (target theory), the change in curve gradient (trajectory theory), the curve deflection as well as the minimum frequency (not in the case of ei/), the maximum frequency, the mean frequency and the frequency range (not in the case of /ui/) to distinguish between /ou/ and the other two diphthongs.

The results of F3, amplitude, B1, B2 and B3 suggest that none of the individual components of the formant pattern can describe diphthongs unambiguously. The possibility that such a description lies in a combination of the different components has to be tested perceptually (cf. Chapter 4).

From these results it is also clear that production tests alone are not sufficient, although they provide important information. Values obtained from production tests are especially important when used in perception tests.

In the following chapter the perception test is discussed; firstly, the experiment (the subjects, the stimulus material, apparatus, the data collection and measuring procedures) is discussed, and secondly the method of data analysis is represented. The results of the perception test is then given, interpreted and discussed.

Chapter 4: THE PERCEPTION TEST

4.1 INTRODUCTION

In Chapter 3 the production test was presented and the results indicated that none of the individual components of the formant patterns of diphthongs could describe the different diphthongs unambiguously. It is of vital importance that these findings be tested perceptually.

In this chapter the perception test is discussed: firstly, the available literature is reviewed and secondly the method of research is described. The stimulus material, the subjects who took part in the perception test, the data collection procedure as well as the data analysis and relevant statistics are given. The results, a discussion and an interpretation of the results, as well as the relevance of these results for the objectives of this study are also presented.

4.2 SPEECH PERCEPTION

4.2.1 General introduction

"The final link in the speech chain is a perceptual process leading to a representation of the speaker's message in the listener" (Picket, 1980:169). According to Van Hessen (1992) and Peeters (1991), perception plays the decisive part in the speech chain.

Borden and Harris (1984) state that speech perception is a specialised aspect of general human ability, the ability to seek and recognise patterns. In this case the patterns are acoustic patterns which listeners use as cues to the understanding of speech. Speech sounds are often not discrete and the listener, therefore, has to use context to decode the message.

The acoustic study of speech perception began early in the nineteenth century and the past 50 years of speech research has involved a very important interaction between perception studies and the acoustic modelling of speech production (Picket, 1980).

There are two general groups of theories on how speech perception proceeds. One group of theories view the listener as relatively passive and the process of speech perception as primarily sensory. The message is sensed, filtered and mapped directly onto the acoustic - phonetic features of the language. Examples of these theories are those of Fant, and Morton and Broadbent (Borden & Harris, 1984).

The other group of theories view the listeners as being more active and postulates that the process of speech perception involves some aspect of speech production; the sounds are sensed, analysed for their phonetic properties by reference to how such speech sounds are produced and thus are recognised. Examples of active theories are the Motor Theory of Liberman and the Analysis-by-Synthesis-Theory of Stevens and Halle (Borden & Harris, 1984; Van Hessen, 1992).

According to Borden and Harris (1984), it is known from the study of speech spectrograms that the acoustic patterns are complex and constantly changing. An important question to be asked is whether the listener uses all this information or are certain parts of the acoustic patterns more important to speech perception than other parts. In research on speech perception the basic problem is to discover which aspects of the sound pattern are the essential ones; the ones used by listeners to identify a given unit of speech (Picket, 1980).

Kent and Read (1992:178) declared that if we conclude from spectral analyses that a certain formant pattern is crucial to the production and comprehension, the real test of that hypothesis is to synthesise that pattern and to see whether listeners perceive it as being that specific sound. They maintained that synthesis is essential in studies of how people perceive speech. By synthesising speech, speech scientists have altered various parameters of the acoustic signal and then tested listeners to discover the effects on perception. This is done for Afrikaans in this study.

In modern synthesis almost any feature of speech which is thought to be important can be controlled. Types of syntheses are formant synthesis, synthesis by rule, articulatory synthesis and synthesis based on linear predictive coding (LPC) (Kent & Read, 1992).

Many different types of experiments can be employed in perception tests. In a **discrimination** experiment the subject compares two stimuli. In a "two-interval, two-alternative forced choice" discrimination experiment (2IFC) the stimuli are always different and the subject has to determine the order in which they are presented. In an AX discrimination experiment the two stimuli are either different or the same, and the subject has to determine whether they are equal or different (Van Hessen, 1992).

In a **fixed discrimination** experiment all possible combinations of only one stimulus pair (two stimuli) are presented a number of times in random order. When all combinations have been presented an equal number of times, a new stimulus pair is presented. In a **roving discrimination** experiment the different combinations of all stimulus pairs are presented in a random order. Roving discrimination differs from fixed discrimination in that the stimulus pair is selected randomly for each presentation.

According to Van Hessen (1992) there are some serious disadvantages in using AX and 2IFC in speech discrimination. For example, if subjects are asked if two stimuli are equal or different, they may decide to respond "different" only if they are very sure of their decision.

Identification or **classification** experiments are also distinguished. In an absolute identification experiment, a subject is asked to name each stimulus, resulting in N possible answers for a set of N different stimuli. Another possibility is an identification experiment where a subject is asked which of two or three categories the presented stimulus resembles most.

According to Sawusch, Nusbaum and Schwab (1980: 421), the identification of any individual stimulus item tends to migrate toward certain categories other than those to which the items are presented. In the so-called **anchoring procedure** subjects are presented with a set of stimuli to be identified under two conditions. The first is an equiprobable control in which each stimulus occurs equally often. In the second, the anchor condition, one of the stimuli occurs more often than the other (Sawusch, Nusbaum & Schwab,1980: 422).

4.2.2 Outline on perception studies of diphthongs

The available literature indicate that researchers use either production or perception tests in their studies on diphthongs. Lehiste and Peterson (1961), de Manrique (1979), Collier et al., (1982) Toledo and Antonanzas-Barroso (1987), Cao, (1991), Stollwerck (1991) and Gottfried et al. (1993) all make use of production tests in studying diphthongs. The following researchers, however, made use of perception studies.

Gay (1967) uses the 'Pattern playback' device to synthesise diphthongs. He analysed the effects of formant frequency movement on the perception of five American English diphthongs, as well as the effects of overall glide duration in two experiments. The results of the first experiment did not reveal whether target frequency or rate of formant frequency change were the cues for specific diphthong recognition.

From the results of the second experiment Gay deduced that transition duration, rather than change in frequency (F2), was important in diphthong identification. Unfortunately, in eliminating either the initial or final portion of the transition, the structure of the diphthong as a perceptual unit was violated (Peeters, 1991). Gay's data in the 1967 and 1968 studies are contradictory. In the first perception experiment of Gay's (1970) study, synthetic formant transitions were presented to ten phonetically trained listeners. Five different F2 onset values ranging from 840 Hz – 1320 Hz were extended to terminal values of either 1920 Hz or 2040 Hz. F1 transitions began at 600 Hz and terminated either at 480 Hz or 360 Hz. The synthetic carrier phrase "The word is..." was inserted before each diphthong.

Results obtained from this experiment indicated that steady states are non-essential for diphthong identification.

The duration of the synthetic stimuli in the second experiment was manipulated in steps of 10 milliseconds; in one case beginning at the initial target, and in the other beginning at the terminal target. Fixed onset and offset stimuli were arranged in two separate lists and were embedded in a carrier phrase. Results showed that the transition duration, rather than the change in frequency position, provided cues for diphthong identification. Gay concludes that the rate of formant change is a fixed feature of diphthong movement.

In his first experiment Bond (1982) investigated the effects of changing steady state and glide durations on the identification of the phonemic diphthongs [ai], [au] and [ɔi]. Synthetic variants of the three phonemic diphthongs were created. Formant values and basic durations of the steady state and glide portions were specified on the basis of measurements from spectrograms. Diphthongs were synthesised with the maximal steady state duration found in natural speech and at two thirds and one third of the maximal duration, as well as at 10 ms. A final steady state value of 0 ms was employed, as well as three glide durations (Bond, 1982:260). Ten subjects took part in the experiment where they had to identify diphthongs.

Bond found that no clearly preferred diphthong structures emerged from this experiment and concluded that, "...listeners need two targets; either a glide beginning and ending at those targets, or the targets without a detectable glide also prove to be sufficient." (Bond, 1982:264).

A point of criticism against Bond's study is that the diphthong identification is too easy a task. Peeters (1991:91) also claims that since the diphthong amplitude contour is a very poor one, it casts doubt on the quality of the stimuli used. Furthermore, Bond (1982) used a glide duration of 10 ms and it is physiologically impossible for a human being to produce such a short glide. Since a diphthong is extremely resistant to manipulations (Peeters, 1991), another point of criticism is that the language-specific relationship of intrinsic inner-component-length categories and overall duration were violated.

Collier and 't Hart (1983) made use of a perception test in their study of Dutch diphthongs. They built two types of continua, one with gradual formant frequency changes and one with abrupt formant frequency transitions. On the basis of the acoustic analysis of diphthongs naturally spoken in isolation, the onset and offset formant frequencies, the duration and the F0 contour were established. Both stimulus continua were given a fixed duration of 350 ms. A point of criticism is that a duration of 350 ms is very long and might have an influence on the degree of difficulty of the task. When the duration of the synthesised diphthongs is not in line with the values of actual diphthongs (as produced in production tests), the task might become too easy.

In the listening tests they elicited two types of judgements; forced choice comparisons as well as absolute judgements. Forced choice comparisons were made between two different types of stimulus pairs. In one type the members of a pair belonged to the same continuum, so that the onset time of the spectral change was the variable to be evaluated. In the other type of stimulus pairs, the comparisons involved stimuli from two different continua, which had identical onset times for their transitions, but different rates of change (Collier & 't Hart,1983: 34).

In the second case, subjects had to make an absolute judgement on the quality of a stimulus presented in isolation. They were asked to express their judgements on a scale ranging from 0 (very poor) to 3 (very good).

Two groups of subjects participated in the listening experiments. The results indicated that no preferred rate of change for formant transitions emerged and this implies no need for a final steady state part in Dutch diphthongs. It was also found that the onset time of formant transitions had an important influence on the quality of diphthongs.

Unfortunately, Collier and 't Hart (1983) did not define 'rate of change' in their experiment. Peeters (1991) also criticises the fact that they compared a genuine diphthong with a pseudo diphthong without knowing their exact properties.

Bladon (1985) wanted to clarify the issue of target versus trajectory in the perception of diphthongs. He made use of a perception test in order to determine whether the listener attends to the diphthong's endpoints or to its spectral rate of change. The vowel combinations (or diphthongs as Bladon calls them) [ia], [ie] and [iɔ] and the diphthong [ai] were used.

In the first experiment he did not synthesise diphthongs but the experimental stimuli were made up from three recorded syllables by computer editing their waveforms. These waveforms were cut back so that much of the latter part of the signal was removed, leaving stimuli consisting of [i] plus a varying amount of the transition. The editing procedure generated five curtailed stimuli of durations of 50 ms, 75 ms, 100 ms, 125 ms and 150 ms (Bladon, 1985: 149). Four phonetically trained listeners took part in the experiments. The task was an identification task and the subjects had to listen to three repetitions of each stimulus. Bladon's results show that the endpoints attained are very important in the perception of diphthongs.

In his second experiment a male speaker recorded five diphthongs. The diphthong transitions were removed by computer editing and the utterances were resynthesised. These utterances were assembled onto an experimental tape, together with five monophthongs as well as five 'transition-only' diphthongs. Four subjects took part in this forced choice experiment. The identification of the monophthongs as well as the transitionless diphthongs were error free, while only 46% correct identifications of transition-only diphthongs were made.

In his first experiment Bladon's results yielded a preference for the target theory over the trajectory theory. It is a problem though, that the vowel combinations are non-existant diphthongs in British English. Therefore, the results cannot be extrapolated to genuine diphthongs. Only the vowel combinations were used in the second experiment and the diphthong [ai] was absent from this experiment.

Peeters (1991) decided in favour of a perceptual approach. A diphthong continuum consisting of formant paths showing variation in the temporal domain only, was devised. Numerous temporal patterns were obtained by varying in fixed steps the durational relations between the onset steady state, glide and offset steady state portions (Peeters, 1991:101). These components varied in duration, each between 0 ms and 240 ms, within the fixed overall duration of 240 ms. All stimuli were given fixed overall onset and offset formant frequencies. Given the overall duration of 240 ms, the step interval of 20 ms and the variability of the temporal patterns, a continuum with 80 arithmetically possible positions was devised.

The generation of the temporal patterns was done with the CHF-programme of LVS which allows manipulation per frame of amplitude gain factor, F0, F1-F5 and B1-B5. (Peeters, 1991: 105). Once the best sounding amplitude gain contour and the F0 course, together with the F4-F5 and B4-B5 parameters, had been defined, they were stored as basic parameters for a particular sound continuum. The relevant parameters, either the first three resonances or a selection of them, were varied temporally. After an auditory check the stimuli were stored.

The synthesised diphthongs (which were as speech-like as possible) were presented to subjects who had to perform a paired-comparison task. The subjects had to distinguish between two stimuli and state which sound, in the pairs presented, was a better representation of the particular sound. The stimuli were presented over headphones to groups of four to seven subjects.

Two types of diphthong patterns emerged from these experiments. A steady state, glide, steady state structure, as well as a steady state, offglide structure. Peeters found that these temporal formant patterns embodiy the distinctive feature with which a diphthong can be described unambiguously. He further maintains that these patterns are language-specific.

The first part of Gerrits' (1995) study involved a production experiment while in the second part of the study synthesised diphthongs were judged by five experienced and five inexperienced listeners in two perception experiments.

A number of diphthongs were synthesised following the results of the production test. During the synthesis the duration and formant frequencies of the material produced by deaf speakers, speech therapists and naïve speakers were used. Three types of synthetic diphthongs were created; synthetic diphthongs with speaker-specific duration; synthetic diphthongs with speaker-specific formant frequencies and synthetic diphthongs with speaker specific duration and formant frequencies (Gerrits, 1995:28).

In the first perception experiment the question was asked whether listeners have a preference for the synthesised diphthongs of a specific group of speakers. The synthesised diphthongs were presented in pairs (a; b; and b; a) and presented to the subjects who had to choose the sound in the pairs which was the best representation of that specific sound. Gerrits found that listeners preferred stimuli with speaker-specific parameters of one particular group of speakers, the naïve group.

In the second experiment, the three types of diphthongs were linked, depending on the original group of speakers. The speaker specific parameter, which influenced the judgements of the listeners most, was tested in this experiment. The material was also presented in pairs and listeners had to indicate which of the two stimuli they preferred. Different results were found for /au/ and /ui/. For /ui/ most judgements were influenced by a variation in duration, while in the case of /au/ the influence of each type of diphthong was equal and there was an interaction between the type of diphthong and the speaker group.

Nabelek et al. (1996) conducted two experiments. In the first experiment [ai] diphthongs were generated with a Klatt synthesiser. The stimulus was 200 ms long and F1 changed in a downward direction from 700 Hz to 310 Hz, while F2 changed in an upward direction from 1220 Hz to 1920 Hz. The stimuli differed in the amount of attenuation of the transition segment which ranged from 0 dB to 15 dB The 16 stimuli were generated ten times in random order and were then tested in quiet, noise and reverberation with ten normal-hearing and seven hearing-impaired subjects (Nabelek et al., 1996:1743).

Their results indicated that identification errors in noise and reverberation for diphthongs might be related to the intensity of their transition segments. In the second experiment naturally produced diphthongs were spectrally analysed.

4.3 METHOD OF RESEARCH

4.3.1 THE EXPERIMENT – INTRODUCTION

The method of research of the perception test is discussed in this section. The specific objectives of the study are to determine which theory (cf. Chapter 2) is more likely to describe Afrikaans diphthongs unambiguously, as well as to determine the temporal formant patterns for Afrikaans diphthongs. Another objective is to ascertain whether, if a specific pattern is found, another pattern will also be acceptable to the listener. The experiment was devised to test the above mentioned objectives. The stimulus material, the choice of subjects to take part in the listening test, the data collection procedure, the data analysis and statistics, as well as the results and a discussion of the results are represented in the following paragraphs.

4.3.2 SUBJECTS

Twenty five male and female subjects took part in the experiment and they did not know the purpose of the experiment. The subjects were either lecturers in the Department of Afrikaans at the Potchefstroom University, or third year students in the same department. All subjects spoke Afrikaans as their mother tongue and no cases of impaired hearing were reported. They participated on a voluntary basis and were not paid for their services.

4.3.3 STIMULUS MATERIAL

In the various investigations of diphthongs considered in this study, the different researchers only tested one of the three theories: the target theory, the trajectory theory, or the temporal formant pattern. The only exception was that of Gottfried et al. (1993), who considered three hypotheses as to the acoustically relevant properties of diphthongs: 'the onset plus offset', the 'onset plus slope' and the 'onset plus direction' hypotheses. In the perception test of the present study the target theory, the trajectory theory and the temporal formant pattern are tested perceptually. As far as the trajectory theory is concerned, the **direction of change**, as well as the **rate of change** are tested.

The average values for the onset and offset of F1 and F2, as well as the total duration of the diphthongs determined in the production test (cf. Chapter 3), were used to synthesise the stimulus material. The onset and offset values were rounded off to the nearest 50 Hz for example, the average onset value for F1 /ei/ of 590 Hz was rounded off to 600 Hz. In the case of the total duration, the average duration values were rounded off to the nearest 10 ms., for example, the actual average duration for /ei/ of 121 ms was rounded off to 120 ms.

In the production test the Wiber program was used to save six measuring points for, inter alia, the F1 and F2 of the different diphthongs (cf. 3.2.4 MEASURING PROCEDURE). Consequently, six values per parameter were available to use in the perception test.

The average (rounded) onset and offset values of the first two formants (F1 & F2) of the three diphthongs of the different subjects are presented in **Table 63**. These values are given in Hertz.

Table 63: Average onset and offset values of the three diphthongs

	[ui]	[ou]	[ei]
F1 – onset	550	550	600
F1 – offset	350	350	350
F2 – onset	1300	1350	1400
F2 – offset	1800	1200	1900

The average (rounded) durational values of the three diphthongs of the different subjects are presented in **Table 64**. These values are given in milliseconds.

Table 64: Average duration of the three diphthongs

[ui]	[ou]	[ei]
160	160	120

The six time intervals (0, t, 2t, 3t, 4t, 5t) for the three diphthongs are given in **Table 65** with t being equal to a frame length. The values of the six measuring points are given in milliseconds.

Table 65: The six time intervals of the three diphthongs.

Measuring points	0	t	2t	3t	4t	5t
/ui/	0	32	64	96	128	160
/ou/	0	32	64	96	128	160
/ei/	0	24	48	72	96	120

An approach to speech synthesis known as HLSyn, was used to synthesise the sounds for the perception test. The HLSyn is a high-level speech synthesiser program and provides an integrated environment for specifying, creating, analysing and comparing speech synthesis files. The HL synthesis method attempts to combine the simplicity of control that characterises articulatory approaches to speech synthesis with the accuracy and computational efficiency of traditional formant synthesis (HLSyn User Manual, 1995).

