# The acoustic characteristics of Greek vowels produced by adults and children

STUDENT: ANNA SFAKIANAKI

SUPERVISOR: PROF. PETER ROACH

“Dissertation submitted in partial fulfilment of the requirements for the degree of MA in Applied Linguistics”

DEPARTMENT OF LINGUISTIC SCIENCE

UNIVERSITY OF READING

SEPTEMBER 1999

# Contents

## Abstract

To our knowledge, no research on the acoustic analysis of children's speech has been published in the Greek language. At the same time, the need for an expanded database, that would include information on children, is underlined in the literature. This study, in an attempt to acknowledge this need, involves the acoustic analysis of men's, women's and children's vowels, with an emphasis on the last, and examines the relationship between adults' and children's acoustic data.

The most important difficulty encountered was the location of the second and third formants of the high, back vowel [u], especially when unstressed, in word-final position and produced by children. Concerning the children's vowels, due to their higher formant frequencies, they were found to be more fronted and open than women's and even more so than men's vowels, so as to form a vowel space placed more "downwards and to the left", as expected from English children's data (Deterding, 1990: 49&51). A comparison with adults' data from previous Greek experiments demonstrated that vowels in this study appear to be more fronted and open.

The scattergrams of adults' versus children's data revealed a relation that can be represented by a linear model quite satisfactorily (R-Sq > 90%). Thus, children's vowels can be predicted from adults' vowels with minor error, using regression equations. This knowledge has value for speech applications, such as the improvement of automatic speech recognition systems.

## Acknowledgements

I would like to thank my parents and Vassilis Spyropoulos for their love and enduring support, and my informants for providing their time for the recordings.

I especially wish to express my gratitude to my supervisor and mentor, Prof. Peter Roach, whose thoughtful guidance inspired and helped me find my way in this scientific field.

## List of Figures

| **Figure** | | **Page** |
|---|---|---|

***Chapter IV***

| Figure | | Page |
|---|---|---|

# List of Tables

# Chapter I: Introduction

## 1.1. Research motivation

Research in acoustic phonetics has been characterised as a field with an "androcratic scientific heritage" (Henton, 1995:422). Lass (1996:221) comments that expanding the acoustic database to include information on children and women is an area of recent progress. The lack of a "complete" database in this sense and the need for an expansion in this direction has been underlined by numerous studies. Especially the value of research in children's speech acoustics has been pointed out in the literature (i.e. Lee et al., 1997, Deterding, 1990:42, Clark & Yallop, 1995:241), as this knowledge would be used for the improvement of automatic speech recognition systems, text-to-speech synthesis and speech therapy methods, and would provide a better understanding of the speech production mechanism or even bring changes upon speech production theories.

Although research in other languages has already acknowledged the importance of this matter, Greek research still focuses on men's speech, except for few studies including women as subjects (Kontosopoulos *et al.*, 1988 and Botinis *et al.*, 1997). Nevertheless, nothing has been published on children's speech, to our knowledge.

This study constitutes an attempt towards this direction. Men's, women's and children's vowels are analysed acoustically and an emphasis on the spectral characteristics of children's vowels is given, as well as on the relationship between children's and adults' vowels.

## 1.2. Dissertation outline

Chapter II describes the theoretical background of this study. A historical review begins with the traditional phonetic theory and continues with the insufficiencies and limitations of this theory, which have led research to the direction of acoustic analysis. Some information about the sound wave and the acoustic model of speech production is provided, and emphasis is given on the acoustic properties of vowel quality. This chapter also touches on the issue of normalisation. Differences between classes of speakers and some of the methods that have been suggested as a solution to this issue are recounted. The last part of this chapter reports the acoustic research on Greek vowels and mentions major findings of this area.

Chapters III, IV and V provide a description of this study. Chapter III refers to the methodology: information about the subjects, the corpus, the recording and measurement techniques and the methods for analysing the data are provided. In Chapter IV, the results of the analysis are presented and discussed. Finally, in Chapter V, a summary of the findings is given and some suggestions for further research are made.

# Chapter II: Theoretical Background

## 2.1. Vowel Quality

### 2.1.1. The traditional phonetic theory

Vowel sounds –also mentioned as *vocalic* (Clark & Yallop, 1995:22) or *vocoid* sounds to avoid "theoretical ambivalence" [1] (Laver, 1994:270)– are produced "by egressive pulmonic airflow through vibrating or constricted vocal folds in the larynx and through the vocal tract" (Clark & Yallop, 1995:22). The vocal tract takes different shapes and sizes through the movements of the vocal organs, or *articulators*, thus modifying the sound. The two major articulators of vowel sounds are the tongue and the lips. Hence the shape and position of the tongue determines the geometry of the oral and pharyngeal cavities, while the shape of the lips controls the front area of the vocal tract and their protrusion can extend its overall length.

As the vocal tract varies, vowel quality changes, and this fact founded Alexander Melville Bell's notion that "the phonetic quality of vowels derived from the position and height of the point of constriction of the tongue" (Lieberman & Blumstein, 1988:164). Consequently, phoneticians tried to specify vowel sounds "in terms of the position of the highest point of the tongue and the position of the lips" (Ladefoged, 1993:12) and place them in the *vowel space*, an area of tilted oval shape, "within which the highest point of the body of the tongue is placed in the production of vocoids" (Laver, 1994:272). The vowel space was stylised into a *vowel chart* (Figure 1) which shows the limits of possible vowel quality (Ladefoged, 1993:219). The points at the four corners of the chart represent vowels with extreme qualities; if

[1] The term "vowel" could refer to the phonological level as well as the phonetic level and is therefore avoided in some introductory books so as not to create confusion. Since this dissertation views the vowel from a phonetic perspective only, there is no need to adopt any alternative term.

the tongue were moved beyond these points the generated sound would not be vocalic.

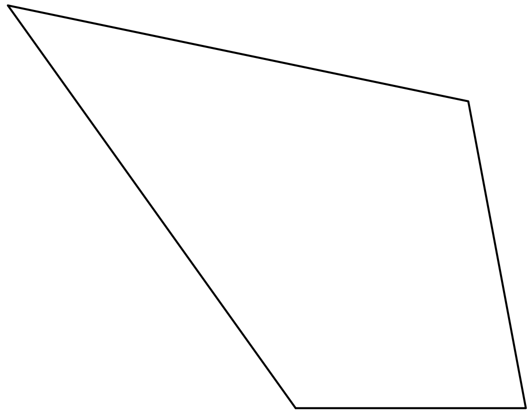


Figure 1 Stylised chart of the vowel space (Jones 1962 & Abercrombie 1967, as cited in Laver, 1994:273)

The above chart does not provide enough reference points for the description of all the vowels in the existing languages. Therefore, Bell tried to define standard categories of vowel quality and associated articulatory positions (Clark & Yallop, 1995:23). In the early part of this century, Daniel Jones proposed a set of *cardinal vowels* as “arbitrary reference points” (Ladefoged, 1993:219), so as to represent the most peripheral tongue positions for vowel sounds (Clark & Yallop, 1995:24). The cardinal vowels occupy specific points in the vowel continuum (Ladefoged, 1967:76) and do not refer to any particular language; they just provide the boundaries of vowel articulation, so that any vowel in any language can be located within the area they encompass. This area was constructed by Jones as an irregular *quadrilateral* (Figure 2), whose horizontal sides demonstrate the tongue *fronting* (or *backness*), while the vertical sides show the tongue *height*.

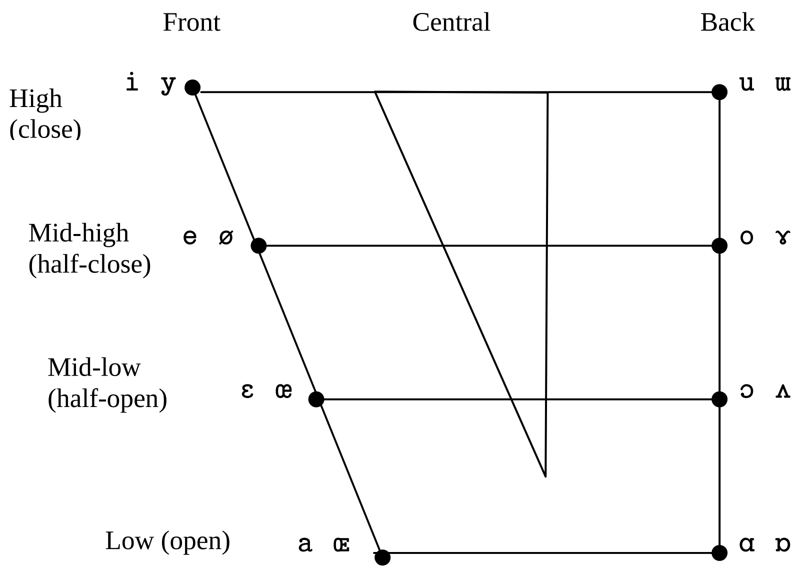



Figure 2 The cardinal vowel chart. The articulatory dimensions[2] are front versus back and high versus low. The first symbol of each pair corresponds to the primary cardinal set and the second to the secondary (figure adopted from Laver 1994:274 & Clark & Yallop 1995:25&27).