There are ten HL parameters which include F0, F1-F4 and parameters such as the rate of vocal tract volume and the area of nasal opening. The latter all have fixed default values. The bandwidths of F1 – F4 are set at fixed values: B1 = 80 Hz, B2 = 90 Hz, B3 = 150 Hz and B4 = 350 Hz.

In this investigation the average values for F0 and F1-F4 were used, but only the F1 and F2 values were manipulated in order to test the three theories. Since the study conducted by Peterson and Barney (1952) it has been a widely held view that the main acoustic determinants of vowel quality are the frequencies of F1 and F2. F1 and F2 are also of vital importance in determining the acoustic quality of **diphthongs**. On these grounds only F1 and F2 were manipulated in the perception test.

The methods used to devise the stimuli to test the different theories are now discussed. Throughout this section, the following abbreveations were used to identify the average onset and offset values:

- P = Average onset value
- Q = Average offset value

4.3.3.1 The target theory

To test the target theory, nine manipulations per diphthong were synthesised. For each sound both the average onset values (P) and the average offset values (Q) of F1 and F2 were varied. The above explanation is illustrated in Figure 7 to Figure 11. The nine sounds are identified as dark green, red, and blue. Since the average onset and offset values of **F1** for /ui/ and /ou/ are the same, they are both presented in Figure 7.

For Figure 7 to Figure 11, descriptions are provided above the figures as follows:
Firstly, the onset and offset values are defined at their (x,y) positions on the graph ('k' defines the respective nine points, starting from the onset values). Secondly, the glide is established at the nine gradients of the curves (y/x), i.e., lines from average onsets P1, P2, P3 to the average offsets Q1, Q2, Q3. Thirdly, the gradients are combined with the onsets to reveal the standard mathematical relation for a straight line, namely y=[gradient]x+[y value at x=0].

The nine different manipulations for /ei/, /ou/ and /ui/ and their different onset and offset values are presented in **Table 66.** The values are given in Hertz

Table 66: Target manipulations

	F1		F2		
Diphthong	**Onset**	**Offset**	**Onset**	**Offset**	
/ei/	500	250	1300	1800	a
/ei/	600	250	1400	1800	b
/ei/	700	250	1500	1800	c
/ei/	500	350	1300	1900	d
/ei/	600	350	1400	1900	e
/ei/	700	350	1500	1900	f
/ei/	500	450	1300	2000	g
/ei/	600	450	1400	2000	h
/ei/	700	450	1500	2000	i
/ou/	450	250	1250	1100	a
/ou/	550	250	1350	1100	b
/ou/	650	250	1450	1100	c
/ou/	450	350	1250	1200	d
/ou/	550	350	1350	1200	e
/ou/	650	350	1450	1200	f
/ou/	450	450	1250	1300	g
/ou/	550	450	1350	1300	h
/ou/	650	450	1450	1300	i
/ui/	450	250	1200	1700	a
/ui/	550	250	1300	1700	b
/ui/	650	250	1400	1700	c
/ui/	450	350	1200	1800	d
/ui/	550	350	1300	1800	e
/ui/	650	350	1400	1800	f
/ui/	450	450	1200	1900	g
/ui/	550	450	1300	1900	h
/ui/	650	450	1400	1900	i

Figure 7: For /ui/ and /ou/ of F1, nine combinations of <u>onset (P_k)</u> = (0,550+k), and <u>offset (Q_k)</u> = (160,350+k) for k= -100,0,+100; <u>Glide</u>: gradient = -(1+m)/1.6 at P1, -m/1.6 at P2, and -(-1+m)/1.6 at P3, thus, the nine <u>descriptive functions</u> are:

$$y= -[k+100m/160]x+[550+k]$$

for m=1 (at Q1), 2 (at Q2),3 (at Q3) and k=-100 (at P1), 0 (at P2), +100 (at P3)

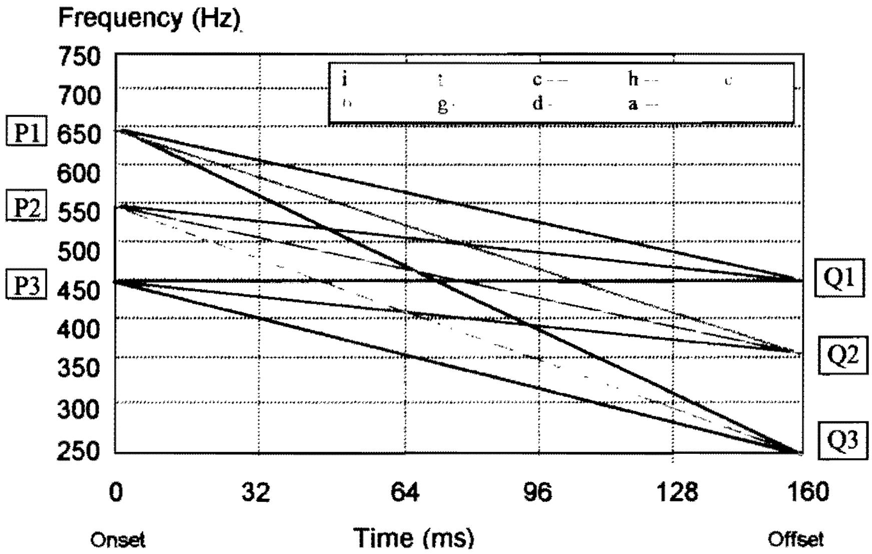


Figure 7: Target theory: /ui/ and /ou/ of F1

Figure 8: For /ei/ of F1 the parameters are nine combinations of <u>onset (P_k)</u> = (0,600+k), and <u>offset (Q_k)</u> = (120,350+k) for k= -100,0,+100; <u>Glide</u>: gradient = -(1.5+m)/1.2 at P1, -(0.5+m)/1.2 at P2, and -(-0.5+m)/1.2 at P3, thus, the nine <u>descriptive functions</u> are: y= -[50+k+100m/120]x+[600+k]

for m=1 (at Q1), 2 (at Q2),3 (at Q3) and k=-100 (at P1), 0 (at P2), +100 (at P3)

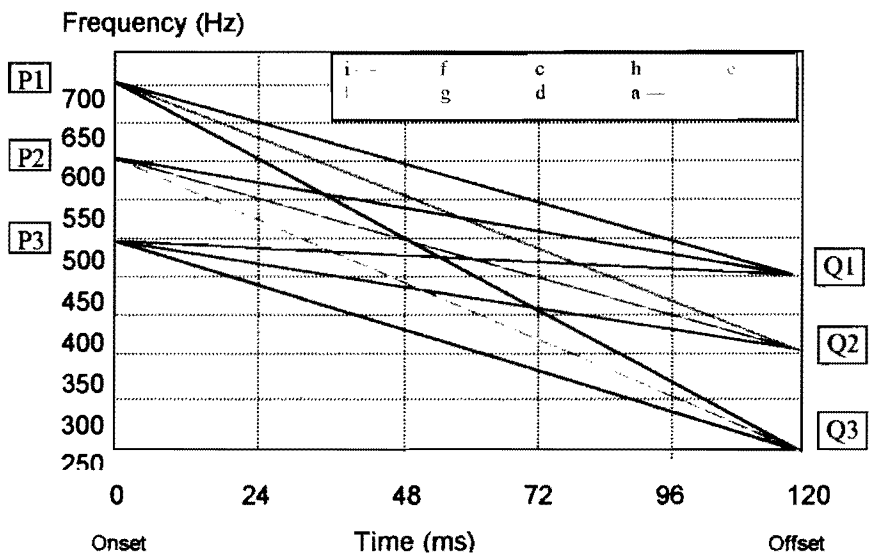


Figure 8: Target theory: /ei/ of F1

Figure 9: For /ui/ of F2 the parameters are nine combinations of onset (P_k) = (0,1300+k), and offset (Q_k) = (160,1800+k) for k= -100,0,+100; Glide: gradient = (2+m)/1.6 at P1, (3+m)/1.6 at P2, and (4+m)/1.6 at P3, the nine descriptive functions are: y= [(300+k+100m)/160]x+[1300+k]
for m=1 (at Q3), 2 (at Q2),3 (at Q1) and k=-100 (at P1), 0 (at P2), +100 (at P3)

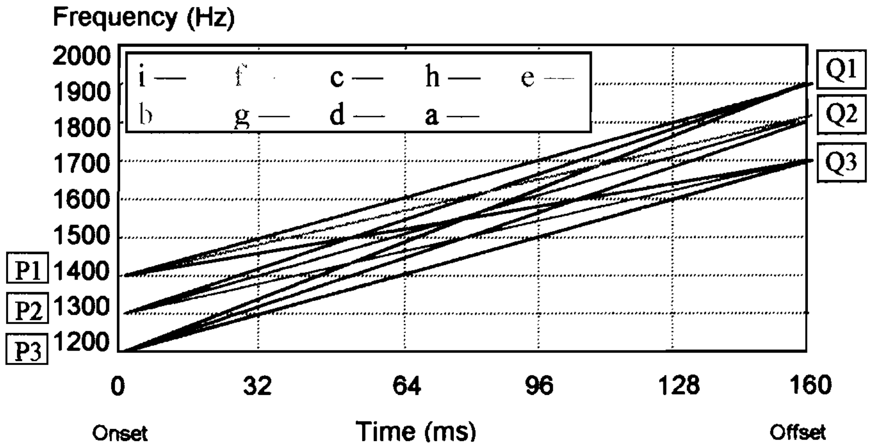


Figure 9: Target theory: /ui/ of F2

Figure 10: For /ou/ of F2 the parameters are nine combinations of onset (P_k) = (0,1350+k), and offset (Q_k) = (160,1200+k) for k= -100,0,+100; Glide: = -(0.5+m)/1.6 at P1, -(-0.5+m)/1.6 at P2, and -(-1.5+m)/1.6 at P3, thus, the nine descriptive functions are: y= -[(-50+k+100m)/160]x+[1350+k]
for m=1 (at Q1), 2 (at Q2),3 (at Q3) and k=-100 (at P1), 0 (at P2), +100 (at P3)

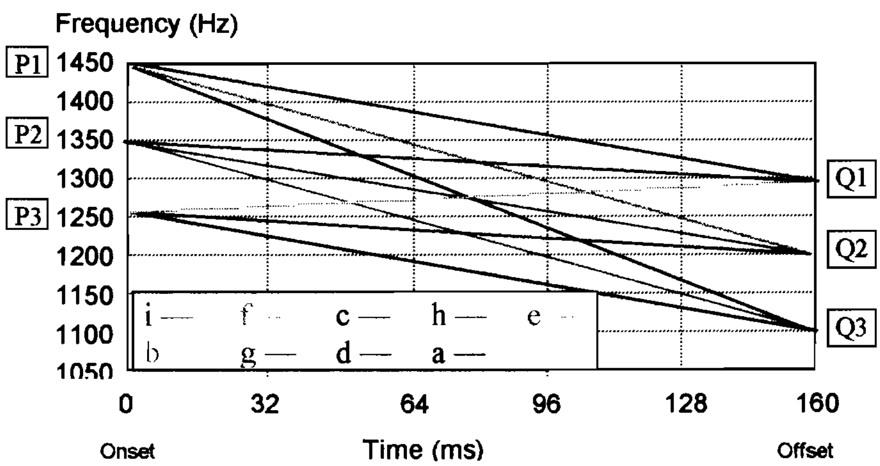


Figure 10: Target theory: /ou/ of F2

Figure 11: For /ei/ of F2 the parameters are nine combinations of onset (P_k) = (0,1400+k), and offset (Q_k) = (120,1900+k) for k= -100,0,+100; Glide: gradient = (2+m)/1.2 at P1, (3+m)/1.2 at P2, and (4+m)/1.2 at P3, the nine descriptive functions are: y=[(300+k+100m)/120]x+[1400+k]
for m=1 (at Q3), 2 (at Q2),3 (at Q1) and k=-100 (at P1), 0 (at P2), +100 (at P3)

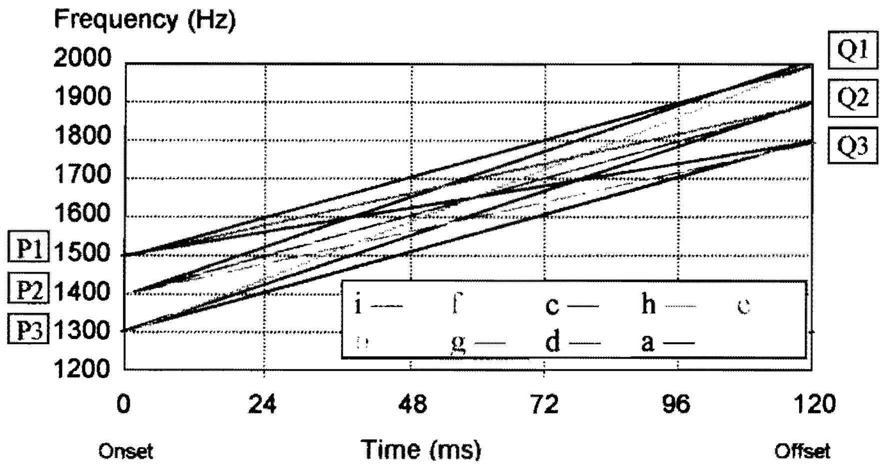


Figure 11: Target theory: /ei/ of F2

4.3.3.2 The trajectory theory – the direction of change

To test the 'direction of change', three manipulations per diphthong were synthesised. For each sound the average F1 and F2 onset values (**P**) were taken at 0 ms and three different offset values for F1 and F2 were synthesised. The first offset value was 100 Hz less than the average offset value (**Q-100 Hz**). The second value was the average value (**Q**) and the third value was 100 Hz more than the average value (**Q+100 Hz**), thus three different directions of change were synthesised. The above mentioned explanation is illustrated in Figure 12 to Figure 16. Since the average onset and offset values of **F1** for /ui/ and /ou/ are the same, they are both presented in Figure 12.

For the sake of convenience the values of F1 and F2 are presented in different figures. The three manipulations are identified as red, blue and green.

From Figure 12 to Figure 16, descriptions are provided, above the figures, as follows:

Firstly, the onset and offset values are defined at their (x,y) positions on the graph ('k' defines the two curves above and below the average offset values). Secondly, the glide is established, simply as the gradient of the curve (y/x). Thirdly, the gradient is combined with the onset to reveal the standard mathematical relation for a straight line, namely y=[gradient]x+[y value at x=0].

The three different manipulations for /ei/, /ou/ and /ui/ and their different onset and offset values are presented in **Table 67**. The values are given in Hertz.

Table 67: Direction of change manipulations

	F1		F2		
Diphthong	**Onset**	**Offset**	**Onset**	**Offset**	**Manipulation**
/ei/	600	250	1400	1800	a
/ei/	600	350	1400	1900	b
/ei/	600	450	1400	2000	c
/ou/	550	250	1350	1100	a
/ou/	550	350	1350	1200	b
/ou/	550	450	1350	1300	c
/ui/	550	250	1300	1700	a
/ui/	550	350	1300	1800	b
/ui/	550	450	1300	1900	c

Figure 12: For /ui/ and /ou/ of F1 the parameters are: Onset (P) = (0,550) constant; Offset (Q) = (160,350+k) for k= -100,0,+100; Glide: gradient y/x = -(100m/160), thus, the descriptive function is: y= -[m/1.6]x+550 for m=1,2,3

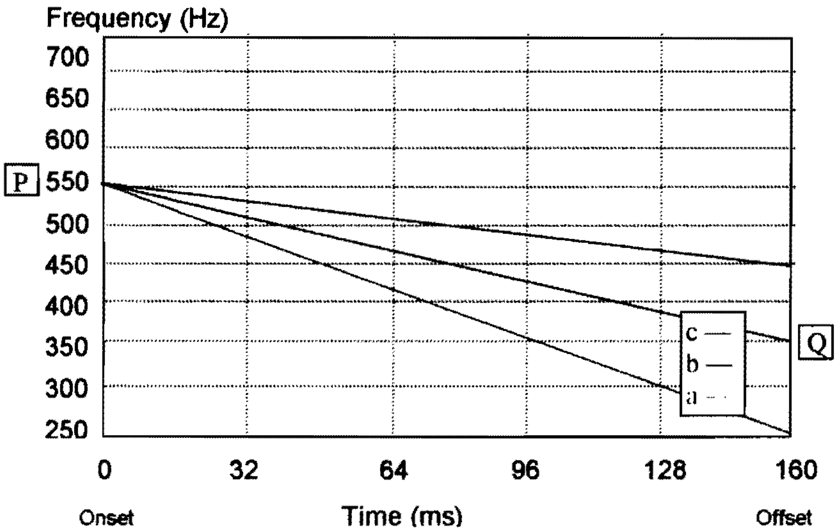


Figure 12: Trajectory theory (Direction): /ui/ and /ou/ of F1

Figure 13: For /ei/ of F1 the parameters are: Onset (P) = (0,600) constant; Offset (Q) = (120,350+k) for k=-100,0,+100; Glide: gradient y/x= -(50+100m)/120), thus, the descriptive function is: y= -[(0.5+m)/1.2]x+600 for m=1,2,3

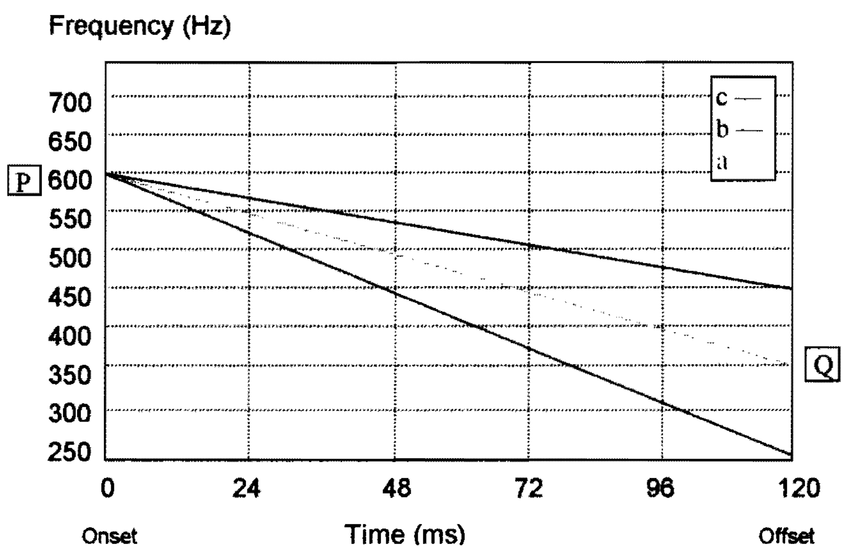


Figure 13: Trajectory theory (Direction): /ei/ of F1

Figure 14: For /ui/ of F2 the parameters are: Onset (P) = (0,1300) constant; Offset (Q) = (160,1800+k) for k= -100,0,+100; Glide: gradient y/x = (300+100m)/160, thus, the descriptive function is: y=[(3+m)/1.6]x+1300 for m=1,2,3

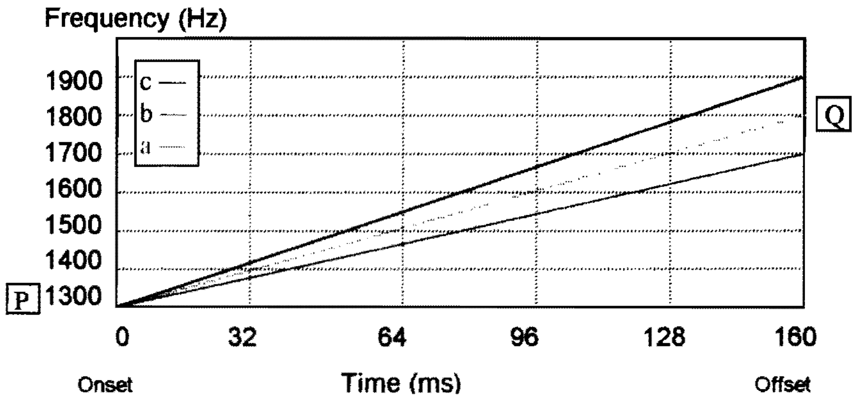


Figure 14: Trajectory theory (Direction): /ui/ of F2

Figure 15: For /ou/ of F2 the parameters are: Onset (P) = (0,1350) constant; Offset (Q) = (160,1200+k) for k= -100,0,+100; Glide: gradient y/x = -(100m-50)/160, thus, the descriptive function is: y= -[(m-0.5)/1.6]x+1350 for m=1,2,3

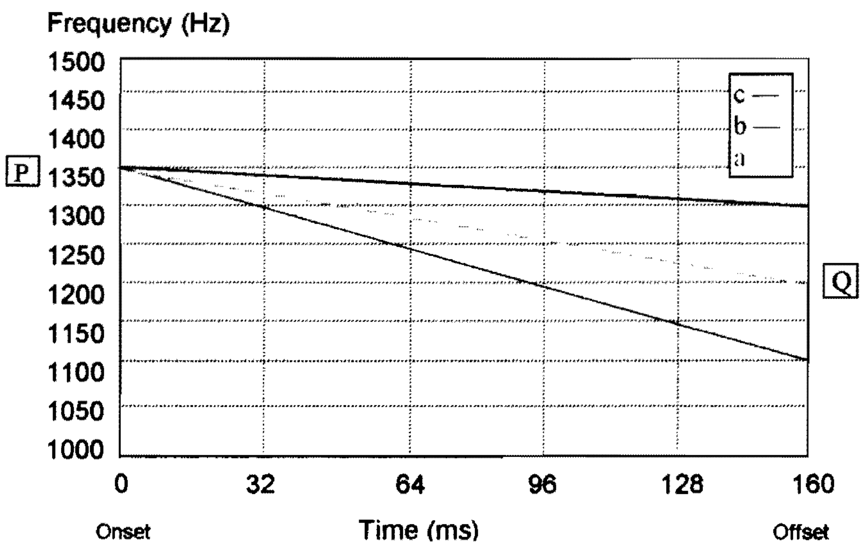


Figure 15: Trajectory theory (Direction): /ou/ of F2

Figure 16: For /ei/ of F2 the parameters are: Onset (P) = (0,1400) constant; Offset (Q) = (120,1900+k) for k= -100,0,+100; Glide: gradient y/x = (100m+300)/120, thus, the descriptive function is: y=[(3+m)/1.2]x+1400 for m=1,2,3

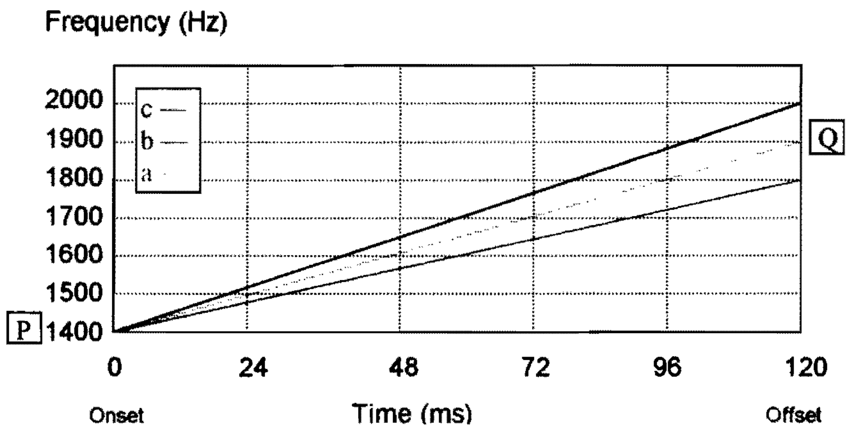


Figure 16: Trajectory theory (Direction): /ei/ of F2

4.3.3.3 The trajectory theory – the rate of change

To test the 'rate of change', five manipulations per diphthong were synthesised. For each manipulation the average onset values (P), as well as the average offset values (Q) for F1 and F2 were kept constant. The rate of change was manipulated by lengthening the onset steady state. For each of the five sounds, the time of keeping the onset constant was extended by one time step or frame. Onsets were at 0, t, 2t, 3t, 4t. This was done to cover all time range possibilities from the onset to the offset.

The above mentioned explanation is illustrated in Figure 17 to Figure 21. Since the average onset and offset values of **F1** for /ui/ and /ou/ are the same, they are both presented in Figure 17.

The five manipulations are identified as dark blue, red, green, light blue, and pink.

The five different manipulations for /ei/, /ou/ and /ui/ per time frame are presented in **Table 68.** The values are given in Hertz

Table 68: Rate of change manipulations

	F1		F2		Manipulation
Diphthong	Onset	Offset	Onset	Offset	
/ei/	(0, 600)	350	(0, 1400)	1900	a
/ei/	(t, 600)	350	(t, 1400)	1900	b
/ei/	(2t, 600)	350	(2t, 1400)	1900	c
/ei/	(3t, 600)	350	(3t, 1400)	1900	d
/ei/	(4t, 600)	350	(4t, 1400)	1900	e
/ou/	(0, 550)	350	(0, 1350)	1200	a
/ou/	(t, 550)	350	(t, 1350)	1200	b
/ou/	(2t, 550)	350	(2t, 1350)	1200	c
/ou/	(3t, 550)	350	(3t, 1350)	1200	d
/ou/	(4t, 550)	350	(4t, 1350)	1200	e
/ui/	(0, 550)	350	(0, 1300)	1800	a
/ui/	(t, 550)	350	(t, 1300)	1800	b
/ui/	(2t, 550)	350	(2t, 1300)	1800	c
/ui/	(3t, 550)	350	(3t, 1300)	1800	d
/ui/	(4t, 550)	350	(4t, 1300)	1800	e

For Figure 17 to Figure 21, descriptions are provided, above the figures, as follows:

Firstly, the onset and offset values are defined at their (x,y) positions on the graph. Secondly, the onset steady state is established by defining the first part of each curve, which are straight lines ('k' distinguishes between various line lengths). Each glide is defined by the gradient of each of the curves (y/x).

Figure 17: For /ui/ and /ou/ of F1 the parameters are: Onset (P) = (0,550) constant with onset steady state lines to (32k,550), k=0,1,2,3,4; Offset (Q) = (160,350); Glide: gradient y/x = -200/(160-32k)

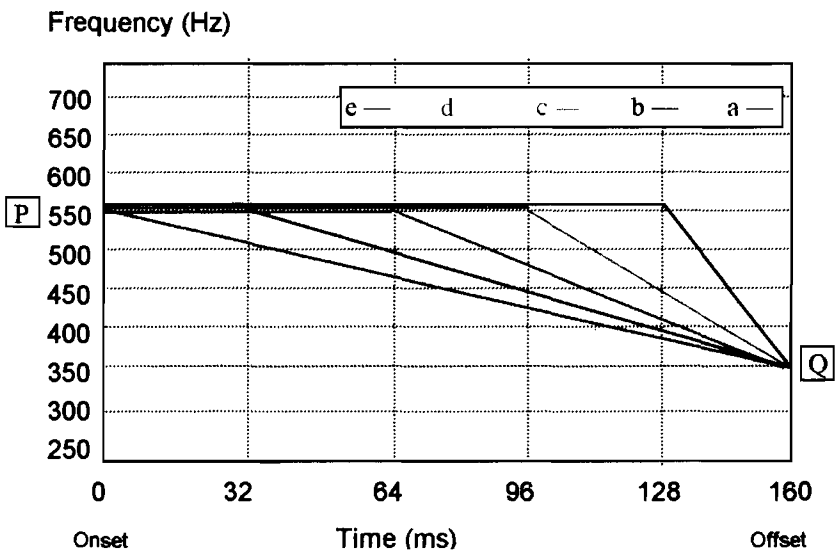


Figure 17: Trajectory theory (Rate): /ui/ and /ou/ of F1

Figure 18: For /ei/ of F1 the parameters are: Onset (P) = (0,600) constant with onset steady state lines to (24k,600), k=0,1,2,3,4; Offset (Q) = (120,350); Glide: gradient y/x = -250/(120-24k)

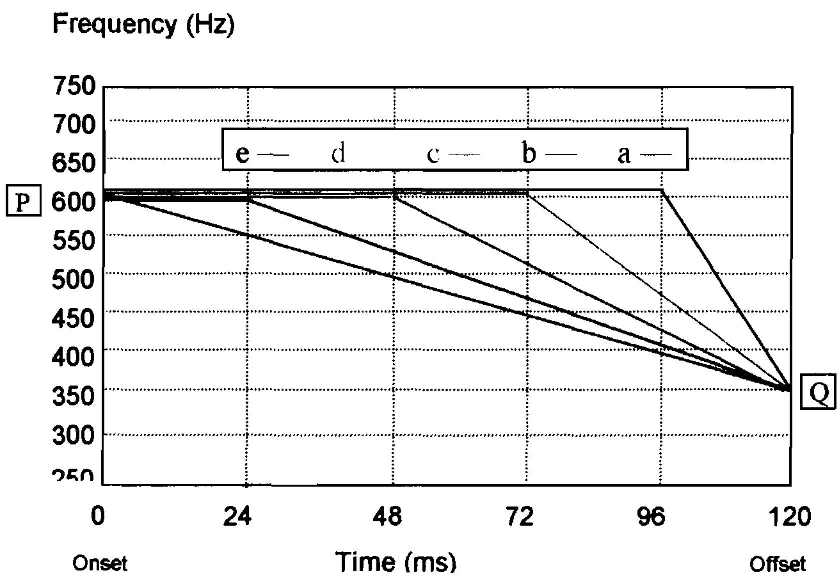


Figure 18: Trajectory theory (Rate): /ei/ of F1

Figure 19: For /ui/ of F2 the parameters are: Onset (P) = (0,1300) constant with onset steady state lines to (32k,1300), k=0,1,2,3,4; Offset (Q) = (160,1800);
Glide: gradient y/x = 500/(160-32k)

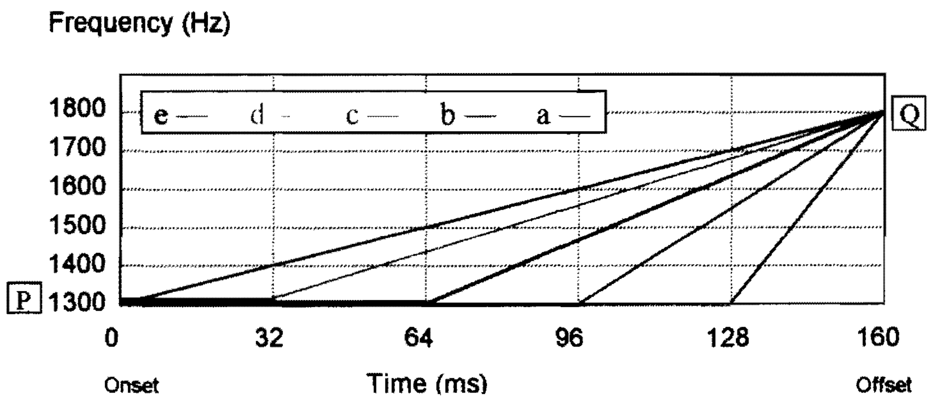


Figure 19: Trajectory theory (Rate): /ui/ of F2

Figure 20: For /ou/ of F2 the parameters are: Onset (P) = (0,1350) constant with onset steady state lines to (32k,1350), k=0,1,2,3,4; Offset (Q) = (160,1200);
Glide: gradient y/x = -150/(160-32k)

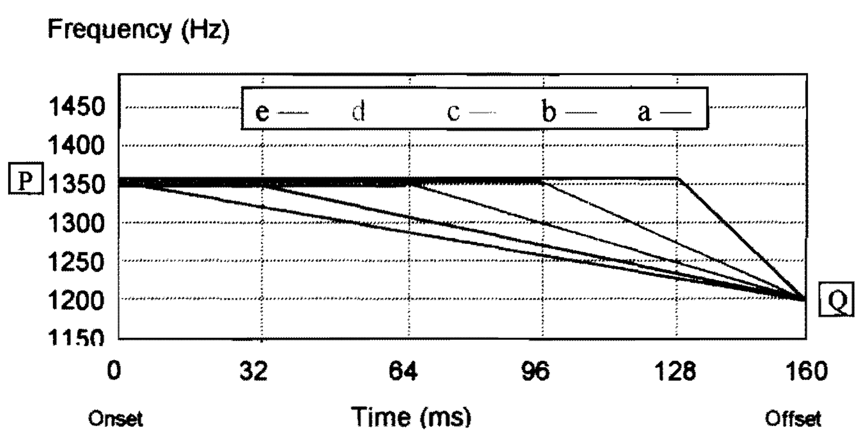


Figure 20: Trajectory theory (Rate): /ou/ of F2

Figure 21: For /ei/ of F2 the parameters are: Onset (P) = (0,1400) constant with onset steady state lines to (24k,1400), k=0,1,2,3,4; Offset (Q) = (120,1900);
Glide: gradient y/x = 500/(120-24k)

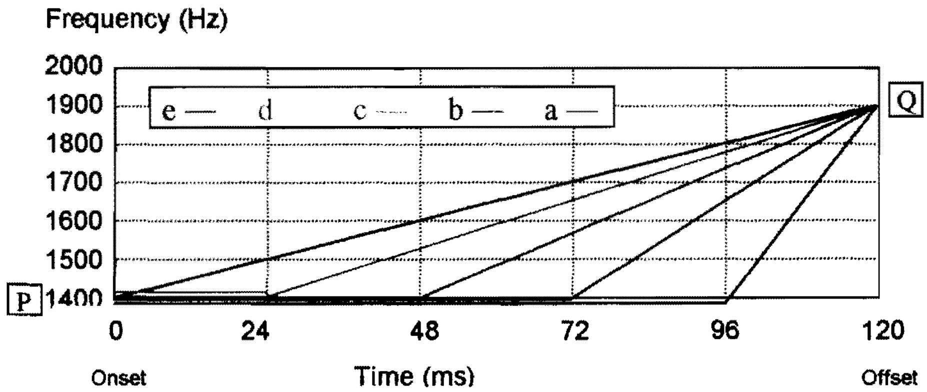


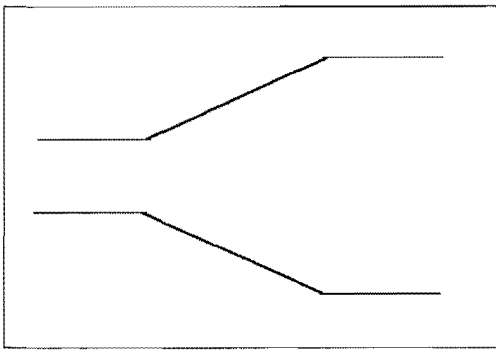
Figure 21: Trajectory theory (Rate): /ei/ of F2

4.3.3.4 Temporal formant pattern

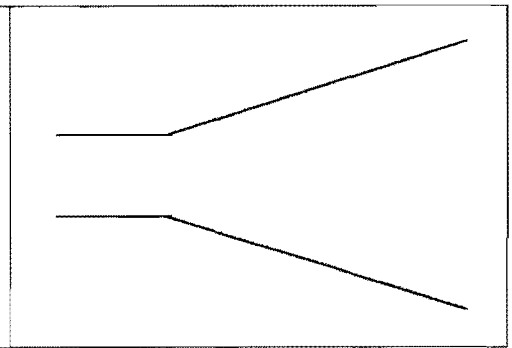
To test the temporal formant pattern, seven manipulations per diphthong were synthesised. For each manipulation the average onset values (P) as well as the average offset values (Q) for F1 and F2 were kept constant. The temporal formant pattern was manipulated by lengthening the onset and offset steady states. For each of the seven sounds, the time of keeping the onset or offset constant was extended by one time step or frame. Onset steady states and onglides were at 0, t, and 2t, and the offset steady states and offglides were at 3t, 4t and 5t.

The manipulations consisted of the following:

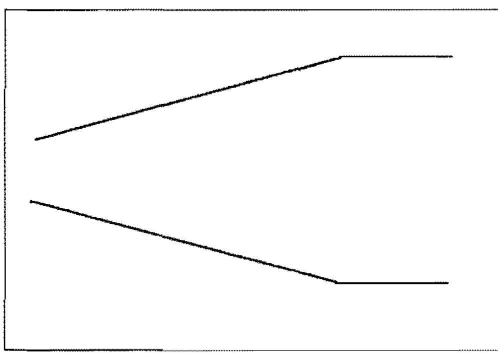
a) **Short onset steady state** (OSS) / **glide / short offset steady state** (oss)



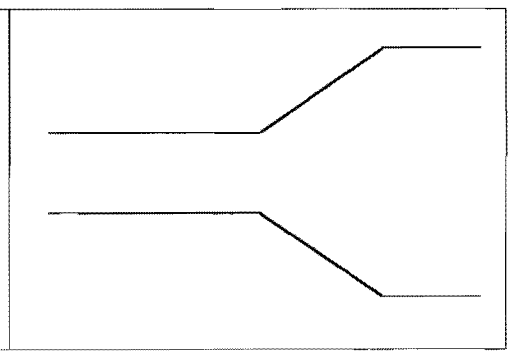
b) **Short OSS/ offglide**



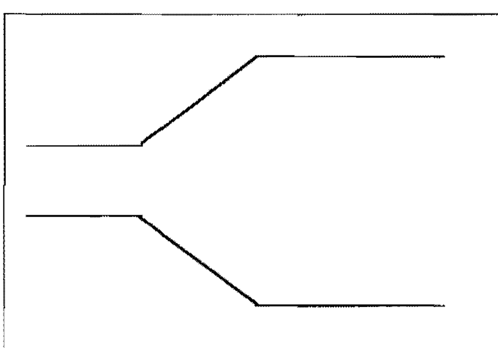
c) **Onglide/ short oss**



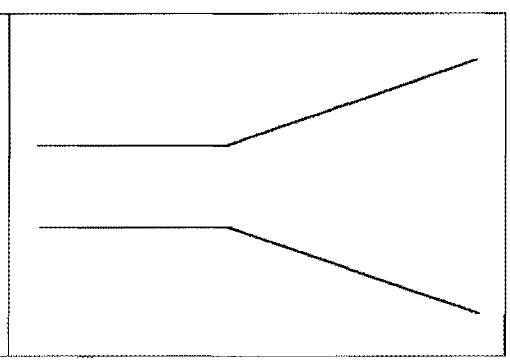
d) **Long OSS/ glide / short oss**



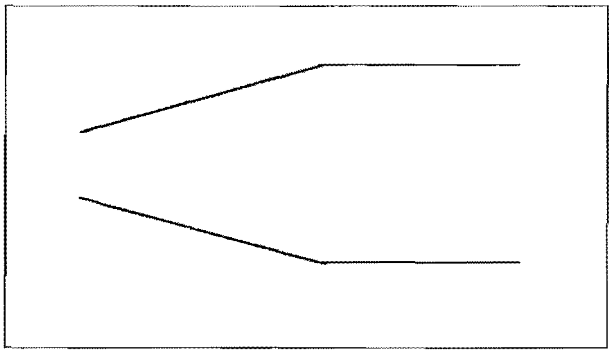
e) **Short OSS/ glide / long oss**



f) **Long OSS/ offglide**



g) Onglide/ long oss



The above mentioned explanation is illustrated in Figure 22 to Figure 26. Since the average onset and offset values of **F1** for /ui/ and /ou/ are the same, they are both presented in Figure 22.