Jones divided[3] the sixteen cardinal vowels into two sets, each one consisting of eight *primary* and eight *secondary* cardinal vowels. In the primary set, two of the cardinal vowels are defined in articulatory terms (Ladefoged, 1993:219), since they are easy to locate by the feel of the tongue. Cardinal 1 (the nearest example in English is the vowel [i] in the word *heed*) is produced with the tongue as high and as far forward in the mouth as possible, and the lips spread, while cardinal 5 (the nearest example is the vowel [ɑ] in the word *hard*) is produced with the tongue as low and retracted as possible (Clark & Yallop, 1995:24). For cardinals 2, 3 and 4 (symbols e, ɛ and a) the tongue is still fronted but it is lowered in equal steps, so that the front

[2] The qualities in the parentheses refer to the degree of stricture of open approximation; i.e. vowels made in the area closest to the roof of the mouth are called close vowels (Laver, 1994:276).
[3] Roach (1992:19) suggests that the primary/secondary division should be abandoned “for the sake of consistency” and the term “rounded” or “unrounded” should be used to characterise each vowel.

primary cardinals are “auditorily equidistant” (Clark & Yallop, 1995:24, Ladefoged, 1993:220), while the lips progress from spread to neutral position. Cardinals 6, 7 and 8 (symbols ɔ, o and u) are formed, starting from cardinal 5 and raising the tongue in a retracted position while rounding the lips. The back primary cardinals are also situated at equal auditory intervals. In the secondary set, the cardinals are produced in the same way, except that the lip positions are reversed. The zoning of the Jones cardinal vowel diagram and most of the phonetic symbols of the vowels have been adopted by the IPA (Laver, 1994:274).

### 2.1.2. The inconsistency of the traditional phonetic theory

According to the traditional phonetic theory, the position of *the highest point of the tongue* determines vowel quality. X-rays of cardinal vowels, though, show that there is only a rough correspondence between the tongue position and the actual auditory qualities of vowels and that measurements required for vowel descriptions are more complex than the ones proposed by the traditional theory (Ladefoged, 1993:222 and Deterding, 1990:25).

The major problem of the theory is its disregard for the role of the vocal tract organs, apart from the tongue and the lips, in determining vowel quality. Thus, the fact that speakers produce a given auditory quality in more than one ways remains unaccounted for. Lindau (as cited in Clark & Yallop, 1995:25) has pointed out that speakers are capable of a considerable degree of *compensatory articulation* to produce a single desired auditory result in vowel quality. Stevens and House (as mentioned in Lieberman & Blumstein, 1988:169) also demonstrated that most vowels can be generated by means of many different articulatory patterns. For example, lip opening can have the same auditory influence as adjustments of overall vocal tract length.

Another fact which is not captured by the theory is that a given tongue height corresponds to different vowels. Ladefoged's study (as cited in Lieberman & Blumstein, 1988:165-166) shows that since the tongue contour is almost identical for the vowels [i], [ɛ] and [e], the acoustic elements that differentiate these vowels must be the result of the total supralaryngeal vocal tract area function. Therefore, the factor determining the auditory quality of the sound produced, is not the position of the highest point of the tongue as such, but the overall configuration of the vocal tract (Laver, 1994:271).

An additional problematic aspect is that the cardinal vowel system confuses articulatory and auditory properties, since cardinals 1 and 5 are established on *physiological* grounds, whereas intermediate vowels are determined by what Jones calls equal "acoustic" *(auditory)* intervals along the continuum (Clark & Yallop, 1995:24). As far as the *equidistance* issue is concerned, Ladefoged (1967:98-100), basing his conclusions on acoustic data, argues that the auditory distance between each of the front cardinal vowels is greater than between each of the back vowels. Lindau (as quoted in Clark & Yallop, 1995:25) also provides data to show that the cardinal vowel idealisation does not accommodate back vowel data of natural languages.

Finally, in the traditional theory, tongue height is defined as the height of the point of the tongue which is closest to the roof of the mouth (Clark & Yallop, 1995:25). Recent research (Clark & Yallop, 1995:26), though, suggests that the location of the *major constriction* formed by the tongue plays a far more important role than the tongue itself.

In summary, Ladefoged (1993:14) outlines the following drawbacks of the cardinal vowel system: i) vowels that are called high do not have the same tongue height, ii) not all back vowels share the same degree of backness, iii) considerable differences in the shape of the tongue in front and back vowels are disregarded, and iv) the fact that the width of the pharynx varies considerably with, and to some extent independently of, the height of the tongue in different vowels is not taken into account.

It has been proven, in conclusion, that the tongue contour, in itself, is not an invariant specification of the supralaryngeal vocal tract area functions that generate the different vowel qualities (Lieberman & Blumstein, 1988:167). Consequently, the position of the highest point of the tongue is not a valid indicator of vowel quality (Ladefoged, 1993:221) and hence the traditional labels high-low and front-back should not be taken as descriptions of tongue positions. Laver (1994:272) suggests that the traditional "highest-point" method of description is convenient for discussing the pronunciation of vowels, but not efficient at explaining the underlying physiology.

### 2.1.3. **Vowel acoustics**

#### 2.1.3.1. The sound wave

An ostensibly more objective and scientific method for examining vowel quality is the acoustic analysis of speech (Roach, 1992:7-8). This analysis is based on the fact that "all sound results from *vibration* of one kind or another" (Clark & Yallop, 1995:207). The vibration is generated by a *source*, i.e. the human vocal tract, and travels through a *propagating medium*, i.e. the air. If the vibration is plotted against time, this graph will be a *waveform*. Figure 3 shows a simple, idealised vibration waveform known as *sinusoidal* vibration or simple harmonic motion. Speech, though, involves damped vibrations (due to friction and air resistance) of a complex nature.

Sound waves are characterised by certain properties. One of these properties is *amplitude,* which refers to the magnitude of displacement in a sound vibration (Clark & Yallop, 1995:222). *Intensity* is a property deriving from amplitude and reveals how power is distributed in a space. For the sake of convenience it is expressed in dB (decibels) so that it can be related to perceived *loudness* (Ladefoged, 1993:187). Another important property of the sound wave is *duration*; the time taken by one complete cycle is called a *period* (Clark & Yallop, 1995:212). Additionally, *frequency* indicates the number of cycles per second and is usually expressed in Hz (Hertz).

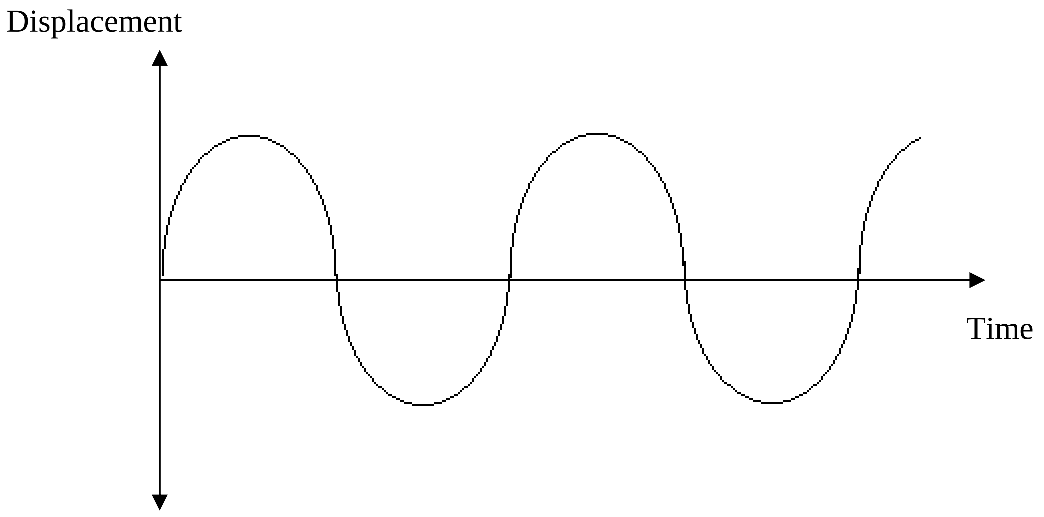



Figure 3 Simple vibration waveform (adopted from Calrk & Yallop, 1995:212)

Being complex, the sound wave consists of more than one vibrations and its frequency of vibration is defined as that of the lowest frequency of the sine (simple) waves that compose it (Clark & Yallop, 1995:215). This frequency is known as *fundamental frequency* ($F_0$). Fundamental frequency largely determines *pitch*, which is the perceived frequency of the sound wave (Lieberman & Blumstein, 1988:36), but their relationship is nonlinear (Clark & Yallop, 1995:234). The sine waves form the *harmonic* components of the sound wave, the fundamental frequency being the first harmonic, the immediately higher component being the second harmonic, etc (Clark & Yallop, 1995:227-228). In periodic waves (i.e. vowels), the frequency values of the harmonics are integral multiples of the fundamental. If the frequency is plotted against amplitude, the harmonic components of the sound wave will appear as vertical lines (Figure 4).