From Figure 22 to Figure 26, descriptions are provided, above the figures, as follows:
Firstly, the onset and offset values are defined at their (x,y) positions on the graph. Secondly, seven lines with three length variations, as defined by 'm' describe the onset steady states. The glides are established with seven gradients (y/x) with similar heights (y) but varying widths (x), again identified with 'm'. Finally, seven straight lines with three length variations, as defined by 'm' describe the offset steady states.

The seven different manipulations for the temporal formant pattern for /ei/, /ou/ and /ui/ per time frame are presented in **Table 69**. The values are given in Hertz.

Table 69: Temporal formant pattern manipulations

	F1		F2		
Diphthong	**Onset**	**Offset**	**Onset**	**Offset**	**Manipulation**
/ei/	(t, 600)	(4t, 350)	(t, 1400)	(4t, 1900)	a
/ei/	(t, 600)	(5t, 350)	(t, 1400)	(5t, 1900)	b
/ei/	(0, 600)	(4t, 350)	(0, 1400)	(4t, 1900)	c
/ei/	(2t, 600)	(4t, 350)	(2t, 1400)	(t4, 1900)	d
/ei/	(t, 600)	(3t, 350)	(t, 1400)	(3t, 1900)	e
/ei/	(2t, 600)	(5t, 350)	(2t, 1400)	(5t, 1900)	f
/ei/	(0, 600)	(3t, 350)	(0, 1400)	(3t, 1900)	g
/ou/	(t, 550)	(4t, 350)	(t, 1350)	(4t, 1200)	a
/ou/	(t, 550)	(5t, 350)	(t, 1350)	(5t, 200)	b
/ou/	(0, 550)	(4t, 350)	(0, 1350)	(4t, 1200)	c
/ou/	(2t, 550)	(4t, 350)	(2t, 1350)	(4t, 1200)	d
/ou/	(t, 550)	(3t, 350)	(t, 1350)	(3t, 200)	e
/ou/	(2t, 550)	(5t, 350)	(2t, 1350)	(5t, 1200)	f
/ou/	(0, 550)	(3t, 350)	(0, 1350)	(3t, 1200)	g
/ui/	(t, 550)	(4t, 350)	(t, 1300)	(4t, 1800)	a
/ui/	(t, 550)	(5t, 350)	(t, 1300)	(5t, 1800)	b
/ui/	(0, 550)	(4t, 350)	(0, 1300)	(4t, 1800)	c
/ui/	(2t, 550)	(4t, 350)	(2t, 1300)	(4t, 1800)	d
/ui/	(t, 550)	(3t, 350)	(t, 1300)	(3t, 1800)	e
/ui/	(2t, 550)	(5t, 350)	(2t, 1300)	(5t, 1800)	f
/ui/	(0, 550)	(3t, 350)	(0, 1300)	(3t, 1800)	g

Figure 22: For /ui/ and /ou/ of F1 the seven parameters are: Onset (P) = (0,550) constant with the onset steady state being seven lines to (32m-32,550), m=1,2,3; Offset (Q) = (160,350), constant, with the offset steady state being seven lines from (64+32m,350) to (160,350); Glide: gradient y/x = -200/(160-32m)

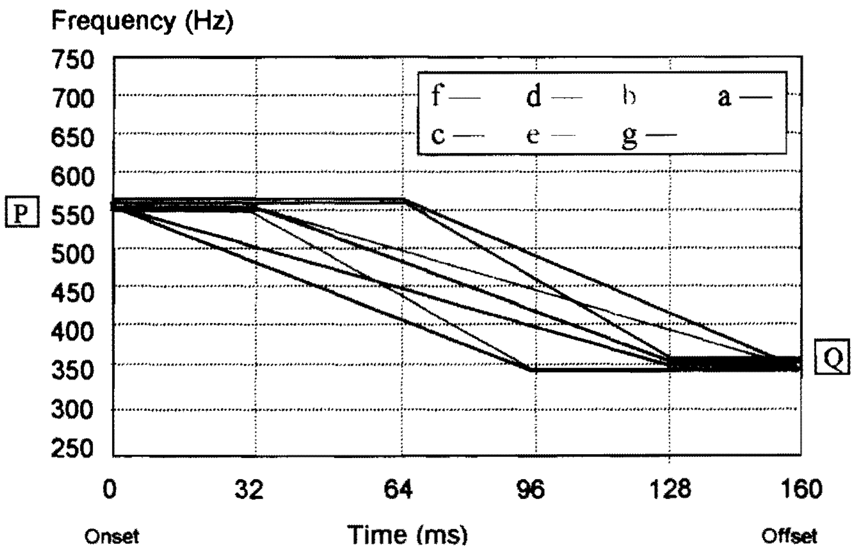


Figure 22: Temporal Formant Pattern: /ui/ and /ou/ of F1

Figure 23: For /ei/ of F1 the seven parameters are: Onset (P) = (0,600) constant with the onset steady state being seven lines from (0,600) to (24m-24,600), m=1,2,3; Offset (Q) = (120,350) constant, with the offset steady state being seven lines from (48+24m,350) to (120,350); Glide: gradient y/x = -250/(120-24m).

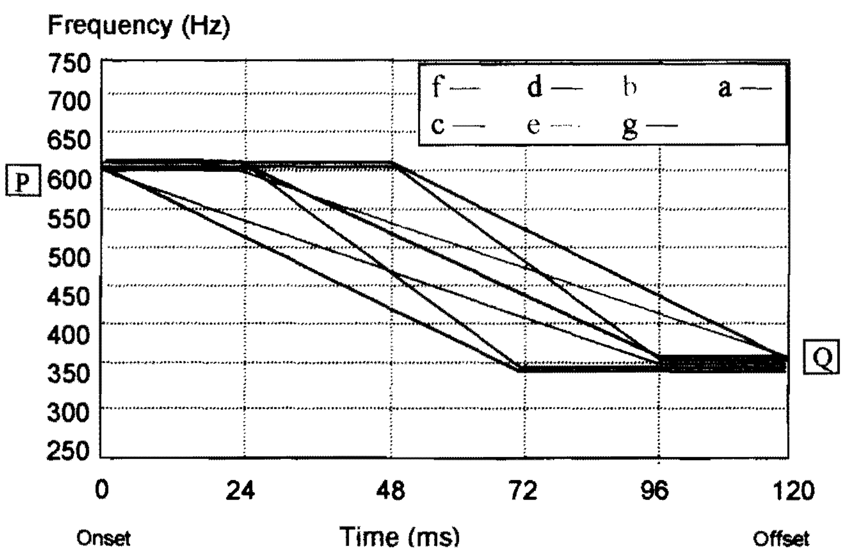


Figure 23: Temporal Formant Pattern: /ei/ of F1

Figure 24: For /ui/ of F2 the seven parameters are: Onset (P) = (0,1300) constant with the onset steady state being seven lines from (0,1300) to (32m-32,1300), m=1,2,3; Offset (Q) = (160,1800) constant, with the offset steady state being seven lines from (64+32m,1800) to (160,1800); Glide: gradient y/x = 500/(160-32m)

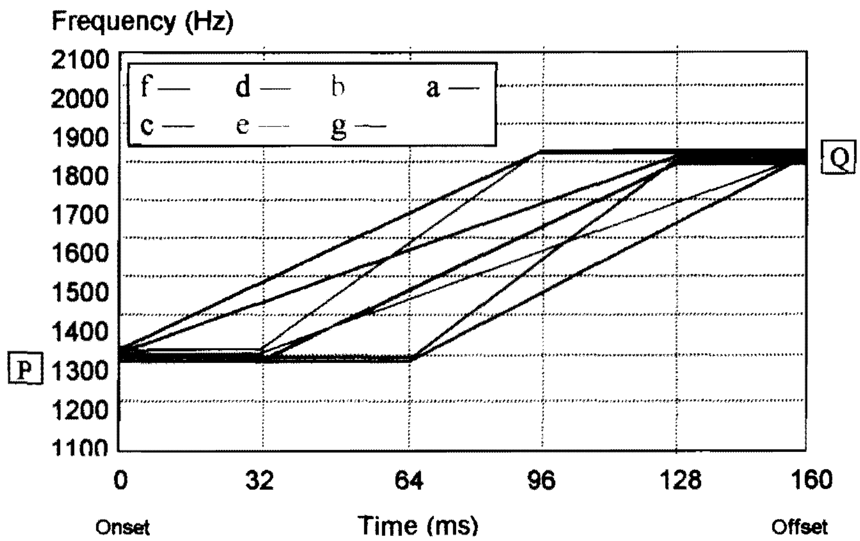


Figure 24: Temporal Formant Pattern: /ui/ of F2

Figure 25: For /ei/ of F2 the seven parameters are: Onset (P) = (0,1400) constant with the onset steady state being seven lines from (0,1400) to (24m-24,1400), m=1,2,3; Offset (Q) = (120,1900) constant, with the offset steady state being seven lines from (48+24m,1900) to (120,1900); Glide: gradient y/x = 500/(120-24m)

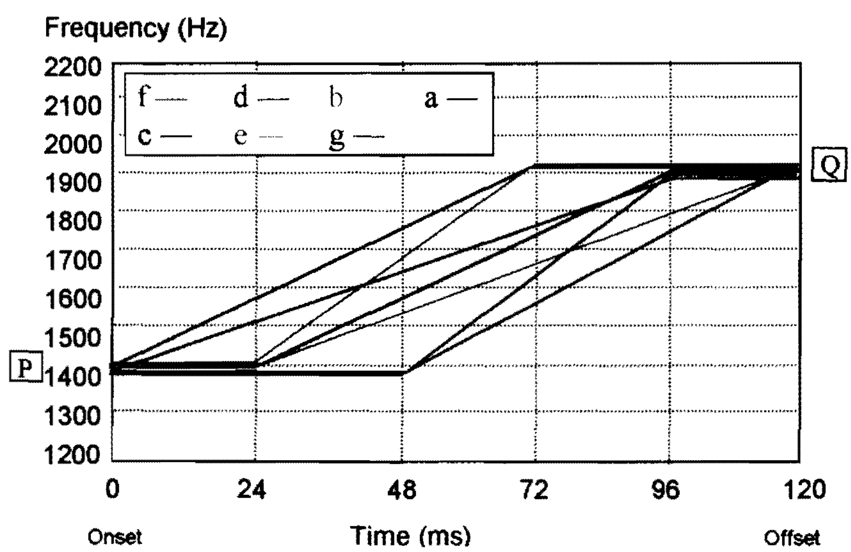


Figure 25: Temporal Formant Pattern: /ei/ of F2

Figure 26: For /ou/ of F2 the seven parameters are: Onset (P) = (0,1350) constant with the onset steady state being seven lines from (0,1350) to (32m-32,1350), m=1,2,3; Offset (Q) = (160,1100) constant, with the offset steady state being seven lines from (64+32m,1100) to (160,1100); Glide: gradient y/x = -250/(160-32m)

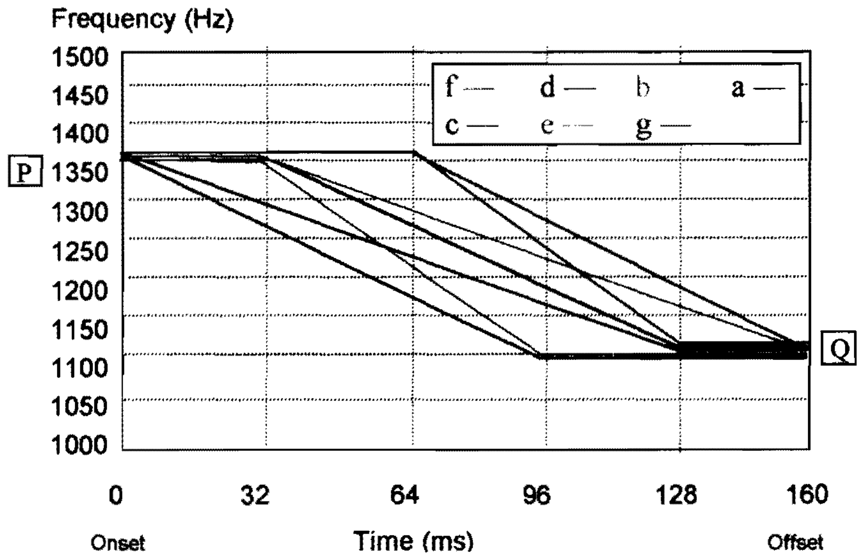


Figure 26: Temporal Formant Pattern: /ou/ of F2

The total number of manipulations per diphthong is: 3 (trajectory – direction of change) + 5 (trajectory – rate of change) + 9 (target) + 7 (temporal formant) = 24. For the three diphthongs the total manipulations are 72.

After the manipulations were synthesised on the HLSyn, the waveforms of the synthesised sounds were exported to the CSL. The CSL (Computerised Speech Laboratory) is a highly flexible audio-processing package that is designed to provide a variety of speech analysis operations. Operations include data acquisition, file management, graphics and numerical display, audio output, signal editing and a variety of analysis functions. Analysis routines include waveform, energy, FFT spectrums, LPC filter response, pitch, formant histories and spectrograms (CSL – Model 4300; Instruction manual).

Files were created on the CSL containing a specific sound, a silent period of 2 seconds, a repeat of the sound and then a silent period of 4 seconds. This was done for all 72 synthesised manipulations that were randomly read into the CSL. Finally, the whole sequence of sounds was copied onto a tape. The whole process was repeated for the repetition of the listening test.

4.3.4 DATA COLLECTION PROCEDURE

The listening test was performed at the Potchefstroom University and the sessions were held in a quiet room. Before the test started, background information (sex, hearing abilities, mother tongue etc.) on the subjects was obtained by means of a questionnaire. The stimuli were presented at a comfortable listening level to groups of maximally 12 people. The design of the experiment was explained to them. In order to get acquainted with the task, for example, the presentation, quality of sounds and the test speed, six stimuli were presented in advance. A sound was presented to the subjects which they had to identify as either /ei/, /ou/ or /ui/. After 4 seconds the same sound was repeated again. The subjects then had to choose from four possibilities to say whether the sound was a very good, good, bad or very bad example of the identified sound.

The test consisted of 72 manipulated, synthesised sounds that were played to the subjects. After the first version the subjects could relax for a few minutes before the second reading took place. The second version was merely a repetition of the first. A total of 3600 answers (25 subjects x 2 readings x 72 sounds = 3600) were obtained.

4.3.5 DATA ANALYSIS AND STATISTICS

Data was analysed with the aid of the *Statistica* software package. In addition to basic descriptive statistics, analyses of variance (ANOVA's) were carried out. Post hoc comparisons were performed and significant differences were tested according to Tukey's HSD (Honest Significant Difference) test. The results of the statistic analyses are presented and discussed in the next section.

4.3.6 RESULTS AND DISCUSSION

The results of the perception test are presented and discussed in the following paragraphs. For the sake of convenience the target theory, the direction of change, the rate of change and the temporal formant pattern are all referred to as "theories". The manipulations of the diphthongs in 4.3.6.1 to 4.3.6.6 are referred to as "diphthongs".

4.3.6.1 Identification and quality judgements: Overall values of /ei/, /ou/ and /ui/ for the different versions

ANOVA's and post hoc comparisons were performed for a combination of all the diphthongs across the different theories, as well as the diphthongs from the different theories. The independent variable was 'version' while, the dependent variables were 'identification' and 'quality judgements'. This was done in order to determine whether the identification of diphthongs on the one hand, and the quality judgements, on the other hand, differed in the first version as opposed to the second version.

The results indicated that the diphthongs were identified slightly better in the second version, but the differences between version 1 and version 2 were not statistically significant. The quality of the diphthongs were also judged better in version 2, but in this case there were significant differences between the two versions ($F_{(2,3393)}$, $p=0.015$). The latter was to be expected, due to the fact that by the time version 2 was played to the subjects, they were more familiar with the quality of the synthesised diphthongs. (It is important to notice that in most cases identification of the diphthongs were made, but quality judgements were not made in all the cases.)

4.3.6.2 Identification and quality judgements: Overall values of /ei/, /ou/ and /ui/ for the different subjects

ANOVA's and post hoc comparisons were performed for a combination of all the diphthongs across the two readings, the different theories, as well as the diphthongs from the different theories. The independent variable was 'subjects' while, the dependent variables were 'identification' and 'quality judgements'. This was done in order to determine whether the identification of diphthongs on the one hand, and the quality judgements, on the other hand, differed significantly for the different subjects.

The results indicated that as far as the identification of the diphthongs was concerned, there were, except from two cases, no statistically significant differences among the identification of diphthongs by the subjects. As far as the judging of the quality of the diphthongs was concerned, there were vast significant differences among all the subjects' judgements of the quality of the diphthongs ($F_{(24,3371)}$, $p<0.05$).

4.3.6.3 Identification and quality judgements: Overall values of /ei/, /ou/ and /ui/

In the perception test subjects were asked to identify a given synthesised diphthong and thereafter, pass judgement on the quality of the diphthong. On this basis ANOVA's and post hoc comparisons were performed for a combination of all the diphthongs across the different theories, as well as the diphthongs from the different theories. This was done in order to ascertain how well diphthongs were identified and how well listeners judged their quality. The independent variable was 'proposed diphthong', while the dependent variables were 'identification' and 'quality judgements'.

Results indicated that /ou/ was identified best, then /ei/ and finally /ui/. In all three cases the differences were statistically significant ($F_{(2,3397)}$, $p<0,05$). It was also found that in **3%** of the cases /ei/ was wrongly identified as /ui/ and in **24%** of the cases /ui/ was identified as /ei/.

Gerrits (1995) used /ei/, /au/ and /ui/ in her production test, but only /au/ and /ui/ were used for the perception test. According to Gerrits (1995;27) the reason for not using /ei/ was that a pilot study indicated that /ei/ repeatedly sounded like /ui/, although the exact formant values for /ei/, obtained from the production test were used in the synthesis. This was also mentioned by Pols (1977).