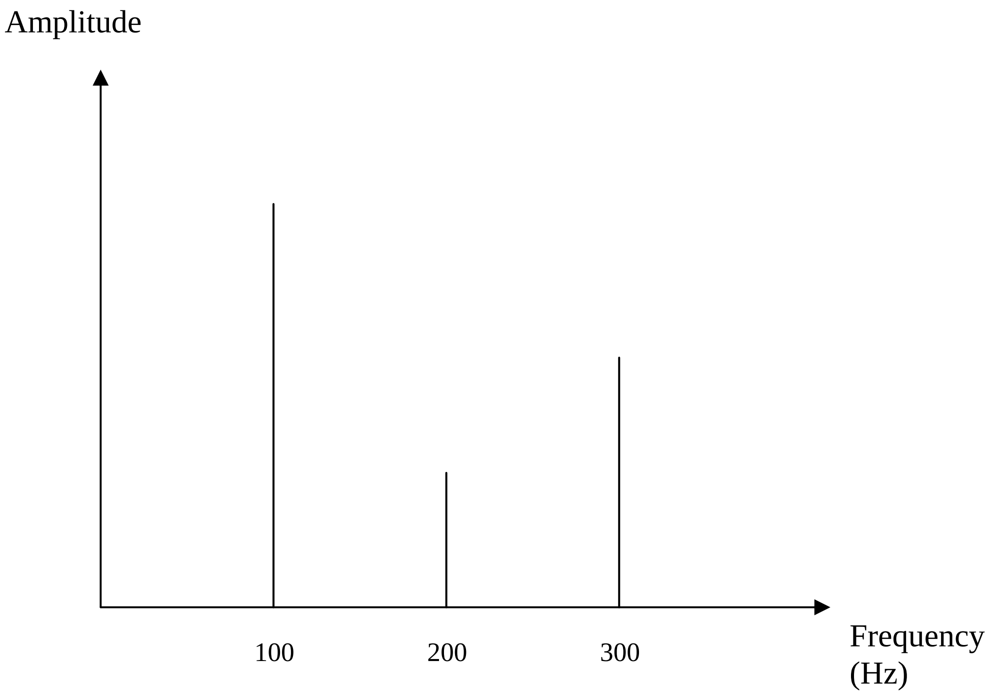



Figure 4 Line spectrum (adopted from Clark & Yallop, 1995:228)

This display is called line *spectrum*. The amplitude peaks of the line spectrum form a shape called *envelope*, which is determined by the degree of damping in the vibrating system. The factor that determines the *spacing* of the harmonic lines has to do with the frequency with which the energy is restored (Clark & Yallop, 1995:230).

This frequency is the effective *fundamental frequency*. The frequency of the maximum amplitude of harmonic energy (in figure 4 it is 100 Hz) is set by the *natural resonant frequency* of the vibrating system (Clark & Yallop, 1995:229), which is a natural frequency at which the system vibrates. A consequence of the latter property is that "a resonant system transmits the energy of input vibration with *selective efficiency*, reaching its peak at the resonant frequency of the system" (Clark & Yallop, 1995:220). In an attempt to define the selectivity of a resonant system, the term *bandwidth* is used, as "the range of frequencies either side of the centre frequency of the system's resonance curve which have an amplitude of 70.7 per cent or greater of the resonant frequency amplitude" (Clark & Yallop, 1995:220).

#### 2.1.3.2. The acoustic model of speech production

The procedure of speech production by the human vocal tract has been considered in terms of a *source and filter model* (Figure 5). The periodic vibration (*phonation* or *voicing*) of the *vocal cords* plays the role of the **source**[4]. Phonation affects voice quality and is characterised by two important properties: firstly, *fundamental frequency*, the frequency of the vibration of the larynx in phonation, and

[4] Fricational sounds, unlike phonation, can be generated at any location in the vocal tract (Clark & Yallop, 1995:241). Frication control (Figure 5) will not be discussed as it is beyond the scope of this dissertation.

secondly, *intensity*, as the primary determinant of overall speech intensity (Clark & Yallop, 1995:240). The range of fundamental frequency employed by speakers is determined mainly by the length and muscular settings of the vocal cords. Consequently there are differences among males, females and children, as well as individual variation. The longer vocal cords of adult males yield a lower range of fundamental frequencies (Lieberman & Blumstein, 1988:36). Average values suggested by Peterson and Barney (1976:119) are around 130 Hz for males, 220 Hz for females and 270 Hz for children.

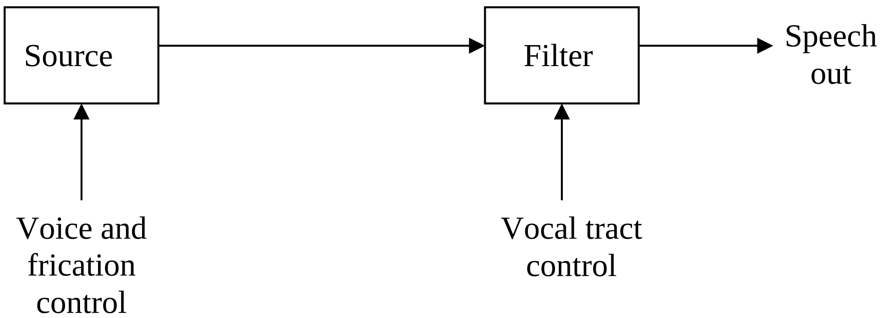



Figure 5 Source and filter model of speech production (Clark & Yallop, 1995:236)

The *supralaryngeal vocal tract* acts as an adjustable acoustic **filter** that allows certain bands of wavelengths of sound to pass through (Lieberman & Blumstein, 1988:31). According to the acoustic model, during phonation, the vocal tract approximates a parallel-sided *tube* with one end closed, and thus, inside the tube, the air column will resonate at a succession of frequencies (*multiple resonance*). At these selected frequencies there are resonances, which are observable as peaks of energy. "These peaks of energy, produced by selective enhancement of the source by the tract resonance, are known as *formants*" (Clark & Yallop, 1995:246). Hence, the formants are centre frequencies at which local energy maxima passes through the supralaryngeal air passages (Lieberman & Blumstein, 1988:32&36). Formants are conventionally numbered upwards from the lowest in frequency ($F_1$, $F_2$, etc.). The three lowest formants play a major part in determining vowel quality. According to Fant and Flanagan, (as cited in Lieberman & Blumstein, 1988:37) the bandwidths of the formants of different vowels also do markedly distinguish different vowels. It is also important to note that static formant values are not the only crucial determinant of vowel quality. We should take equal interest in the relative relationships between the formants and their movements next to consonants.

The one-tube approximation can be acceptable for the formation of vowels, like [ɜ], during which the articulators are close to a neutral posture. For other vowel sounds, though, the cross-sectional area of the vocal tract ceases to be uniform and its characteristics become more complex. As a result, the location of the resonant peaks on the frequency scale ceases to be equally distributed and a different representation model is needed. To estimate the unequally distributed resonance patterns of a vocal tract with a varying cross-sectional area, we can approximate it to *two tubes* of different size connected to each other. Fant (as cited in Clark & Yallop, 1995:248) provides nomographs which allow us to derive the four lowest resonances from the lengths of the resonators and their cross-sectional areas. Nevertheless, the two-tube representation does not cease to be only a crude approximation of this complex system; in fact, the more tubes we use to represent the vocal tract, the better the approximation.

#### 2.1.3.3. Spectrography

As the first three formants play the major role into specifying vowel sounds, an instrument called *spectrograph* was developed which could produce a threedimensional display of acoustic energy across a range of frequencies, where the more intense the energy, the darker the display (Laver, 1994:103). This display is the *spectrogram*, on which formants are represented by continuous bands of relatively intense energy of changing frequency. The spectrograph initially appeared in an analog version, but later digital versions share the same basic principles with the traditional one (Lieberman & Blumstein, 1988:53).

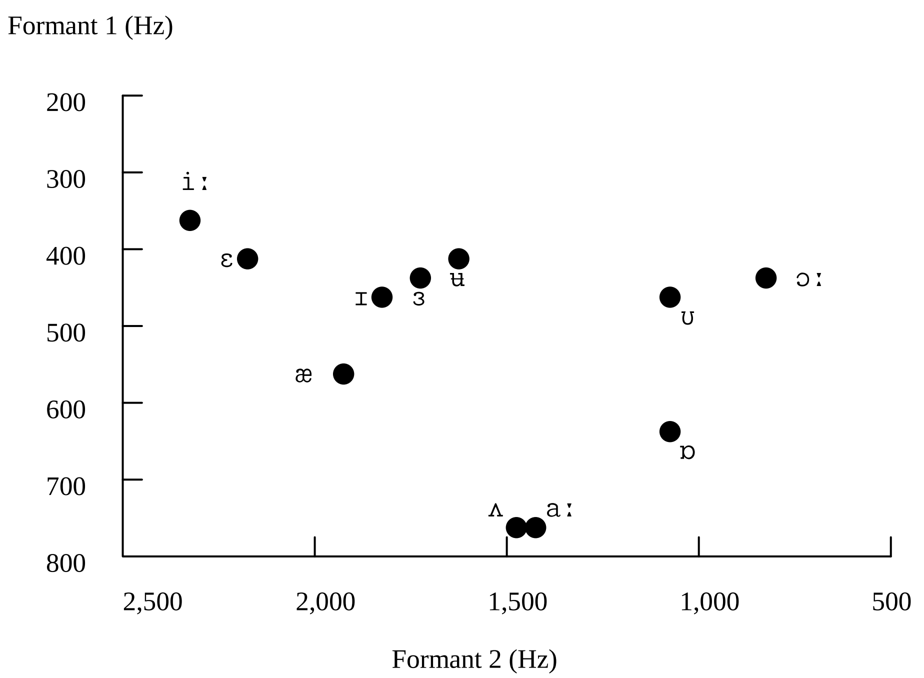
The information displayed on the spectrogram depends on the values we have selected for certain variables. For example, in the analysis of vowels the frequency range is commonly set at 0-5 kHz, as there is little phonological interest above this range (Clark & Yallop, 1995:255). Another important variable is the frequency resolution of the spectral analysis, which is set by the bandwidth of the analysing filter. A filter with a wide bandwidth in relation to harmonic spacing yields a *wide-band*[5] spectrogram. These spectrograms are very accurate in the time dimension, but less accurate in the frequency dimension (Ladefoged, 1993:208). In wide-band spectrograms the formants are visible, because the filter responds rapidly to changes in the energy of the acoustic signal, and the fundamental frequency is accurately determined by counting the number of vertical striations that appear in the dark bands per unit of time (Lieberman & Blumstein, 1988:57 and Farmer, 1984:27). If the filter has a narrow bandwidth, it pinpoints the energy from the individual harmonics. Hence, narrow-band spectrograms are more accurate in the frequency dimension, but at the expense of accuracy in the time dimension (Ladefoged, 1993:209). Consequently, narrow-band spectrograms are most useful for determining the fundamental frequency. Therefore, conventional spectrographs are usually provided with at least two analysis filters: the narrow band filter is used for analysis of $F_0$, and

[5] An example of a wide-band spectrogram can be seen in section 3.4., p. 45.

the wide band filter is for formant analysis (Clark & Yallop, 1995:256 & Ladefoged, 1967:79).

### 2.1.3.4. Acoustic properties of vowel quality

After 1946, the spectrograph became available and formant structure was associated with the auditory qualities of speech sounds, testing the traditional vowel theory. It was recognised that a plot of $F_2$ on the horizontal axis, with values increasing from right to left, against $F_1$ on the vertical axis, with values increasing from top to bottom, bore a remarkable resemblance to the traditional auditory map (see p. 5) of vowel quality (Clark & Yallop, 1995:266). In this set-up, the value of $F_2$ is proportional to vowel *fronting*, while the value of $F_1$ is inversely proportional to vowel *height*.




<u>Figure 6</u> Acoustic mapping of vowels to correspond to auditory map – New Zealand English –(from Clark & Yallop, 1995:267)

The source and filter model has contributed to our understanding of the above relationship (see p. 12). As far as the formation of high vowels is concerned, the cross-sectional area in the front part of the tube is narrowed (or the cross-sectional area in the back half is widened), resulting in a decrease of the first formant frequency (Stevens, 1998:261). On the other hand, low vowels are characterised by a high $F_1$ frequency, as a narrowing is made in the posterior one half of the vocal tract (or a widening in the anterior region), during their articulation (Stevens, 1998:268). In summary, for the high vowels, $F_1$ is low and close to the fundamental frequency, whereas, for the low vowels, $F_1$ is high and the spacing between $F_1$ and $F_0$ is large. Concerning the front-back distinction, Stevens (1998:283) reports that a forward movement of the tongue body causes an increase of the $F_2$ frequency; the maximum value of $F_2$ is higher for the high vowels than for the low vowels. Thus, front vowels are characterised by an "empty space" in the spectrum in the mid-frequency range between $F_1$ and $F_2$. For the back vowels, on the other hand, $F_2$ is displaced to a value that is maximally low and close to $F_1$ for a proper selection of the tongue body position (Stevens, 1998:283).

It is obvious that the plot in Figure 6 does not match the cardinal vowel chart (p. 5) as closely as it might be hoped. Ladefoged (1993:196) comments that the correlation between $F_2$ and degree of backness is not as good as that between $F_1$ and vowel height, even when the formant data are converted to the mel or pitch scale (Clark & Yallop, 1995:268). Therefore, he proposes the replacement of the $F_2$ dimension by the difference between $F_2$ and $F_1$ ($F_2 - F_1$), as there is a better correlation between the degree of backness and the distance between the first two formants, which are far apart in front vowels and close together in back vowels (Ladefoged, 1993:196 & Clark & Yallop, 1995:268).

Until now the third formant frequency has not been mentioned, although it also contributes to vowel quality. The two-dimensional plot, no matter which of the two dimensions ($F_2$ or $F_2 – F_1$) it has, does not account for $F_3$. Ladefoged (1967:91-92) argues that $F_3$ contribution to vowel quality depends on the type of vowel. For example, $F_3$ contribution is significant in a vowel like [e] (Ladefoged, 1967:88), because $F_2$ and $F_3$ have approximately the same intensity as $F_1$. On the other hand, $F_3$ contributes very little to the total quality effect of a vowel like [o] (Ladefoged, 1967:88), as its intensity is 33dB below the level of $F_1$. In addition, Ladefoged (1993:227) mentions that $F_3$ falls markedly in a rhotacized vowel. As a way to display $F_3$ information, Fant (as cited in Clark & Yallop, 1995:269) suggested the use of a weighted $F_2$, which would take account of $F_3$ as $F_2$ increases in frequency. Clark & Yallop (1995:269) suggest that an $F_3$ axis should be added as an extension of the $F_1$ axis of the two-dimensional plot, so that useful information can be provided.

Despite the fact that formants are important for the description of a vowel sound, Ladefoged (1967:80-81) observes that no operational definition of a formant has been given which can be easily applied. The centre of a formant is sometimes difficult to locate for various reasons. But we cannot assume that a formant frequency has “disappeared” because it is not marked, and likewise we have to be careful to avoid interpreting every dark bar as though it reflects the presence of a formant frequency (Lieberman & Blumstein 1988:67). For these reasons, Lieberman & Blumstein (1988:42) mention that speech scientists have to make use of their knowledge of where the formant frequencies of various sounds should be. Ladefoged (1967:86) also underlines the important role of experience gained by looking at many speech samples. He notes though that this procedure is characterised by circularity, as some answers are prejudged. Nevertheless, in some cases the formant frequencies cannot be spotted, despite this prior knowledge and experience.

Some of the difficulties encountered while examining spectrographic data are given by Ladefoged (1967:81-84) and are summarised below:

i) The centre of $F_1$ is difficult to locate when it is low in frequency. The reason is that there is no peak in the spectrum and it is not certain whether the centre is nearer to the fundamental or to the second harmonic.

ii) The centre frequencies of $F_1$ and $F_2$ are difficult to locate when $F_1$ and $F_2$ are close together. It seems as though they coincide.

iii) The above problems become more prominent when the fundamental frequency is high (also Peterson & Barney, 1976:115). This problem is evident in vowels produced by women and children (Lieberman & Blumstein, 1988:42 and Clark & Yallop, 1995:250).

iv) When $F_2$ is much lower in intensity than $F_1$, it is difficult to locate. There is no second formant with sufficient intensity for its frequency location to be measured.

v) When $F_2$ is low in intensity, $F_3$ is also difficult to locate for the same reason.

vi) Sometimes "spurious" formants occur in vowels. A peak might appear at a position not associated with any formant. These "spurious" formants must be ignored.

All the above points led to Ladefoged's (1967:101-103) observation that there are two areas on a formant chart or on the cardinal vowel chart (Figure 7) in which vowels cannot be specified simply in terms of the frequencies of their formants. In area A, it is difficult to locate the centre of the first two formants, because $F_1$ has a very low frequency, while in area B, the same task is difficult, because the first and second formants are very close together. Cues utilised by the ear in assessing the quality of vowels in area A are probably the high intensity of $F_3$ in comparison with $F_2$ and the mean frequency of $F_2$ and $F_3$. Area B is more problematic, but possible cues are the mean frequency of $F_1$ and $F_2$, and the absence of energy in the upper part of the spectrum.

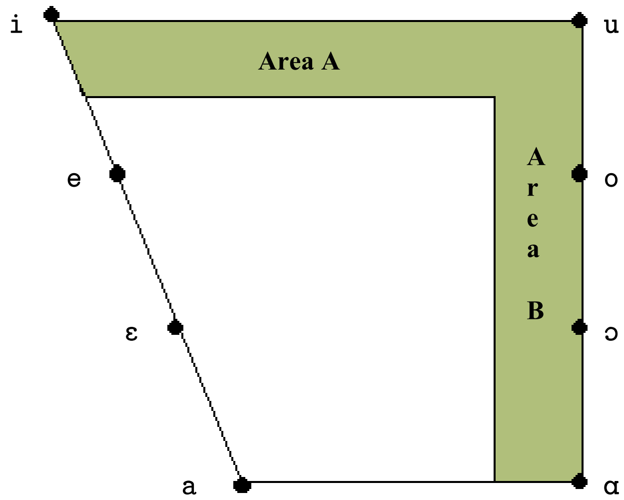



Figure 7 A cardinal vowel diagram, the coloured areas of which show the areas in which vowels cannot be specified simply in terms of frequencies of their formants (taken from Ladefoged, 1967:102)

There are also problems when analysing vowel targets within the dynamic spectra of syllables. Clark & Yallop (1995:270) remark that making accurate estimations of vowel formant frequencies is less straightforward when the vowel is between consonants. A possible explanation is that the syllable peak is of short duration and the articulators do not have sufficient time to establish a stable target. The effects of preceding and following consonants also hinder a stable target.

Despite all the above difficulties, Ladefoged (1967:84-85) points out that the *formant theory* of vowel quality is well established. One of the main reasons is that spectrograms show quite clearly the pattern that develops in a conversational utterance. Additionally, even if some formants do not have auditory effects and are hard to locate, once they are found, they provide the best specification of a sound. Moreover, the fact that intelligible speech can be synthesised on the basis of formant frequencies reveals that formants are indeed important in the acoustic analysis of speech.

Finally, as we have mentioned, the formant frequency pattern is closely related to the vocal tract state and Stevens (as cited in Clark & Yallop, 1995:295) noted that this pattern has to do with phonological distinctiveness (*quantal theory*). Thus, the universal language triangle of [i], [a], and [u] (*quantal vowels*) is the preferred three vowel system, as quantal vowels represent three stable and acoustically non-critical articulatory positions. The oral & pharyngeal tubes are maximally expanded and/or maximally constricted in the production of these vowels and as a result they have well-defined spectral peaks because of the convergence of two formant frequencies (Lieberman & Blumstein, 1988:174). Ladefoged (1993:225) mentions that the universal triangle is based on the *principle of sufficient perceptual separation*. The perceptual distance between the sounds of a language has to be maximised, if they are to be acoustically distinct. Consequently, the formant frequencies of the vowels will be as far as possible when plotted on a vowel chart and spaced at approximately equal distances apart (Ladefoged, 1993:268). This tendency is more evident in languages with a comparatively small number of vowels (i.e. the Greek language).