From these results it is clear that /ui/ sounds, in Afrikaans, are more likely to be wrongly identified as /ei/ than vice versa. The reason for this might be due to the neutralisation of /ui/ to /ei/. When the contrast of the opposition which normally exists between two phonological units, are cancelled, neutralisation takes place (Hawkins, 1984:104). For Afrikaans the opposition between rounded vowels and their unrounded counterparts are mostly neutralised in colloquial speech (De Villiers & Ponelis, 1987). According to Wissing, (1995) this is not only true for colloquial speech, but it is also observed in different varieties, contexts and styles.

The absence of the neutralisation of /ei/ to /ui/ in Dutch might provide an explanation for the reversed occurrence in Afrikaans where /ui/ was identified as /ei/ in 24% of the cases rather than the above-mentioned occurrence in Dutch. As expected /ou/ was never identified as either /ei/ or /ui/.

The quality judgements indicated that /ou/ sounds were judged to have the highest quality, then /ei/ and finally /ui/. In all three cases the differences were statistically significant ($F_{(2,3393)}$, $p<0,05$).

4.3.6.4 Identification and quality judgements: Overall values of /ei/, /ou/ and /ui/ for the different theories

ANOVA's and post hoc comparisons were performed for a combination of all the diphthongs across the different theories, as well as the diphthongs from the different theories. This was done in order to determine whether the identification of all the diphthongs and the judgements of their quality differed statistically significantly among the four theories. The independent variable was 'theory', while the dependent variables were 'identification' and 'quality judgements'.

The results indicated that the diphthongs of the temporal formant pattern were identified best, then diphthongs of the target theory, the direction of change and finally, diphthongs of the rate of change. There were highly significant differences between the diphthongs from the temporal formant pattern and the direction of change ($F_{(3,3597)}$, $p=0.003$), the temporal formant pattern and the target theory ($F_{(3,3597)}$, $p=0.000$), as well as the temporal formant pattern and the rate of change ($F_{(3,3597)}$, $p=0.000$).

One of the specific objectives of this study was to determine which of these; the target theory, the trajectory theory (direction and rate of change) or the temporal formant pattern was more likely to unambiguously describe Afrikaans diphthongs.

Since the diphthongs from the temporal formant pattern were identified as statistically significantly better than those diphthongs of the target theory as well as the trajectory theory (direction and rate of change), it can be concluded that the temporal formant pattern is more likely to unambiguously describe Afrikaans diphthongs. This is in accordance with the findings of the production test (cf. Chapter 3). These results indicated that none of the individual components of the formant pattern (neither the target theory nor the trajectory theory – the direction of change and rate of change) could describe Afrikaans diphthongs unambiguously. This is also in accordance with the findings of Peeters (1991), Stollwerck (1991) and Cao (1991). They maintained that the temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously.

Diphthongs from the temporal formant pattern were also judged as of the highest quality, then diphthongs from the direction of change, the target theory and rate of change. Once again there were highly significant differences between the temporal formant pattern and the direction of change ($F_{(3,3392}$, $p=0.001$), the temporal formant pattern and the target theory ($F_{(3,3392)}$, $p=0.000$) and the temporal formant pattern and the rate of change ($F_{(3,3392)}$, $p=0.000$).

The quality of the diphthongs from the temporal formant pattern were judged as significantly better than the diphthongs from the target theory as well as the trajectory theory (direction and rate of change) and it can, therefore, be concluded that the temporal formant pattern is more likely to unambiguously describe Afrikaans diphthongs. This is in accordance with the findings of the production test (cf. Chapter 3). These results indicated that none of the individual components of the formant pattern (neither the target theory nor the trajectory theory – the direction of change and rate of change) could describe Afrikaans diphthongs unambiguously. This is also in accordance with the findings of Peeters (1991), Stollwerck (1991) and Cao (1991). They maintain that the temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously.

4.3.6.5 Identification and quality judgements: Specific values of /ei/, /ou/ and /ui/ for the different theories

ANOVA's and post hoc comparisons were also performed for the specific diphthongs across the different theories, as well as the diphthongs from the different theories. This was done in order to ascertain whether the identification of the specific diphthongs and the judgements of their quality differed statistically significantly among the four theories. The independent variables were 'proposed diphthong' and 'theory', while the dependent variables were 'identification' and 'quality judgements'.

The results showed that for the diphthongs /ei/, /ou/ and /ui/ respectively, diphthongs from the temporal formant pattern were identified the best. The /ei/ from the temporal formant pattern, however, only differed statistically significantly from the rate of change ($F_{(3,1195)}$, $p=0,043$). The diphthong /ou/ of the temporal formant pattern differed statistically significantly from diphthongs of the target theory, the direction of change and rate of change ($F_{(3,1197)}$, $p=0.000$ in all three cases). For /ui/ diphthongs from the temporal formant pattern only differed statistically significantly from diphthongs from the rate of change ($F_{(3,1196)}$, $p=0,000$).

Since the specific diphthongs from the temporal formant pattern were identified better than those diphthongs from the target theory, as well as the trajectory theory (direction and rate of change) it can be concluded that the temporal formant pattern is more likely to unambiguously describe Afrikaans diphthongs. This is in accordance with the findings of the production test (cf. Chapter 3). These results indicated that none of the individual components of the formant pattern (neither the target theory nor the trajectory theory – the direction of change and rate of change) could describe Afrikaans diphthongs unambiguously. This is also in accordance with the findings of Peeters, (1991), Stollwerck (1991) and Cao (1991). They maintain that the temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously.

Cao (1991) found that the temporal formant structure of diphthongs is also important in differentiating between diphthongs from a language. It has already been stated that /ei/ and /ui/ were wrongly identified in certain cases. From the results it is evident that the specific diphthongs from the temporal formant pattern were identified better than those diphthongs from the other three theories. Therefore, it can be stated that the temporal formant structure of diphthongs is important in differentiating between diphthongs within a language, in this case Afrikaans. It should be mentioned, however, that although the /ei/ and /ui/ of the temporal formant pattern were identified best, they did not differ statistically significantly from the diphthongs from the direction of change and the target theory.

The diphthong /ei/ of the temporal formant pattern was judged as of the highest quality but did not differ statistically significantly from diphthongs from the other three theories. The diphthongs /ou/ and /ui/ of the temporal formant pattern were judged by the listeners as of the highest quality and differed highly statistically significantly ($p=0.000$ for all the cases, with $F_{(3,1116)}$ for /ou/ and $F_{(3,1117)}$ for /ui/) from diphthongs from the direction of change, the target theory and the rate of change.

This is in accordance with the findings of the production test (cf. Chapter 3). These results indicated that none of the individual components of the formant pattern (neither the target theory nor the trajectory theory – the direction of change and rate of change) could describe

Afrikaans diphthongs unambiguously. This is also in accordance with the findings of Peeters, (1991), Stollwerck (1991) and Cao (1991). They maintainethat the temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously. It should be mentioned, however, that although the /ei/ of the temporal formant pattern was judged as of the highest quality, the difference between the diphthongs from the temporal formant pattern and the other three theories was not statistically significant.

4.3.6.6 Identification and quality judgements: Values of /ei/, /ou/, /ui/ excluding sounds identified as 'junk'

Sounds that were not identified as either, /ei/, /ou/ or /ui/ were identified as "junk". From the descriptive analyses done, it was found that **15%** of the sounds of the direction theory was identified as 'junk', **10%** of those of the target theory, **1%** of the temporal formant pattern, while **38%** of the rate of change were identified as 'junk'. Since it is not possible to judge the quality of 'junk' sounds, no analyses of quality judgements could be made in this case.

These results also support the idea that the temporal formant pattern rather than any of the other theories, embodies the features with which Afrikaans diphthongs can be described unambiguously.

Excluding those diphthongs that were identified as junk, ANOVA's and post hoc comparisons were also performed for the specific diphthongs across the different theories as well as the manipulations of the diphthongs from the different theories. This was done in order to ascertain whether the identification of the specific diphthongs and the judgements of their quality differed statistically significantly among the four theories. The independent variables were 'proposed diphthong' and 'theory', while the dependent variables were 'identification' and 'quality judgements'.

The results indicated that the diphthong /ei/ of the temporal formant pattern were identified best but there were no statistically significant differences among the diphthongs of the temporal formant pattern on the one hand, and the direction of change and the target theory, on the other hand. Differences between diphthongs of the temporal formant pattern and the rate of change were statistically significant ($F_{(3,1151)}$., p=0.027). The diphthong /ou/ was identified equally well among all four theories with no statistically significant differences. For /ui/, diphthongs of the temporal formant pattern were identified statistically significantly better than diphthongs from the other three theories

The diphthong /ei/ from the direction of change was judged of a higher quality than the /ei/ from the temporal formant pattern, but the difference was not statistically significant. The differences between diphthongs of the target theory and the temporal formant pattern, on the one hand, and the direction and rate of change, on the other hand, were statistically significant ($F_{(3,1151)}$, p<0,000). The diphthongs /ou/ ($F_{(3,1116)}$, p<0.000) and /ui/ ($F_{(3,1117)}$, p<0.000) of the temporal formant pattern were also judged by the listeners as being of a higher quality than diphthongs of the rate of change, the direction of change and the target theory. Once again there were highly sstatistically significant differences between diphthongs from the temporal formant pattern and diphthongs from the other three theories

These results also support the idea that the temporal formant pattern, rather than the target theory or the trajectory theory (direction and rate of change), embodies the features with which Afrikaans diphthongs can be described unambiguously.

4.3.6.7 Identification and quality judgements: Manipulations of /ei/, /ou/, /ui/ of Temporal formant pattern

ANOVA's and post hoc comparisons were performed to determine which manipulations of the temporal formant pattern were identified best and which manipulations were judged as being of the highest quality.

From these results the manipulation for each diphthong that was identified best was established. Then those manipulations that did not differ statistically significantly from the best manipulations were also chosen. These values are given in Table 70.

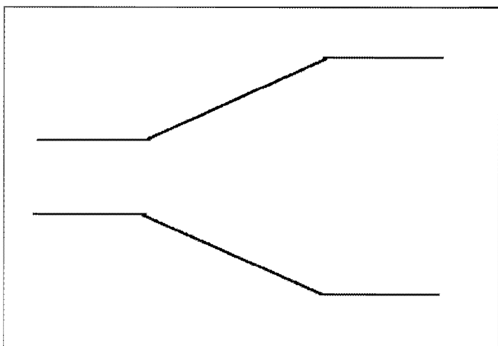
The manipulations of /ei/ /ou/ and /ui/ for the temporal formant pattern that were identified best are presented in **Table 70.** The best identification manipulations are presented first and it is followed by those manipulations that did not differ statistically significantly from the best manipulations.

Table 70: Temporal formant pattern: Best identification manipulations

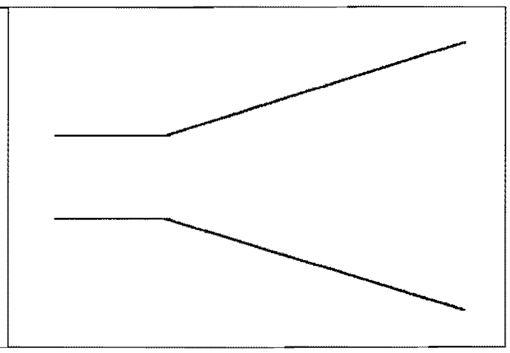
	/ei/	/ou/	/ui/
Formant Pattern	g, f, e	e, (a-g)	f, c, a

The following manipulations were used in the perception test and are presented again for the reader's convenience (cf. 4.3.3.4).

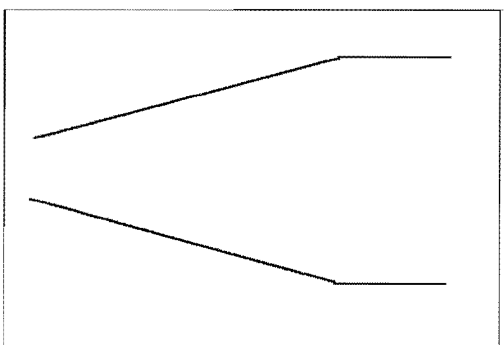
a) Short onset steady state (OSS) / **glide / short offset steady state** (oss)



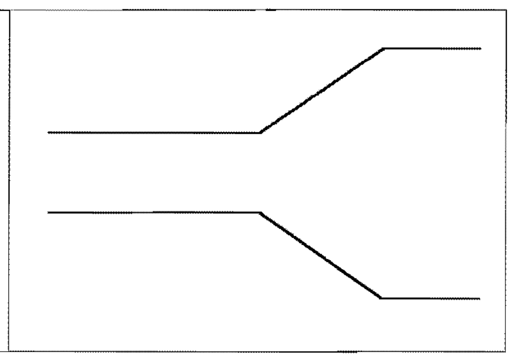
b) Short OSS/ offglide



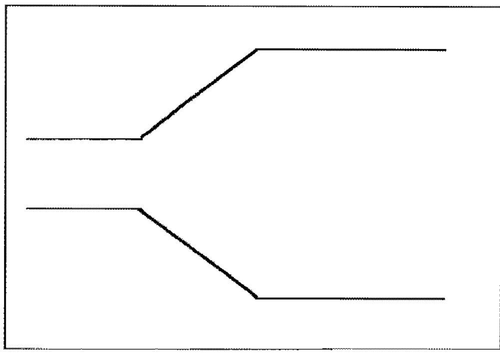
c) Onglide/ short oss



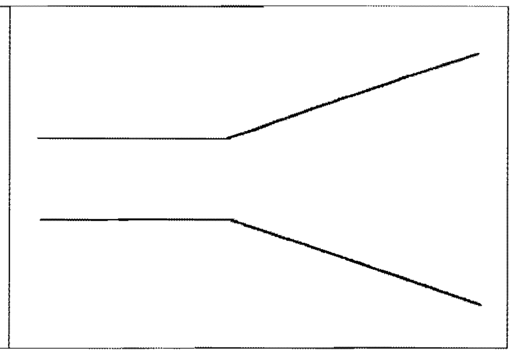
d) Long OSS/ glide / short oss



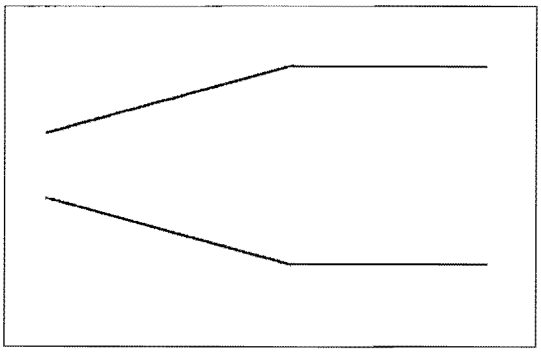
e) Short OSS/ glide / long oss



f) Long OSS/ offglide



g) Onglide/ long oss



From the results of the best identification manipulations of the different theories (cf. Table 70) it is clear that for the different diphthongs of the temporal formant pattern the following emerged: for /ei/ manipulation 'g' was identified best, for /ou/ manipulation 'e' and for /ui/ manipulation 'f'.

One of the objectives of this study was to determine the temporal formant patterns of diphthongs in Afrikaans. In the previous paragraph the different manipulations (formant patterns) which were identified best were stated. Therefore, the following can be established:

- The temporal formant pattern which was identified best for the /ei/ sound is 'g' which is an **onglide and a relatively long offset steady state**.
- The temporal formant pattern which was identified best for the /ou/ sound is 'e' which is **a relatively short onset steady state, a glide and a relatively long offset steady state**.

- For /ui/ the temporal formant pattern which was identified best is 'f' which is **a relatively long onset steady state and an offglide.**

Since these patterns were identified best it can be stated that these patterns describe the specific diphthongs the best (cf. 4.3.3 – STIMULUS MATERIAL – for an explanation of the different manipulations).

Those manipulations that did not differ statistically significantly from the best identification manipulation of each diphthong are also given in Table 70. For /ei/ the manipulations 'f', and 'e' did not differ statistically significantly from the best identified manipulation 'g'. For /ou/ the manipulations 'a-g' did not differ statistically significantly from 'c' and for /ui/ 'c' and 'a' did not differ statistically significantly from 'f'.

Another objective of this study was to determine whether, if a specific pattern was found, another pattern would also be acceptable to the listener. From these results it is evident that for /ei/, /ou/ and /ui/ respectively, at least two other manipulations (formant patterns) were identified almost as well as the manipulations that were identified best. Therefore, it can be concluded that other patterns that the best identified patterns are also acceptable to the listener.

- For /ei/ not only the **onglide and a relatively long offset steady state** pattern (g), but also **a relatively long onset steady state and an offglide** pattern (f), as well as a **relatively long onset steady state and an offglide** pattern (e) are acceptable.
- For /ou/ not only **a relatively short onset steady state, a glide and a relatively long offset steady state** pattern is acceptable (c), but **all** the other patterns are acceptable.
- For /ui/ not only **a relatively long onset steady state and an offglide** pattern (f) is acceptable, but also an **onglide and a relatively short offset steady state** pattern (c), as well as a **relatively short onset steady state, a glide and a relatively short offset steady state** pattern (a) are acceptable.

From the results of the ANOVA's and the Post hoc comparisons performed, the best quality judgements of the manipulations for each diphthong from the temporal formant pattern were established. Then those manipulations, which did not differ statistically significantly from the best manipulations, were also chosen. These values are given in Table 71.

The manipulations of /ei/ /ou/ and /ui/ for the temporal formant pattern that were judged best are presented in **Table 71.** The best identification manipulations are presented first and it is followed by those manipulations that did not differ statistically significantly from the best manipulations.

Table 71: Temporal formant pattern: Best quality judgement manipulations

	/ei/	/ou/	/ui/
Formant Pattern	e, a, g	a, b, c	f, a, e

From the results of the best quality judgement manipulations of the different theories (cf. Table 71) it can be seen that for the different diphthongs of the temporal formant pattern the following emerged: for /ei/ manipulation 'e' was judged best, for /ou/, manipulation 'a' and for /ui/ manipulation 'f'.

One of the objectives of this study was to determine the temporal formant patterns of diphthongs in Afrikaans. In the previous paragraph the different manipulations (formant patterns) which were judged as of the highest quality are stated. Therefore, the following can be established:

- The temporal formant pattern which was judged as of the highest quality for the /ei/ sound is (e), which is **a relatively short onset steady state, a glide and a relatively long offset steady state**.
- The temporal formant pattern which was judged as of the highest quality for the /ou/ sound is (a), which is **a relatively short onset steady state, a glide and a relatively short offset steady state**.
- For /ui/ the temporal formant pattern which was identified best is (f), which is **a relatively long onset steady state and an offglide**. Since these patterns were judged as of the highest quality it can be stated that these patterns describe the specific diphthongs the best.