## 2.2. The issue of normalisation

Despite the swift progress in the analysis of speech, one of the puzzles that remain unanswered is the following: since the aforementioned acoustic characteristics of a sound depend greatly on the physical characteristics of the speaker's vocal tract, how is it possible that different speakers produce sounds that are considered the "same" even by trained phoneticians? It seems that the human brain has the ability to compensate for this acoustic variation so that it can recognise the same utterance produced by different talkers. This ability is referred to as *perceptual normalisation* (Lass, 1996:330). Peterson and Barney (1976:118) suggest that part of the variation is caused by the differences between classes of speakers, that is men, women, and children. A direct consequence of this variety is that children's formants are highest, the women's intermediate, and the men's lowest in frequency (Peterson and Barney, 1976:118).

Little is known about the perceptual process responsible for the aforementioned compensations, nor is it known whether a normalisation procedure takes place in the human brain at all. Verbrugge *et al.* (as cited in Lass, 1996:296) suggest that adjustment to talkers may have more to do with tracking articulatory dynamics than with frequency-based calibration. Nevertheless, scientists have tried to find a procedure of speaker *normalisation,* which would adjust the acoustic data to cancel differences associated with vocal tract size. Thus, a variety of algorithms have been proposed for performing mathematical normalisations of formant data. These procedures can be used in order to program digital computers to "recognise" vowels. The computer program has access to a memory in which the acoustic consequences of various possible vocal tract shapes are stored. Thus, the spectra of the incoming speech signal are matched against the internal spectra generated by the memory (Lieberman & Blumstein, 1988:42).

One of the earliest algorithms was Funt's scaling of formant data in relation to vocal tract size (Clark & Yallop, 1995:269). Bladon (1985) also proposed an *auditory-phonetic approach* to sex normalisation. As the human auditory system does not analyse speech like a spectrograph, he suggests (1985:30-31) that the acoustical vowel spectrum should be transformed into an auditory spectrum, using psychological and electrophysiological knowledge. The resulting male and female pseudo-auditory spectra are normalised to a great extent, when the female sound is displaced downward in frequency by one Bark. Bladon (1985:35) admits, however, that the outcome of this procedure still needs adjustments[6].

As the greatest difference between the classes of speakers (men, women, children) is the size of the vocal tract, this may lead to the assumption that "a *uniform shift* along the log Hertz frequency axis of all spectral features will achieve a simple, first-order normalisation" (Deterding, 1990:3). Deterding (1990:43-46), however, demonstrates that a uniform normalisation will not cover all cases. He points out that a uniform shift on the log Hertz scale is not enough to normalise sex and age, as the lines in Figures 8(a) and 8(b) are not of the same length and do not have the same gradient of 1.0. If a gradient is less than 1.0, $F_2$ needs to be shifted more than $F_1$, while if a gradient is more than 1.0, $F_1$ needs a greater shift than $F_2$. Concerning sex normalisation (Figure 8(a)), he observes that $F_1$ of open vowels and $F_2$ of front vowels need greater than average shifts- a finding confirmed by Fant (as cited in Deterding, 1990:46) in a study of Swedish male and female speakers and in data from

[6] See p. 25 (about sociological variation and spectral tilt).

a number of languages. Concerning age normalisation (Figure 8(b)), he notes that $F_2$ of close back vowels [u, ʊ] requires a larger shift than others.

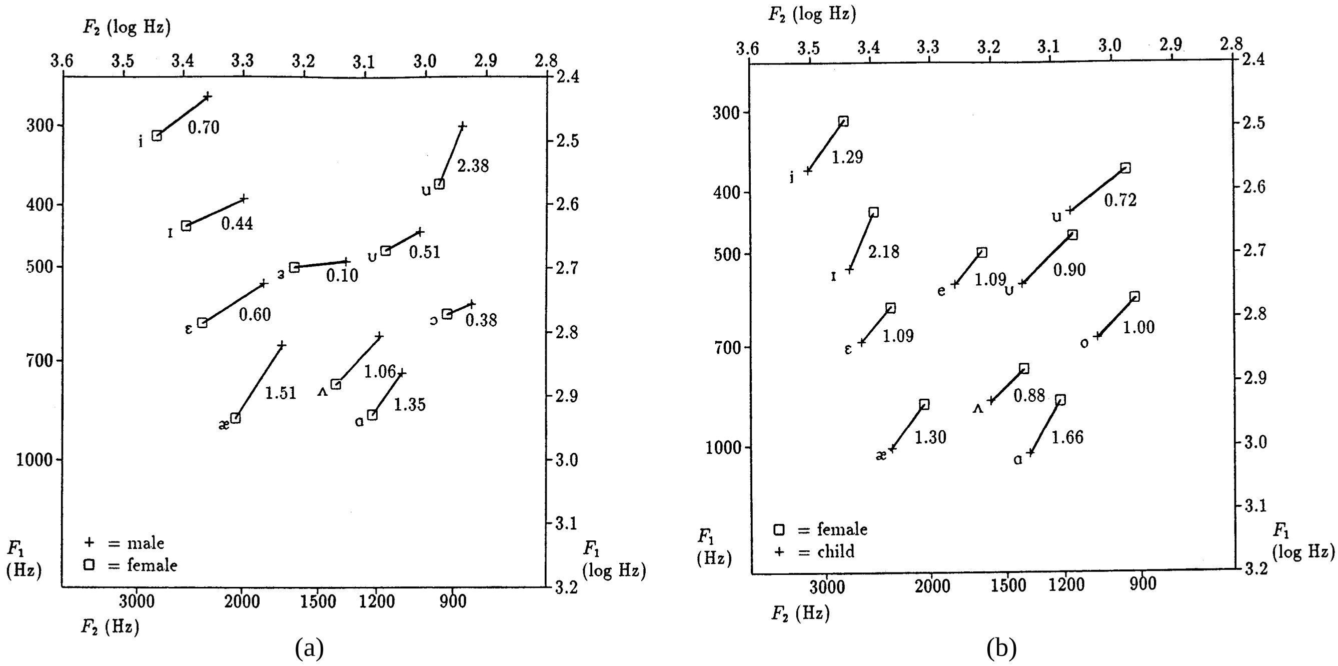


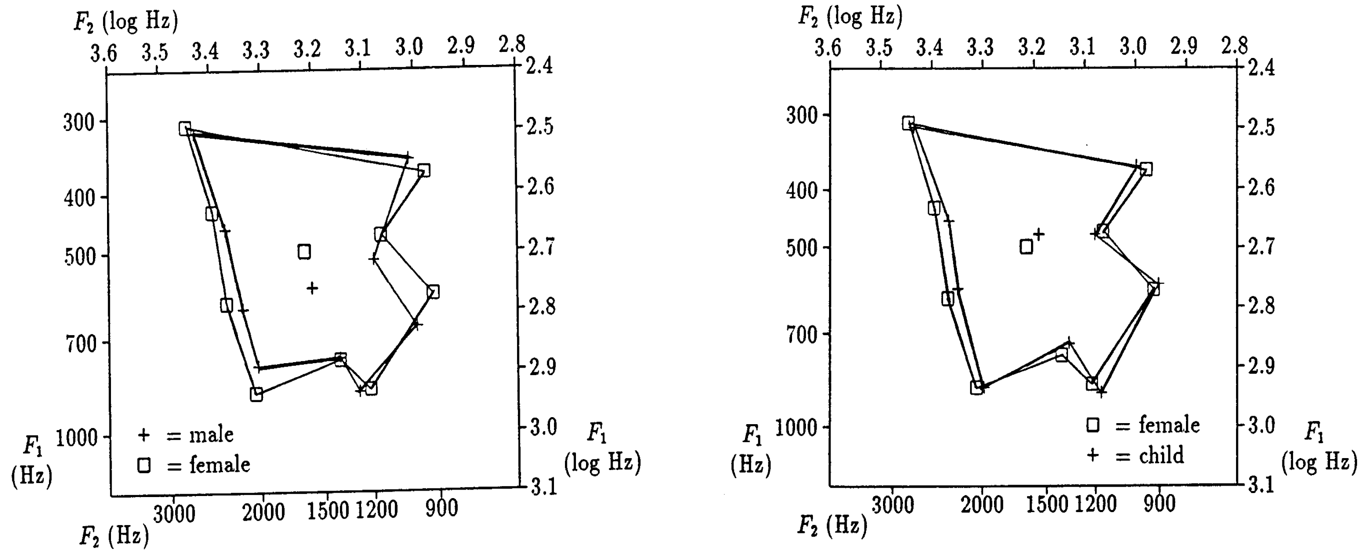

Figure 8 Average male and female (a) and female and child (b) $F_1$ against $F_2$ for the 10 monophthong vowels of American English, using the data from Peterson and Barney (adopted from Deterding, 1990:44&45).

Deterding (1990:46) also observes that male vowels and possibly child vowels tend to be less *peripheral* (or more central) than female vowels (Figure 9). Henton (1995:420) also finds that women use the periphery of the articulatory space, compared with men, whose vowels might be closer to the centre.

Deterding (1990:50-60) mentions the following factors as possible sources for the observed greater centralisation of male vowels in comparison to female vowels.

1) Vocal tract length. Adult female vocal tracts tend to be 17% shorter than those of men. The greater length of the male vocal tract causes all resonance features

of male speech to be at a lower frequency than the corresponding features in female speech.




(a) (b)

Figure 9 Normalisation of average male and female (a) and average female and child (b) American English vowels by a uniform shift on a log Hertz scale (from Deterding, 1990:47&49).

2) Ratio of pharynx and oral cavities. Men have a proportionately longer pharynx than women. The pharynx represents about 52% of the total length of the male vocal tract, while for women it represents only 45% of the total length. Concerning children, the proportion of the total length occupied by the pharynx is about 43% for both males and females of 11 years of age. Therefore, the vocal tracts of children are similarly proportioned to those of women but not to those of men. The differently proportioned vocal tract length of men and women can partly explain the greater $F_2$ shift in back vowels.

3) Size of maximum constriction. The male vocal tract is proportionately more open, affecting the frequency of $F_1$ and resulting in a tendency for more central vowels.

4) Sociological variation. There is evidence that the degree of male-female variation can vary considerably from one community to the other. Pickering (as cited in Blandon, 1990:55) suggests that the size of constriction depends on gender, but can also be controlled by the speakers. Bladon (1985:36) also notes that “in some communities, a sex-linked, socially motivated, learned characteristic is responsible, along with the factor of sexual dimorphism, that males speak more like (or unlike) females”. The fact that females’ vowel spaces are larger and more peripheral than those of males, indicates that females’ articulatory gestures are more extreme, resulting in more careful speech. Greater articulatory distinction may be equalled with standard or prestige forms, so a possible explanation given by a great number of studies is that women play the role of the guardians of the standard (Deterding, 1990:56 and Henton, 1995:421). An alternative explanation is that the higher fundamental frequency of female speech results in an under-sampling of their spectra which is compensated by the use of peripheral vowels.

5) Fundamental frequency. This is the major difference between male and female speech[7].

6) Coupling. Female speech has a proportionately longer open phase. This results in the average formant frequencies and bandwidths being raised, which affects vowel quality.

7) Spectral tilt. The fact that female speech has a greater spectral tilt has important implications for the whole-spectrum based vowel recognition. If the spectral envelopes of male and female speech were compared without making the normalising shift Bladon (1985:34) proposes, then no adjustment should be needed

[7] See also section 2.1.3.2., p. 12.

for a spectral tilt. This suggests that any adjustment for spectral tilt may relate to the amount of normalising shift.

8) Spectral noise. As female speech has a longer open phase, a greater volume of air is able to pass through the glottis, resulting in a slight audible friction. The additional spectral noise and the high spectral tilt constitute important acoustic correlates of breathy voice.

As far as *adult-child variability* is concerned, Lee *et al.* (1999:1455) report that children's speech, compared to adults' speech, exhibits higher pitch and formant frequencies, longer segmental durations and greater temporal and spectral variability. The differentiation of male and female $F_2$ and $F_3$ patterns begins around age 11 and the formants become fully distinguishable around age 15. Physical growth of the speech apparatus occurs gradually up to approximately age 14 for females and age 15 for males. Between ages 10 and 15, formant frequencies of male speakers decrease faster with age and reach much lower absolute values than those of female speakers (Lee *et al.*, 1999:1464), although Smith *et al.* (1998:95) mention that not all speech production characteristics mature on the same schedule for a given child.

Deterding (1990:42) mentions that there has been less research on the acoustics of children's speech, while Lass (1996:221) underlines the need for more acoustic data on children of both genders. The collection of such data is essential for the creation of a better developmental model of the vocal tract for speech production research, as well as for the improvement of automatic recognition programs of children's speech (Lee *et al.*, 1997). Potamianos *et al.* (as cited in Lee *et al.*, 1999:1455) has shown that a speech-recognition system trained on adults' speech degrades substantially when tested on the speech of children age 12 and younger. This degradation in recognition performance can be attributed to the acoustic differences between children's and adults' speech, as well as to the acoustic variability inherent in children's speech.

Apart from sex and age differences, there are more factors which influence the acoustic realisations of phonetic contrasts. Different phonetic contexts, speaking rate differences, idiosyncratic articulatory strategies and dialects are some of them (Lass, 1996:295). Ladefoged (1993:211) stresses the importance of knowing how to discount purely individual features in an acoustic record, if one is to measure features that are linguistically significant. He mentions that spectrograms show *relative vowel quality*: for two different speakers, the relative positions of the vowels on a formant chart will be the same, but the absolute values of the formant frequencies will differ (1993:212-213). This is why Eli Fischer Jørgensen (as cited in Ladefoged, 1967:97) has stated that it is somewhat dubious to plot the vowels of different persons indiscriminately on the same chart. Because a formant plot, besides the information about the phonetic qualities of the vowels, also carries information about individual characteristics, it is preferable to combine the vowels of the same person by lines, so that whole patterns are compared. The fact that speakers maintain their systemic contrasts, despite the variability in the phonetic realisations of their vowels, reveals the general principle, that "*phonological distinctiveness* is a matter of relative contrast within a system rather than a matter of absolute or universal phonetic values" (Clark, 1995:273). This means that the exact phonetic quality of a vowel does not depend on the absolute values of its formant frequencies, but on the relationship between the formant frequencies for that vowel and the formant frequencies for other vowels pronounced by the same speaker (Ladefoged, 1967:97).

## 2.3. Greek vowels

### 2.3.1. Acoustic characteristics

The vowel system of Modern Greek has been traditionally characterised as a "very common symmetrical" one (Joseph & Philippaki-Warburton, 1987:263). The vowels are arranged as follows (Philippaki-Warburton, 1992):

| | Front | | Back |
|---|---|---|---|
| High | /i/ | | /u/ |
| Mid | /e/ | | /o/ |
| Low | | /a/ | |

Koutsoudas & Koutsoudas (as cited in Fourakis *et al.*, 1999:29) transcribe the mid vowels as [ɛ] and [ɔ], instead of [e] and [o][8].

#### 2.3.1.1. Spectral characteristics

Not many acoustic analyses of Greek vowels have been conducted in the past. Kontosopoulos *et al.* (1988) analysed stressed and unstressed Greek vowels produced by 7 male and 7 female subjects, and on the basis of the acoustic measurements, the "dispersion field" was composed (Figure 10). They stated that there is no overlap

[8] For explanation., see below, p. 29.

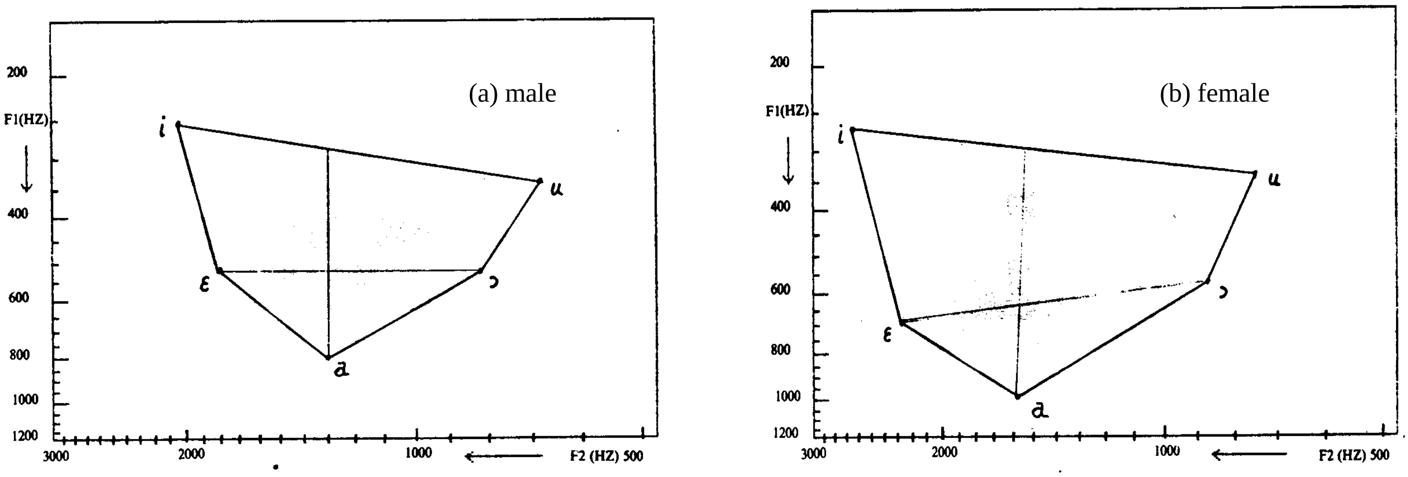


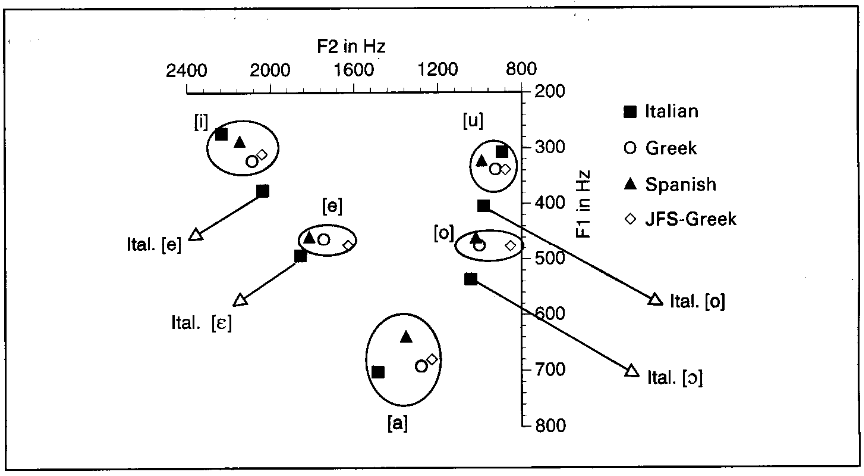

Figure 10 Mean values of the first two formants of the Greek vowels (stressed and unstressed) produced by (a) males and (b) females (adopted from Kontosopoulos *et al.*, 1988:116).

between articulatory spaces of neighbouring vowels and hence Greek vowels are "distinct", so that "no acoustic confusion is caused" (1988:107).