Those manipulations that did not differ statistically significantly from the highest quality manipulation of each diphthong are also given in Table 71. For /ei/ the manipulations 'a', and 'g' did not differ statistically significantly from the highest quality manipulation 'e'. For /ou/ the manipulations 'b' and 'c' did not differ statistically significantly from 'a' and for /ui/ 'a' and 'e' did not differ statistically significantly from 'f'.

Another objective of this study was to determine whether, if a specific pattern was found, another pattern would also be acceptable to the listener. From these results it was evident that for /ei/, /ou/ and /ui/ respectively, at least two other manipulations (formant patterns) were almost of the same quality as the manipulations that were judged of the highest quality. Therefore, it can be concluded that other patterns than those patterns that are judged of the highest quality are also acceptable to the listener.

- For /ei/ not only **a relatively short onset steady state, a glide and a relatively long offset steady state** pattern (e), but a also a **relatively short onset steady state, a glide and a relatively short offset steady state** pattern (a), as well as an **onglide and a relatively long offset steady state** pattern (g), are acceptable.
- For /ou/ not only **relatively short onset steady state, a glide and a relatively short offset steady state** pattern (a) is acceptable, but also **a short onset steady state and an offglide** pattern (b), as well as a **onglide and a short offset steady state** pattern (c), are acceptable.
- For /ui/ not only **a relatively long onset steady state and an offglide** pattern (f) is acceptable, but also a **relatively short onset steady state, a glide and a relatively short offset steady state** pattern (a), as well as a **relatively short onset steady state, a glide and a relatively long offset steady state** pattern (e) are acceptable.

4.3.6.8 Summary and conclusions

One of the objectives of this study was to determine which theory (cf. Chapter 2) was more likely to unambiguously describe Afrikaans diphthongs. Synthetic stimuli for the perception test was devised to test whether the target theory, the trajectory theory (the direction and the rate of change) or the temporal formant pattern could describe diphthongs in Afrikaans unambiguously. Subjects were asked to identify and give quality judgements on synthetic diphthongs in a listening test.

The data was analysed and ANOVA's and post hoc comparisons were performed. Results indicated that for the specific diphthongs /ou/ was identified best, then /ei/ and finally /ui/. While /ou/ was never identified as either /ei/ or /ui/, it was found that /ui/ was more likely to be identified as /ei/ than vice versa. This might be due to the appearance of neutralisation in Afrikaans where /ui/ is neutralised to /ei/.

The overall values of all the diphthongs were analysed and results showed that diphthongs of the temporal formant pattern were **identified** best and were also **judged** by the listeners as being of a **higher quality** than diphthongs from the other three theories. The same analyses were done for the specific diphthongs and the results suggested that for /ei/, /ou/ and /ei/ respectively, diphthongs of the temporal formant pattern were identified best and were also judged as being of the highest quality.

Sounds that were not correctly identified were identified as 'junk'. Only 1% of the diphthongs of the temporal formant pattern were identified as 'junk', while diphthongs from the other theories, had a much higher rate of incorrect identifications. Analyses performed, excluding those diphthongs that were identified as 'junk', once again showed that the specific diphthongs of the temporal formant pattern were better identified and their quality judged better than diphthong from the other theories.

Cao (1991), Peeters (1991) and Stollwerck (1991, stated that the temporal formant pattern of a diphthong is language specific and this pattern embodies the features with which a diphthong can be described unambiguously. These results are in accordance with their findings, as well as the results of the production test (cf. Chapter 3).

Another objective of the study was to determine the formant patterns of Afrikaans and to ascertain whether if a specific pattern was found, another pattern would also be acceptable to the listener. Analyses were done to establish which manipulations (patterns) for each diphthong of the temporal formant pattern were identified and judged best. It was found that, when a specific pattern was preferred, other patterns were also acceptable to the listeners.

Chapter 5: Conclusions

The main objective of this study was to investigate the acoustical features (spectral and, to a lesser degree, the temporal features) of diphthongs in Afrikaans. In order to find a way to give an adequate description of diphthongs, the target theory, the trajectory theory, as well as the temporal formant pattern were studied.

From curve fits performed on the spectral data (F1-F3, amplitude, B1-B3) it was found that not only do the values of the constants (a-e), as well as the minimum, maximum and mean frequencies and the frequency range in **identical diphthongs** vary greatly, but in the case of **different diphthongs,** these values overlapped in most cases.

The results of F1-3, amplitude and B1-B3 indicated that none of the different components of the formant pattern could **individually** describe diphthongs unambiguously. The target theory's demand that the onset and offset values are significant in diphthong identification was contradicted, as well as the trajectory theory's claim that the direction and rate of change of the formant transitions are essential in distinguishing between different diphthongs. For F2 it was possible though, to distinguish between /ou/ and the other two diphthongs.

Synthetic stimuli for the perception test were devised to determine which theory could describe diphthongs in Afrikaans unambiguously. Results showed that for the specific diphthongs, /ou/ was identified best, then /ei/ and finally /ui/. While /ou/ was never identified as either /ei/ or /ui/, it was found that /ui/ was more likely to be identified as /ei/ than vice versa. This might be due to the appearance of neutralisation in Afrikaans where the opposition between /ui/ and /ei/ is neutralised.

From the results it was clear that diphthongs of the temporal formant pattern were identified best and were also judged by the listeners as being of a higher quality than diphthongs from the target theory, the direction of change or the rate of change. Results also suggested that for /ei/, /ou/ and /ei/ respectively, diphthongs of the temporal formant pattern were identified best and were also judged as being of the highest quality. Analyses performed, excluding those diphthongs that were identified as 'junk', once again showed that the specific diphthongs of the temporal formant pattern were better identified and were also judged as being of a higher quality than diphthongs from the other theories.

In recent literature it was stated that the temporal formant pattern embodies the distinctive features with which a diphthong can be described unambiguously (Cao, 1991: Peeters, 1991; Stollwerck, 1991). The results of the perception test are in accordance with the findings of the production test (cf. chapter 3) as well as the statements of Cao (1991), Peeters (1991) and Stollwerck (1991) on diphthongs.

Another objective of the study was to determine the formant patterns of Afrikaans and to ascertain whether if a specific pattern was found, another pattern would also be acceptable to the listener. Analyses were done to establish which manipulations (patterns) for each diphthong of the temporal formant pattern were identified and judged best. It was found that, when a specific pattern was preferred, other patterns were also acceptable to the listeners.

Abstract

The main purpose of the study was to shed more light on the acoustical features of diphthongs in Afrikaans. To achieve this goal diphthongs were examined and analysed in a production test as well as a perception test.

In order to find a way to be able to give an adequate description of diphthongs acoustically the **target theory**, the **trajectory theory,** as well as the **temporal formant pattern** were discussed and critically evaluated. The production test was performed and in pursuit of finding a way of analysing the whole diphthong, curve fits were performed for the F1-F3, amplitude and B1-B3.

The result of the production test indicated that none of the different components of the formant pattern could individually describe diphthongs unambiguously, and therefore, has to lie in a combination of these components.

On the grounds of the results obtained from the production test synthetic stimuli for the perception test was devised to test whether the target theory, the trajectory theory (the direction and the rate of change) or the temporal formant pattern could describe diphthongs in Afrikaans unambiguously. Subjects were asked to identify and give quality judgements on synthetic diphthongs in a listening test.

The results showed that diphthongs of the temporal formant pattern were identified best and were also judged by the listeners as being of a higher quality than diphthongs of the target theory, the direction of change or the rate of change. These results are also in accordance with the findings of the production test

BIBLIOGRAPHY

AALTONEN, O. 1985. The effect of relative amplitude levels of F2 and F3 on the categorisation of synthetic vowels. Journal of Phonetics, 14:1-9.

BLADON, A. 1985. Diphthongs: a case study of dynamic auditory processing. Speech Communication, 4:145-154.

BOND, Z.S. 1978. The effects of varying glide durations on diphthong identification. Language and Speech, 21:253-263.

BOND, Z.S. 1982. Experiments with synthetic diphthongs. Journal of Phonetics, 10:259-264.

BORDEN, G.J., & HARRIS, K.S. 1984. *Speech science primer.* Baltimore: Williams and Wilkens. 302 p.

CAO, J. 1991. Temporal structure of diphthongal finals in Standard Chinese. (*In* Report of phonetic research. Institute of Linguistics, Chinese Academy of Social Sciences, p. 39-54.)

CLARK, J., & YALLOP, C. 1995. *An introduction to Phonetics and Phonology.* 2nd ed. Oxford: Blackwell Publishers Ltd. 468 p.

COETZEE, A. 1981. *Fonetiek.* Pretoria: Academica. 119 p.

COLLIER, R., BELL-BERTI, F. & RAPHAEL, L.J. 1982. Some acoustic and physiological observations on diphthongs. Language and Speech, 25:305-323.

COLLIER, R. & 'T HART, H.J. 1983. The perceptual relevance of the formant trajectories in Dutch diphthongs. (*In* Van den Broecke, M.P.R., van Heuven, V.J. & Zonneveld, W. Sound Structures. Studies voor Antonie Cohen. Dordrecht: Foris Publications, p.31-45.)

COMBRINK, J.H.G. & DE STADLER, L.G. 1987. *Afrikaanse fonologie*. Johannesburg: Macmillan. 217 p.

COMPUTERIZED SPEECH LABORATORY. 1992 CSL Model 4300 – Instruction manual. Kay Elemetrics Corporation. Pine Brooke

DE MANRIQUE, A.M.B. 1979. Acoustic analysis of Spanish diphthongs. Phonetica, 36:194-206.

DE VILLIERS, M. & PONELIS, F.A. 1987. Afrikaanse Klankleer. Kaapstad: 4 Tafelberg Uitgewers. 193 p.

DOLAN, W.B. & MIMORI, Y. 1986. Rate-dependent variability in English and Japanese complex vowel F2 transitions. (*In* UCLA Working Papers in Phonetics, 63: p. 125-153.)

FANT, G. 1973. *Speech sounds and features*. Massachusetts: The MIT Press.

GAY, T. 1967. A perceptual study of English diphthongs. (*In* Supplement to Haskins Laboratories - Status Report on Speech Research, June, 1967.)

GAY, T. 1968. Effect of speaking rate on diphthong formant movements. Journal of the Acoustical Society of America, 44:1570-1573.

GAY, T. 1970. A perceptual study of American English diphthongs. Language and Speech, 113:65-88.

GERBER, S.E. 1971. Perception of segmental diphthongs. (*In* Proceedings of the 7th International Congress on Phonetic Sciences, Montreal p. 479-492.)

GERRITS, E. 1995. Diftongen van dove en horende sprekers: Produktie en Perceptieve beoordeling. Nijmegen: Catholic University of Nijmegen. (MA Dissertation) 82 p.

GOTTFRIED, M., MILLER, J.D. & MEYER, D.J. 1993. Three approaches to the classification of American English diphthongs. Journal of Phonetics, 21:205-229.

HAWKINS, A. 1984. Introducing phonology. Hutchinson:London. 326p.

HLSyn User manual. 1995. Sensimetrics Corporation, Cambridge Massachusetts.

HOUSE, A.S. & FAIRBANKS, G. 1953. The influence of consonant environment upon the secondary acoustical characteristics of vowels. Journal of the Acoustical Society of America, 25:105-114.

HOLBROOK, A. & FAIRBANKS, G. 1962. Diphthong formants and their movements. Journal of Speech and Hearing Research, 5:38-58.

KENT, R.D. & READ, C. 1992. The acoustic analysis of speech. San Diego: Singular.

KLATT, D.H. 1974. The duration of [s] in English words. Journal of Speech and Hearing Research, 17:41-50.

KLATT, D.H. 1976. Linguistic uses of segmental duration in English: acoustic and perceptual evidence. Journal of the Acoustical Society of America, 59:1208-1221.

KLATT, D.H. 1987. Review of text to speech conversion for English. Journal of the Acoustical Society of America, 59:1208-1221.

LEHISTE, I. & PETERSON, G.E. 1961. Transitions, glides and diphthongs. Journal of the Acoustical Society of America, 33:268-277.

NABELEK, A.K., CZYZEWSKI, Z. & CROWLEY, H. 1994. Cues for perception of the diphthong [ai] in either noise or reverberation. Part I. Duration of the transition. Journal of the Acoustical Society of America, 95(5):2651-2693.

NABELEK, A.K., ORCHINNICOV, A., CZYZEWSKI, Z. & CROWLEY, H. 1996. Cues for perception of synthetic and natural diphthongs in either noise or reverberation. Journal of the Acoustical Society of America, 99(3):174-1753.

NARAHARA, Y., SHIMODA, H. & OKAMOTO, T. 1977. Akustisch -Phonetische Studie uber die deutschen Diphthonge. (*In* Narahara, Y., Okamoto, T. & Shimoda, H. eds. Beitrage zur Phonetic des Deutschen. Hamburg: Helmut Buske. p. 44-85.)

NEARY, T.M. & ASSMANN, P.F. 1986. Modelling the role of inherent spectral change in vowel identification. Journal of the Acoustical Society of America, 80(II): 1297-1308.

NOOTEBOOM. S.G. 1972. Production and perception of vowel duration. A study of durational properties of vowels in Dutch. Utrecht: University of Utrecht. (Doctoral Thesis).

ODENDAL, F.F. 1989. Afrikaans Fonetiek. (*In* T.J.R.Botha ed. Inleiding tot die Afrikaanse Taalkunde. p. 493)

OLIVE, J.P., GREENWOOD, A. & COLEMAN, J. 1993. *Acoustics of American English speech*. New York: Springer Verlag. 396 p.

PEETERS, W.J.M. 1991. Diphthong Dynamics. Utrecht: University of Utrecht. (Doctoral Thesis.) 365 p.

PETERSON, G.E. & BARNEY, H.L. 1952. Control methods used in a study of the vowels. Journal of the Acoustical Society of America, 24:175-184.

PICKETT, J.M. 1980. *The sounds of speech communication.* Baltimore: University Park Press. 249 p.

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

RAPHAEL, L.J. 1972. Preceeding vowel duration as a cue to the perception of the voicing characteristics in American English. Journal of the Acoustical Society of America, 51: 1296-1303.

RAUBENHEIMER, H. 1994. Enkele aspekte van die temporele eienskappe van lang vokale en diftonge in Afrikaans. Potchefstroom: Potchefstroom University for Christian Higher Education. (MA Dissertation). 91 p.

SAWUSCH, J.R., NUSBAUM, H.C., SCHWAB, E.C. 1980. Contextual effects in vowel perception II: Evidence for two processing mechanisms. Perception and Psychophysics, 27(5): 421-434.

SLIS, I.H. & KATWIJK, A.F.V. 1963. (*In* Onderzoek naar Nederlandse tweeklanken. I.P.O. Report 31. Eindhoven.

STOLLWERCK, L. 1991. A contrastive study of the dynamic nature of the diphthongs /au/ and /ai/ in the production of English and German native speakers. London: University College London. (MA Dissertation). p89.

TAYLOR, J.R. & UYS, J.Z. 1988. Notes on the Afrikaans vowel system. Leuvense bijdragen, 77: 429-449.

TOLEDO, G.A., & ANTONANZAS-BARROSO, N. 1987. Influence of speaking rate on Spanish diphthongs. (In Proceedings of the eleventh International congress of Phonetic Sciences. Tallinn, 3: p. 125-128.)

UYS, J.Z. 1981. Oor erkende en nie-erkende diftonge in Afrikaans. Taalfasette, 1:26-36.

VAN DER MERWE, H.J.J.M. 1951. *An introduction to Afrikaans.* Cape Town: Balkema.

VAN DER MERWE, A., GROENEWALD, E., VAN AARDT, D., TESNER, H.E.C. & GRIMBEEK, R.J. 1993. Die formantpatrone van Afrikaanse vokale soos geproduseer deur manlike sprekers. South African Journal of Linguistics, 11(2):71-79.

VAN RENSBURG, C. 1979. Die herkoms van die Afrikaanse sogenaamde diftonge. Taalseminaar (1979):2-7.

VAN WYK, E.B. 1979. *Praktiese fonetiek vir taalstudente: 'n Inleiding.* Durban: Butterworth.

VAN WYK, E.B. 1983. Opmerkings oor enkele klankvariasies in Afrikaans. (*In* Sinclair, A.J.L. ed. G.S. Nienaber: 'n Huldeblyk. University of the Western Cape: Publication Committee UWC.)

WISSING, D.P. 1971. Fonologie en morfologie van die simplekse selfstandige naamwoord in Afrikaans: 'n Transformasioneel-generatiewe beskrywing. Amsterdam: Buijten & Schipperheijn. (Doctoral Thesis). 121 p.

WISSING, D.P. 1992. Vowel duration in Afrikaans: The influence of post-vocalic voicing and syllable structure. Journal of the Acoustical Society of America, 92(1): 589-592.

WISSING, D.P. 1995. Ontronding in twee Afrikaanse variëteite: 'n produksie en 'n persepsiestudie. Internasionale vereniging voor Neerlandistiek. Vrije Universiteit van Amsterdam.

WISSING, D.P & BURGER, W.H. 1991. Sillabestruktuur se invloed op vokaallengte. South African Journal of Linguistics, Supplement, 11:157-164.

WISSING, D.P. & RAUBENHEIMER, H. 1994. Lengtevariasies van sommige Afrikaanse vokale en konsonante in verskillende sinsposisies. South African Journal of Linguistics, 12(4):139-143.

WISSING, D.P. & COETZEE, A. 1996. Die akoestiese eienskappe van stemlose eksplosiewe van Afrikaans. South African Journal of Linguistics, Supplement 34:63-82.

WISSING, D.P. & ZONNEVELD, W. 1996. Final devoicing as a robust phenomenon in second language acquisition: Tswana, English and Afrikaans. South African Journal of Linguistics, Supplement 34:103-122.

APPENDIX A

STIMULUS MATERIAL FOR THE PRODUCTION TEST

puik, buit, muis, vuis, wuif, tuit, duif, ruis, kuit, guit, pruik, bruin, fruit, trui, pluis, stuit, spruit, kruid, bruid, vuil, huil, kuil, suil, muil, luie, kuier, uie

In 'n tuin êrens buite Muiden kruip sonder 'n geluid 'n vuil tuinman met sy gebruinde huid. Tersluiks gluip die guit na 'n ruit ver voor hom uit, van waaruit die deurgaans uithuisige Trui met 'n spuit spruitjies spuit. Terstond ontluik 'n liefde uitsluitend vir Trui en in 'n huiwerende bui sluip hy deur die fruitstruike na 'n huisie van trui. Snuiwend en huilend wuif hy, maar luimige Trui met haar guitige snuit beduie die tuinman: "Dit is uit!" pruilend druip die tuinman af, die tuin uit

pyl, byl, myl, feil, vyl, wyl, Nyl, teil, steil

Op 'n pleintjie in Beilen bly twee lywige reisigers. Beide kyf tot kort voor vyf oor die beleid van sy majesteit. "In hierdie tyd", sê een van beide in sy nyd, "word 'n yster beleid vereis. Sy majesteit skyn in die paleis te verwyl by wyse van tydverdryf. Hy moes dit tog vermy". Na die bytende venynige verwyt sê sy ysig "Spytig en pynlik is dit wat jy my sê. Jy wys my op my en jou plig om ons te vermei in die vryheid wat hy, sy majesteit ywerig vir ons berei. Hy is vry in die styl en wyse van beleid". By klokslag vyf wou geen van beide nog langer bly.

pou, bou, bout, boud, mout, vou, dou, sout, rou, koud, Paul, koue, roue, sous

Woutjie wou van Woubach na Spoubeek sjoue. Om dit uit te kon hou, koop hy in die volste vertroue by 'n gebou 'n paar nuwe blou kouse. Trouens, in sy nou moue sou hy nogal gou 'n pakkie kougom stou. Sy vrou kon so vertrou dat nou geen floute hom sou benoud maak nie en dat die gesjou haar Woutjie nie sou berou nie. So gaan stoute Wout douvoordag na 'n gesellige koutjie, sonder die roue gesnou van sy vrou in die koue oggenddou aan't sjoue.