Jongman *et al.* (as cited in Fourakis *et al.*, 1999:29) analysed stressed vowels produced by 4 male speakers and also reported that Greek vowels are well separated in an acoustic space, allowing for maximal contrast between vowel categories. This finding was also replicated in a perceptual study on the identification of synthetic stimuli by American and Greek subjects, carried out by Hawks & Fourakis (as cited in Fourakis *et al.*, 1999:29 and Botinis *et al.*, 1997). In this study, Greek listeners, unlike their American counterparts, rejected large numbers of stimuli as not possible Greek vowels. Additionally, the responses of Greek and American subjects were compared, and it was demonstrated that the subspaces for Greek [e] and [o] overlapped the American subspaces for [e]-[ɛ] and [o]-[ɔ] respectively.

Another study on the Greek vowel space was carried out by Fourakis *et al.* (1999:39-40) and compares Greek to Italian, Spanish and Greek data from Jongman *et al.* (as cited in Fourakis *et al.*, 1999:39) (Figure 11). They note that point vowels [i,a,u] lie in about the same position, whereas the mid front vowel for Spanish and

Greek, [e], lies close to the Italian mid front lax vowel, and the mid back vowel for the two languages, [o], lies between the Italian lax and tense mid back vowels. These results, as well as the results of Hawks & Fourakis' study, mentioned above, reflect the contrast-based principle. As we can see in Figure 11, Spanish vowels have higher $F_2$ values than Greek vowels. This observation was also made by Bradlow (as cited in Fourakis *et al.*, 1999:29), who ascribed this difference to a language-specific base-of-articulation property, which, in this case, involves a more front tongue position for Spanish than for Greek. Fourakis *et al.* (1999:39) also note that the Spanish vowel space is 3% larger than the Greek space, while the Italian space is 49% larger than the Greek. This great difference is due to the fact that the Italian vowel space expands in order to accommodate the two extra vowels.




<u>Figure 11</u> The vowels of Greek (from two different experiments), Italian and Spanish in an $F_1$ x $F_2$ space. The ellipses are used to group points for ease of exposition (adopted from Fourakis *et al.*, 1999:39).

Greek vowels have also been compared to Mexican and Castilian vowels. Botinis (in Kontosopoulos *et al.*, 1988:118) places mean values of the Greek vowels in Mexican and Castilian vowel subspaces (Figure 12).

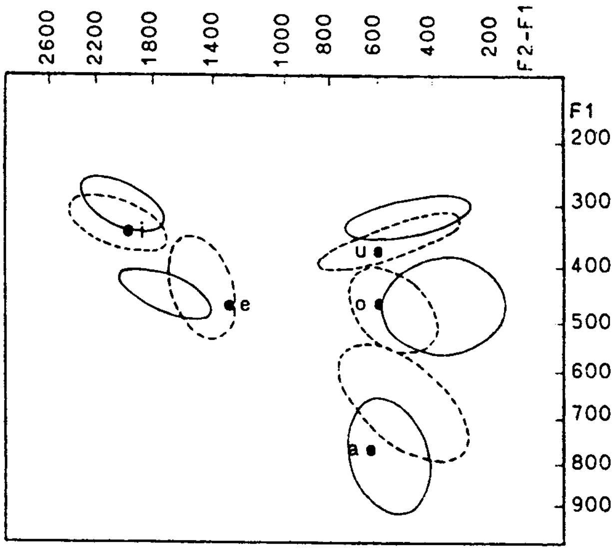



Figure 12 Continuous line: Mexican pronunciation, dashed line: Castilian pronunciation, black dots: mean value of the corresponding Greek vowels (adopted from Kontosopoulos *et al.*, 1988:118).

Another perceptual study on Greek vowel space using synthetic stimuli was conducted by Botinis *et al.* (1997). Four female subjects listened to 465 synthetic vowel tokens with $F_1$ frequencies ranging from 250 to 800 Hz and $F_2$ frequencies ranging from 900 to 2900 Hz in 50 Hz steps. The subjects were asked to identify each stimulus as one of the five Greek vowels or reject it, and also state their certainty on a certainty scale. The perceptual vowel maps constructed for each subject shows that the points assigned to the [e] category are more numerous than any of the other categories and thus it occupies more space than others. Additionally, there seems to be little or no overlap between categories. If there is any overlap, it is between [a] and [o], while [i] and [u] are well separated for each subject. The composite vowel map for all subjects (Figure 13) shows that all categories are well separated. The high average rejection rate (64%) is reflected in the large unoccupied portions of space. It can be, therefore, concluded that "the Greek vowel space is organised in a maximally contrastive manner, as proposed by Liljencrants and Lindblom" (Botinis *et al.*, 1997 and Fourakis *et al.*, 1999:42).

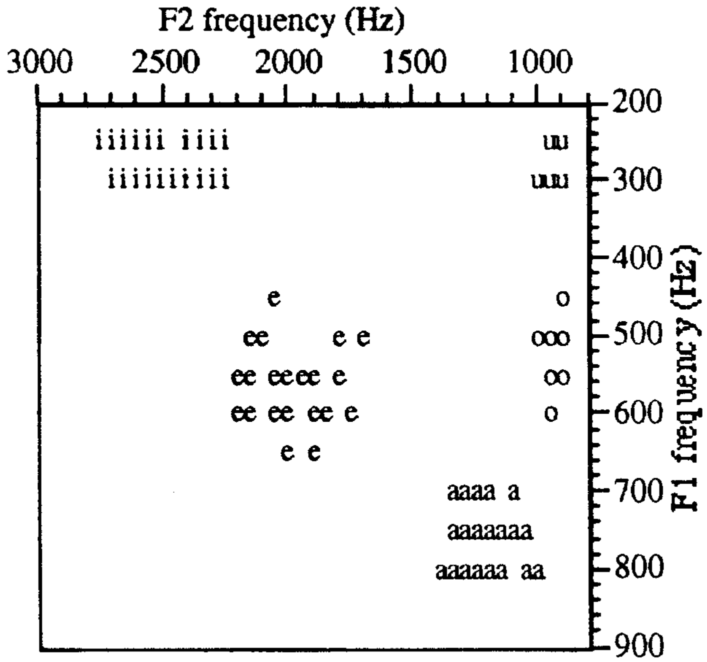



Figure 13 A composite perceptual vowel map constructed out of those points for which at least three subjects assigned the same category code with high certainty ratings (adopted from Botinis *et al.*, 1997).

Botinis *et al.* (1995) and Fourakis *et al.* (1999) have also studied the influence of focus, stress and tempo on the first two formants and the spectral characteristics of Greek vowels. Five male speakers produced the five Greek vowels at slow and fast tempo, in lexically stressed and unstressed syllables, and in lexically stressed syllables of words appearing in focus position.

Concerning the influence of stress and tempo, they made the following observations (Botinis *et al.*, 1995:405 and Fourakis *et al.*, 1999:38) (Figure 14).

1) Lack of stress causes a reduction of the overall vowel space, which is 30% for slow tempo and 23% for fast tempo.

2) The shift from slow to fast tempo causes a reduction in the vowel space, which is 11% for stressed nonfocus vowels and 2% for unstressed vowels.
3) At both tempi, all vowels (except [e] at the fast tempo) have lower $F_1$ frequencies, which results in an overall raising of the unstressed vowel space.

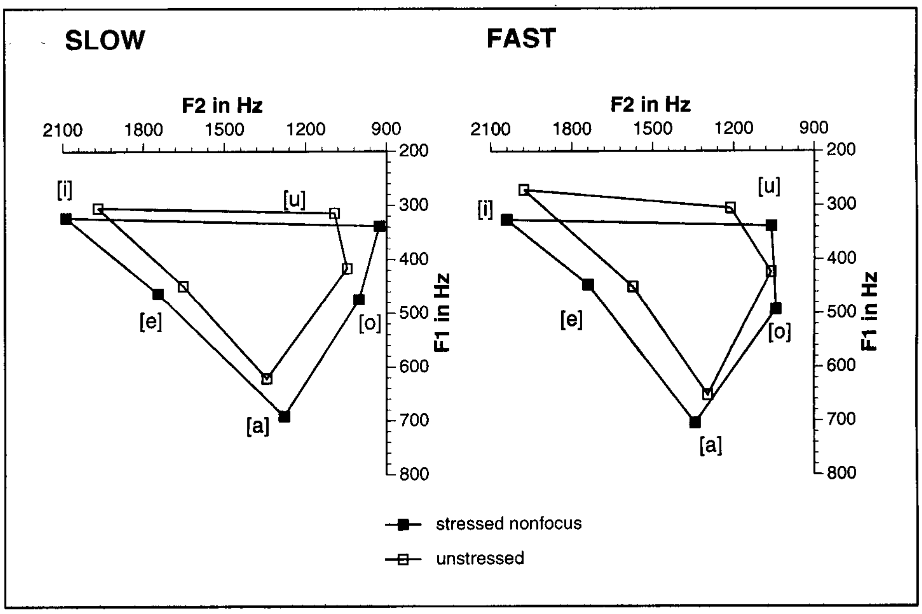



Figure 14 The vowels of Greek plotted in an $F_1$ x $F_2$ space, using mean values, at the two tempi, comparing stressed nonfocus to unstressed vowels (adopted from Fourakis *et al.*, 1999:37).