APPENDIX B

RESULTS OF THE PRODUCTION TEST: DURATION, F0, AMPLITUDE, F1-F3, B1-B3

The total durational values of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 72.** The durations are given in milliseconds

Table 72: Duration of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
Total values	121	162	158

The values of the six measuring points of the fundamental frequencies (F0) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 73.** The fundamental frequencies are given in Hertz.

Table 73: F0 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	136	138	137
2)	134	138	137
3)	134	139	138
4)	136	141	139
5)	137	144	140
6)	137	144	141

The values of the six measuring points of the amplitude values of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 74.** The values for the amplitude are logarithmic values and therefore the values of the following parameters are are not given in decibel

Table 74: Amplitude of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	7457	7863	6936
2)	8832	9119	8631
3)	9064	7399	9315
4)	7943	4848	8584
5)	6535	3080	6911
6)	5647	2931	4947

Figure 27: Amplitude - /ui/: This figure represents the /ui/ - values per frame of amplitude of the five subjects, as well as the average of the five subjects. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

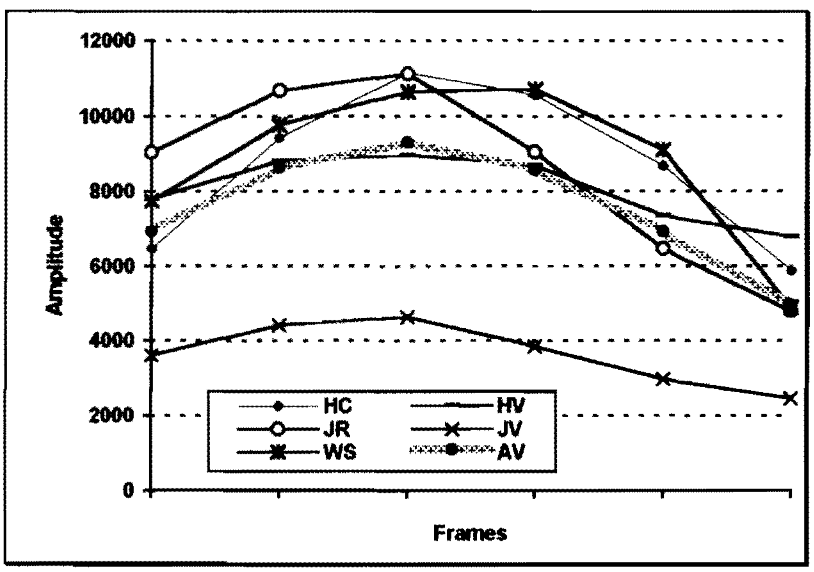


Figure 27: Amplitude - /ui/

Figure 28: Amplitude - /ei/: This figure represents the /ei/ - values per frame of amplitude of the five subjects, as well as the average of the five subjects. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

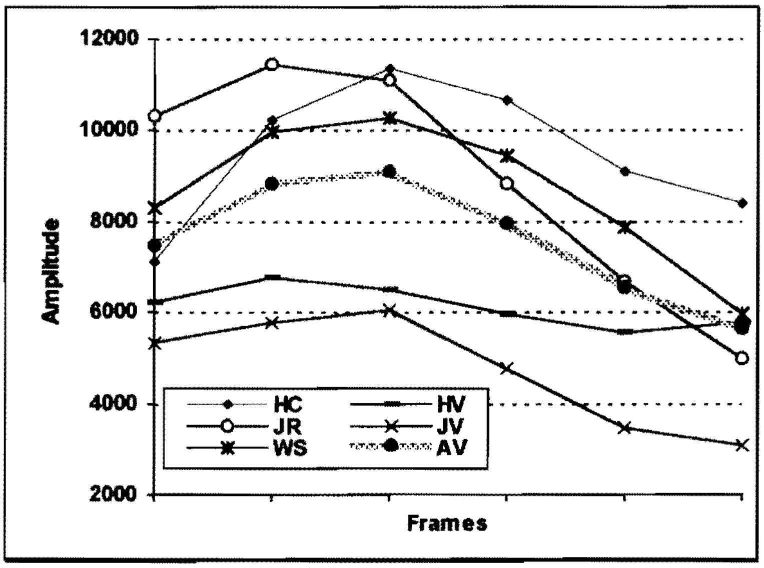


Figure 28: Amplitude - /ei/

Figure 29: Amplitude - /ou/: This figure represents the /ou/ - values per frame of amplitude of the five subjects, as well as the average of the five subjects. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

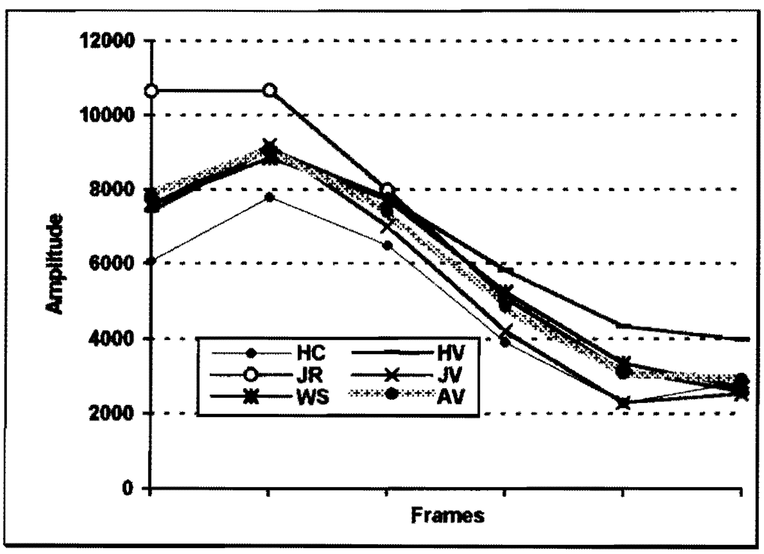


Figure 29: Amplitude - /ou/

The values of six measuring points of formant 1 (F1) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in Table 75. The formant frequencies are given in Hertz.

Table 75: F1 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	596	544	539
2)	593	547	548
3)	541	492	523
4)	474	424	453
5)	411	366	381
6)	358	346	334

Figure 30: Formant 1 - /ui/: This figure represents the /ui/ - values per frame of F1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

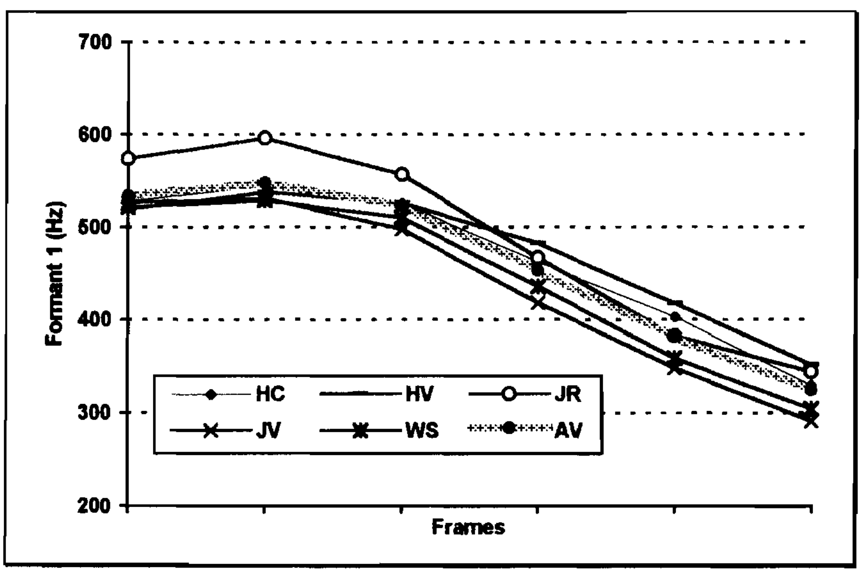


Figure 30: Formant 1 - /ui/

Figure 31: Formant 1 - /ei/**:** This figure represents the /ei/ - values per frame of F1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

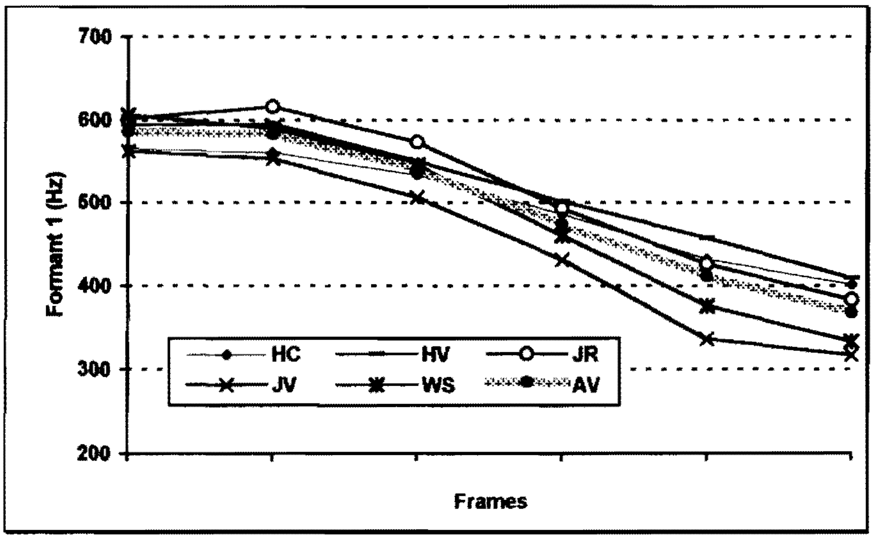


Figure 31: Formant 1 - /ei/

Figure 32: Formant 1 - /ou/**:** This figure represents the /ou/ - values per frame of F1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

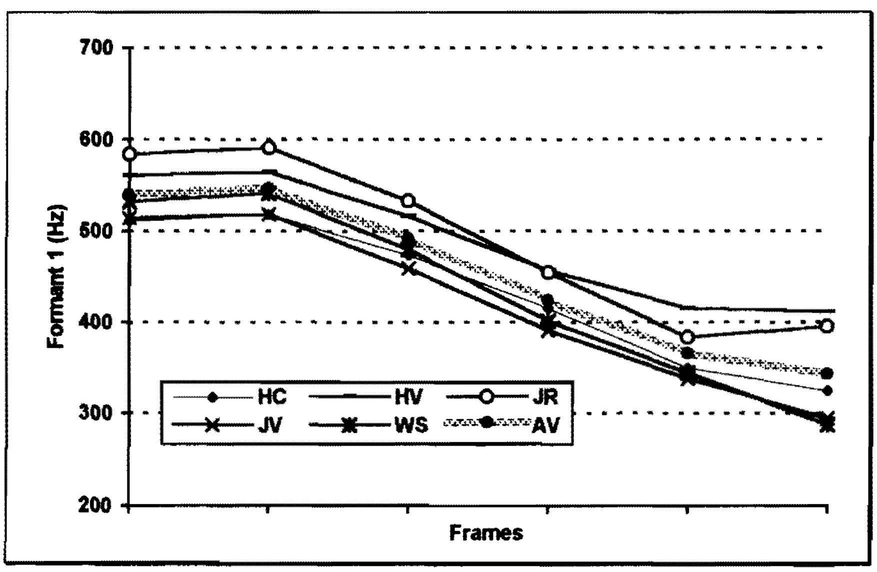


Figure 32: Formant 1 - /ou/

The values of six measuring points of the frequencies of formant 2 (F2) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in Table 76. The formant frequencies are given in Hertz.

Table 76: F2 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	1418	1366	1310
2)	1427	1324	1311
3)	1624	1282	1454
4)	1763	1188	1649
5)	1880	1103	1826
6)	1890	1188	1812

Figure 33: Formant 2 - /ui/: This figure represents the /ui/ - values per frame of F2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

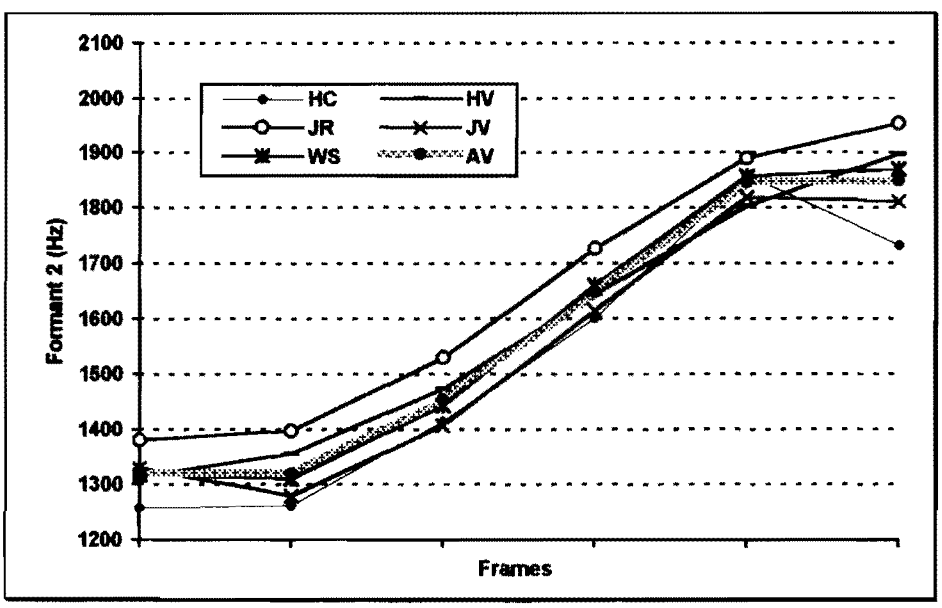


Figure 33: Formant 2 - /ui/

Figure 34: Formant 2 - /ei/: This figure represents the /ei/ - values per frame of F2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

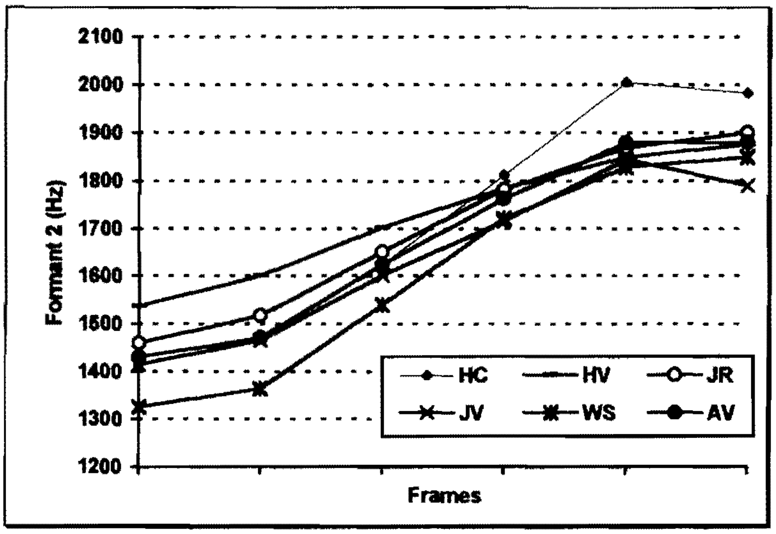


Figure 34: Formant 2 - /ei/

Figure 35: Formant 2 - /ou/: This figure represents the /ou/ - values per frame of F2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

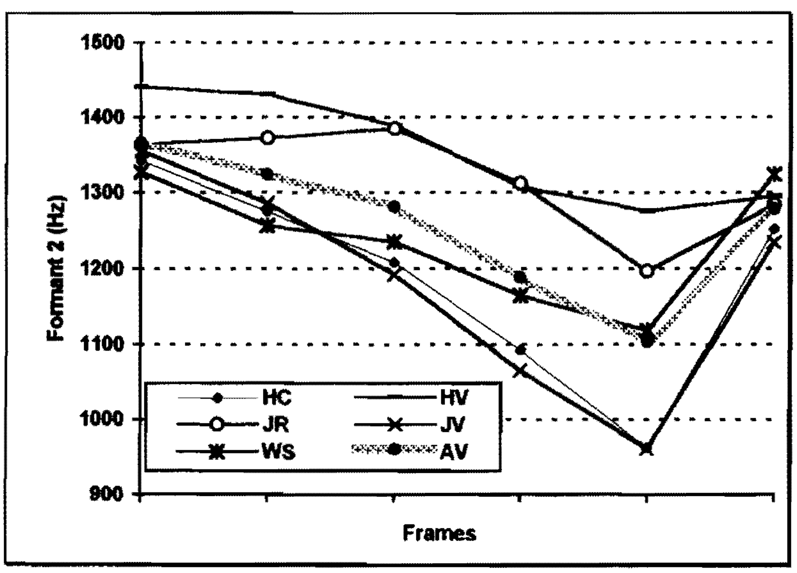


Figure 35: Formant 2 - /ou/

The values of the six measuring points frequencies of formant 3 (F3) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in Table 77. The formant frequencies are given in Hertz.

Table 77: F3 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	2354	2303	2308
2)	2324	2229	2257
3)	2342	2216	2261
4)	2394	2219	2287
5)	2458	2241	2382
6)	2510	2363	2510

Figure 36: Formant 3 - /ui/: This figure represents the /ui/ - values per frame of F3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

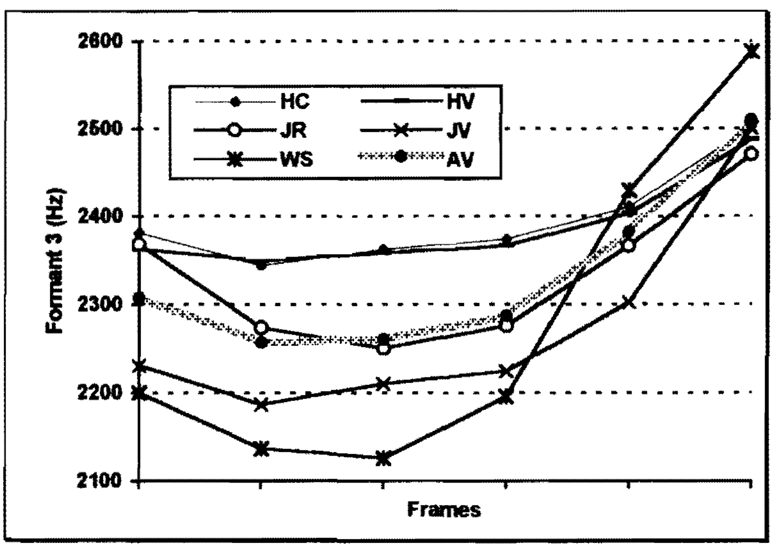


Figure 36: Formant 3 - /ui/

Figure 37: Formant 3 - /ei/: This figure represents the /ei/ - values per frame of F3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

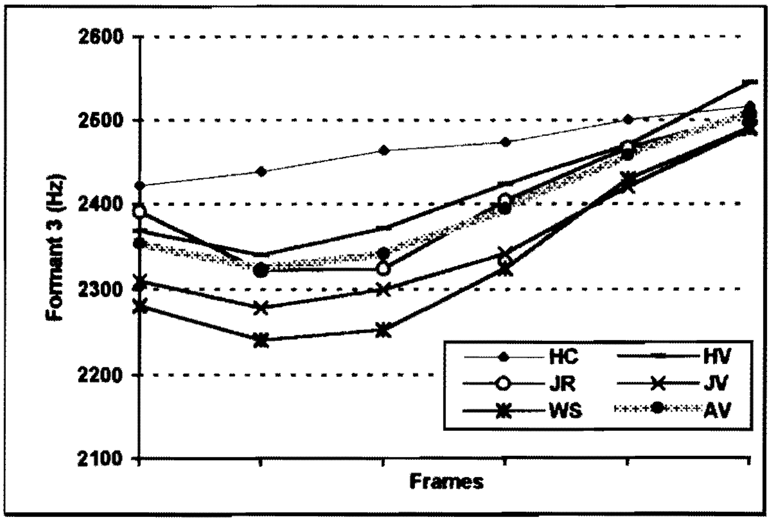


Figure 37: Formant 3 - /ei/

Figure 38: Formant 3 - /ou/: This figure represents the /ou/ - values per frame of F3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

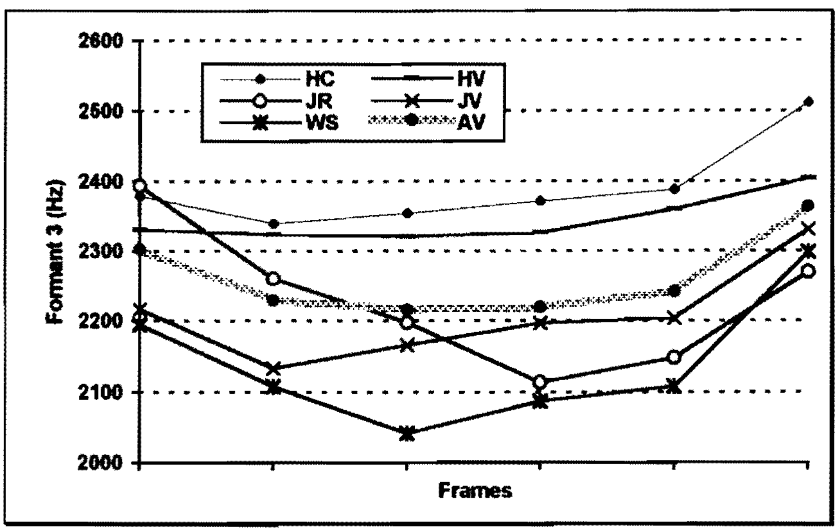


Figure 38: Formant 3 - /ou/

The values of six measuring points of the frequencies of bandwidth 1 (B1) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 78.** The bandwidth frequencies are given in Hertz.

Table 78: B1 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	206	172	272
2)	151	130	161
3)	138	144	152
4)	129	144	138
5)	123	186	126
6)	210	452	250

Figure 39: Bandwidth 1 - /ui/: This figure represents the /ui/ - values per frame of B1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

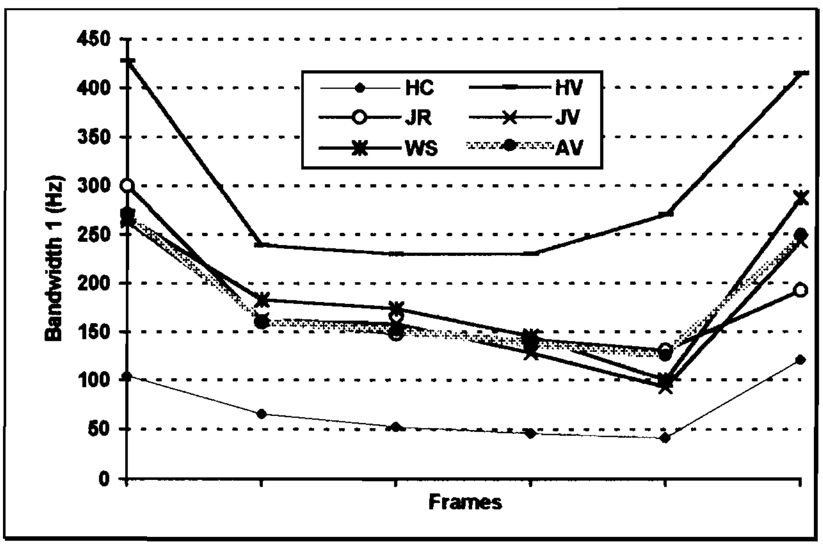


Figure 39: Bandwidth 1 - /ui/

Figure 40: Bandwidth 1 - /ei/: This figure represents the /ei/ - values per frame of B1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

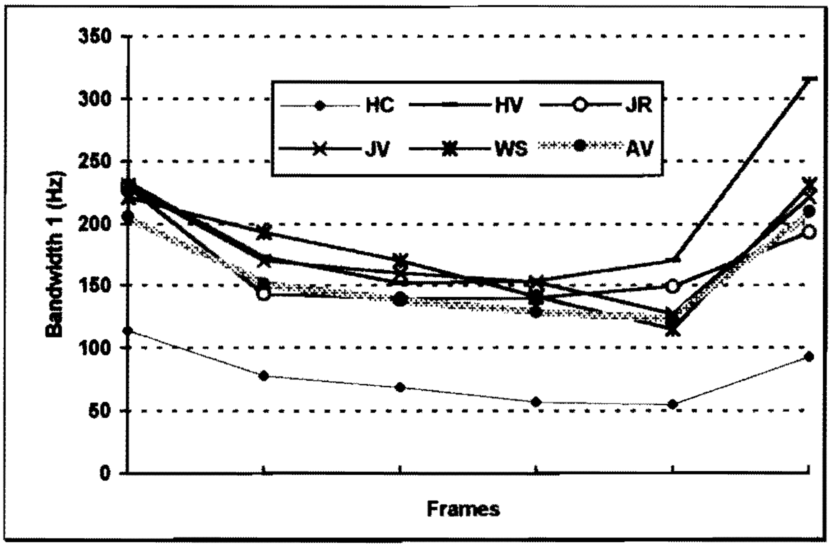


Figure 40: Bandwidth 1 - /ei/

Figure 41: Bandwidth 1 - /ou/: This figure represents the /ou/ - values per frame of B1 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

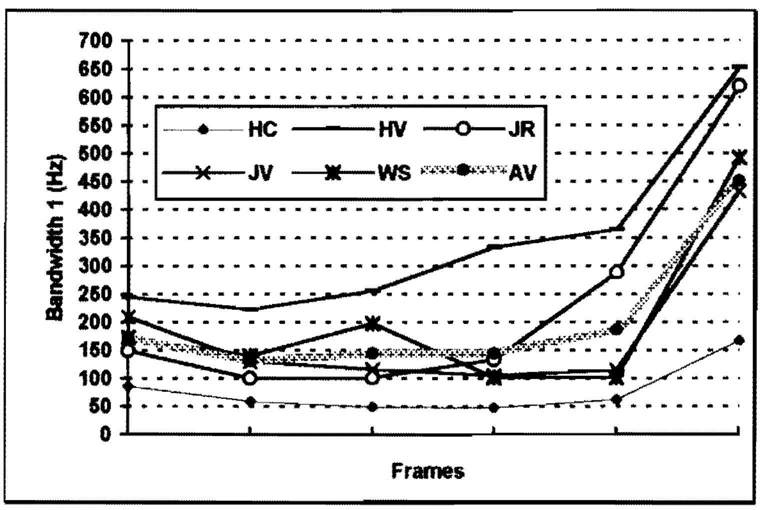


Figure 41: Bandwidth 1 - /ou/

The values of six measuring points of the frequencies of bandwidth 2 (B2) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 79.** The bandwidth frequencies are given in Hertz.

Table 79: B2 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	277	306	323
2)	211	254	220
3)	201	257	208
4)	259	275	233
5)	265	328	269
6)	365	662	462

Figure 42: Bandwidth 2 - /ui/: This figure represents the /ui/ - values per frame of B2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

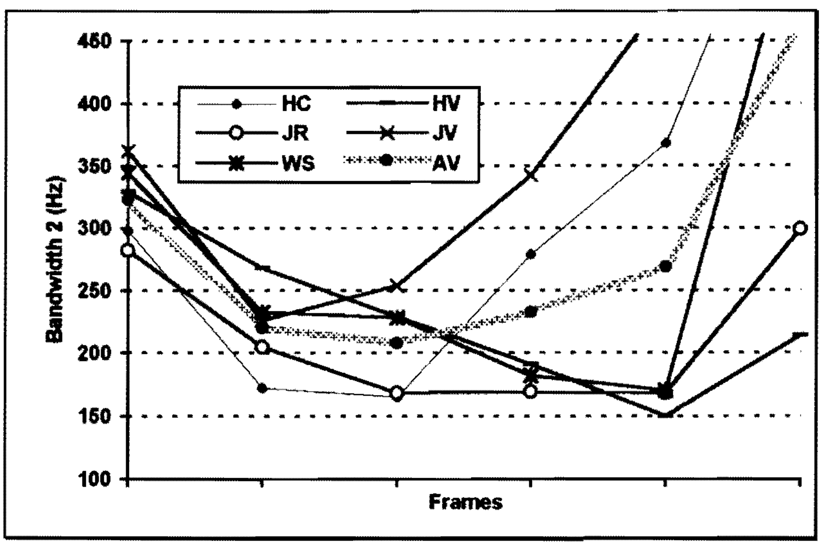


Figure 42: Bandwidth 2 - /ui/

Figure 43: Bandwidth 2 - /ei/ This figure represents the /ei/ - values per frame of B2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

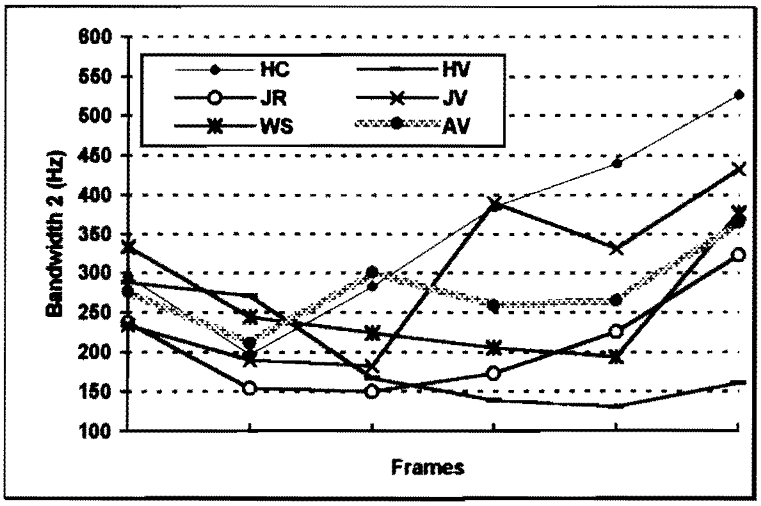


Figure 43: Bandwidth 2 - /ei/

Figure 44: Bandwidth 2 - /ou/: This figure represents the /ou/ - values per frame of B2 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

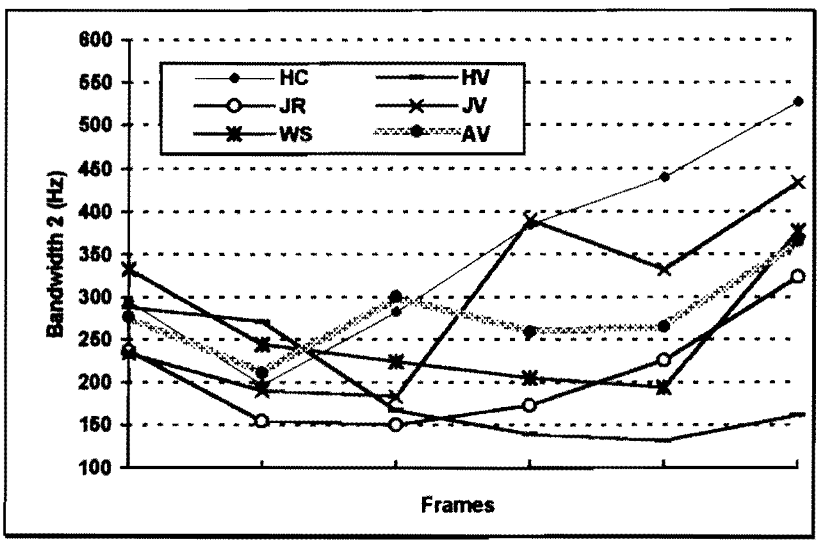


Figure 44: Bandwidth 2 - /ou/

The values of six measuring points of the frequencies of bandwidth 3 (B3) of the diphthongs /ei/, /ou/ and /ui/ of the average of the five subjects are presented in **Table 80**. The bandwidth frequencies are given in Hertz.

Table 80: B3 of /ei/, /ou/ and /ui/

	/ei/	/ou/	/ui/
1)	311	371	332
2)	266	263	269
3)	298	277	272
4)	354	245	251
5)	354	277	268
6)	420	730	374

Figure 45: Bandwidth 3 - /ui/: This figure represents the /ui/ - values per frame of B3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

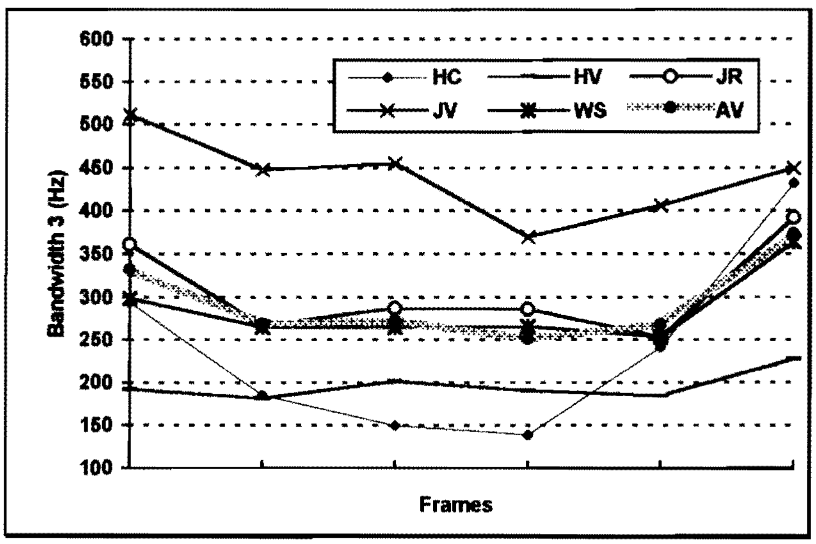


Figure 45: Bandwidth 3 - /ui/

Figure 46: Bandwidth 3 - /ei/: This figure represents the /ei/ - values per frame of B3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

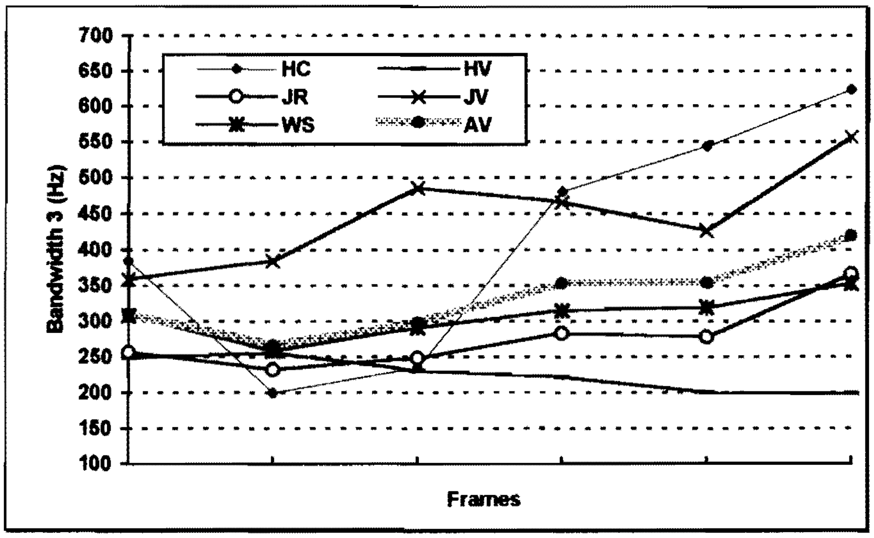


Figure 46: Bandwidth 3 - /ei/

Figure 47: Bandwidth 3 - /ou/: This figure represents the /ou/ - values per frame of B3 of the five subjects, as well as the average of the five subjects. The values on the y – axis are given in Hertz. Legend explanation: HC: subject 1, HV: subject 2, JR: subject 3, JV: subject 4, WS: subject 5, AV: Average of the five subjects.

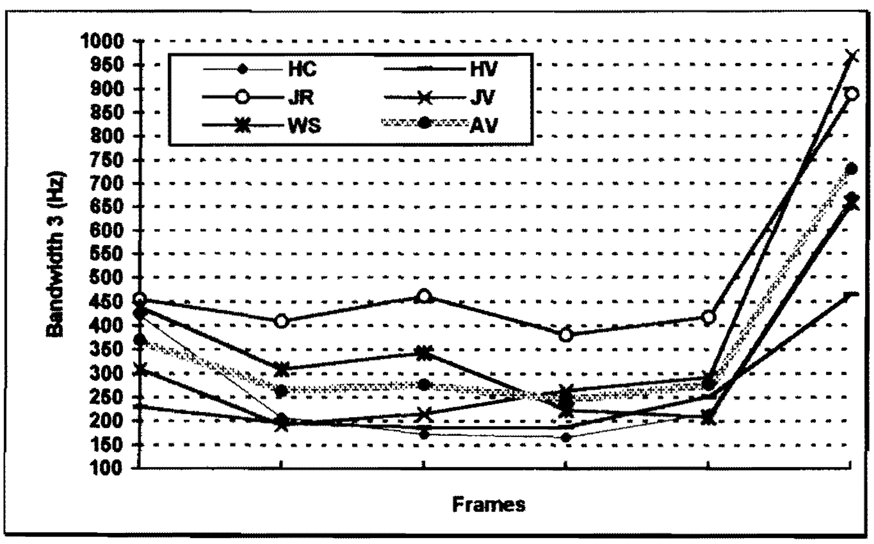


Figure 47: Bandwidth 3 - /ou/