As far as the influence of focus and tempo are concerned, they concluded that the slow-tempo, stressed focus vowels define the largest vowel space, followed by slow-tempo, stressed nonfocus vowels, while the smallest spaces are defined by the unstressed vowels at the two tempi (Fourakis *et al.*, 1999:38) (Figure 15).

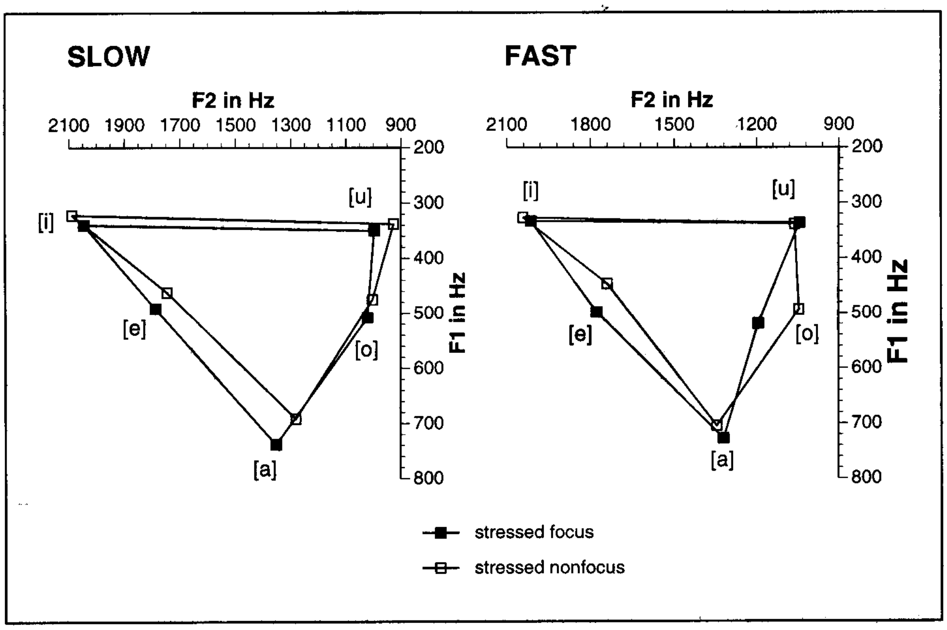



Figure 15 The vowels of Greek plotted in an $F_1$ x $F_2$ space, using mean values, at the two tempi, comparing stressed focus to stressed nonfocus vowels (adopted from Fourakis *et al.*, 1999:37).

### 2.3.1.2. Fundamental Frequency ($F_0$)

Fundamental frequency is one of the main correlates of focus in Modern Greek. Botinis (as cited in Fourakis *et al.*, 1999:30) found that $F_0$ increases substantially when focus is realised. In the aforementioned study, Fourakis *et al.* (1999:35) make the following observations (Figure 16).

1) All three types of vowels have higher $F_0$ values at the fast tempo than at the slow tempo.
2) Stressed nonfocus vowels have significantly higher $F_0$ values than unstressed values, and this effect is more pronounced at the fast tempo.
3) Stressed focus vowels have much higher $F_0$ values than stressed nonfocus vowels.

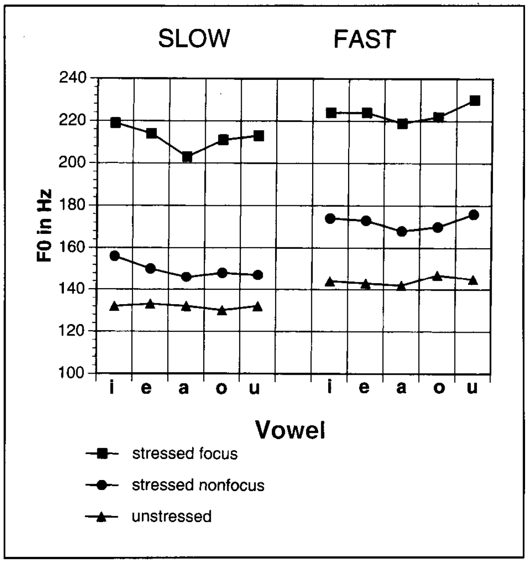



Figure 16 Mean $F_0$, measured in the middle of the vowel, at the two tempi and in the different stress-focus conditions (adopted from Fourakis *et al.*, 1999:35).

An interesting point noted by Fourakis *et al.* (1999:38-39) is that vowel quality influence on $F_0$ can be detected only in the slow-focus position. In the other five conditions, this influence is very weak or absent. They comment that this result is "in stark contrast to the phenomenon of intrinsic pitch of vowels". Therefore, Greek does not seem to follow the so-called universal hierarchical distribution of intrinsic $F_0$. Fourakis *et al.* (1999:41) also comment on the remarkably high values of $F_0$, which were consistently higher than 200 Hz for all male speakers, and conclude that this result demonstrates the important role of $F_0$ for focus in Greek.

### 2.3.1.3. Amplitude

Fourakis *et al.* (1999:35-36) mention that vowel amplitude is influenced by tempo, stress and focus in the following ways (Figure 17).

1) Vowels at fast tempo have significantly lower amplitudes than at the slow tempo.

2) Stressed nonfocus vowels have significantly higher amplitudes than unstressed vowels.
3) The amplitudes of stressed focus vowels are greater than those of stressed nonfocus vowels, but this effect is marginally significant.

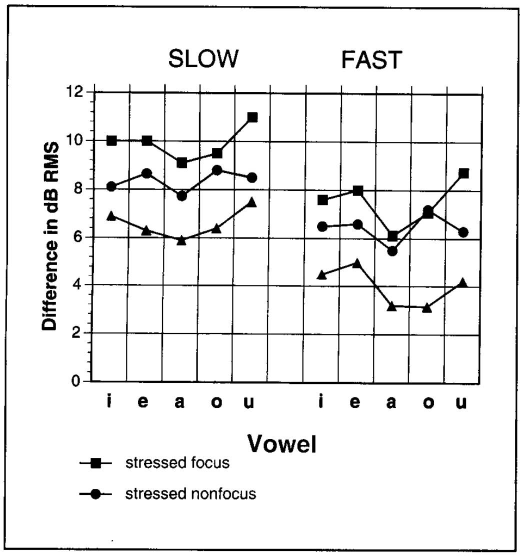



Figure 17 Mean amplitude difference in decibel RMS between the target vowel and the target word, at the two tempi and the different stress-focus conditions (adopted from Fourakis *et al.*, 1999:36).

Figure 17 demonstrates that low and high vowels are not intrinsically different in terms of amplitude, which is another difference between Greek and other languages. For example, vowel [a] should have the greatest amplitude values, according to the hierarchical structure of intrinsic intensity distribution; nevertheless, it is found to have the lowest values in all prosodic conditions (Fourakis *et al.*, 1999:39).

#### 2.3.1.4. Duration

Dauer (as cited in Fourakis *et al.*, 1999:30) mentions that the intrinsic factor of quality affects the duration of Greek vowels, and hence high vowels are the shortest and low vowels the longest. Additionally, she states that vowels in stressed syllables are longer and have higher intensity. This finding is also reported by Fourakis (as cited in Fourakis *et al.*, 1999:30), who points out that unstressed Greek vowels are 25% shorter than stressed ones. In addition, Botinis (as cited in Botinis *et al.*, 1995:404) characterises duration and intensity as the main prosodic correlates of stress in Greek.

In the aforementioned study, Fourakis *et al.* (1999:34-35) examine the relationship between duration and factors like vowel quality, stress, tempo and focus, and reach the following conclusions (Figure 18).

1) The quality of the vowel has a significant effect on duration, causing a tripartite categorisation regardless of stress and tempo. Vowel [i] has consistently the shortest duration, vowel [a] the longest, and vowels [u], [o] and [e] are in between.
2) Vowels in the slow tempo are longer than in the fast tempo.
3) Stressed nonfocus vowels are longer (40%) than unstressed vowels. However, a shift from slow to fast tempo causes a 30% reduction to stressed nonfocus vowels, whereas unstressed vowels are shortened by only 15%.
4) Stressed focus vowels are significantly shorter than stressed nonfocus vowels at the slow tempo, but marginally so at the fast tempo.

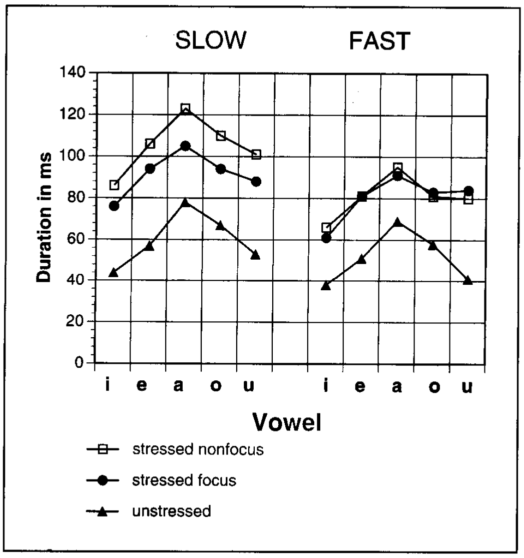



Figure 18 Mean target vowel durations at the two tempi and in the different stress-focus conditions (adopted from Fourakis *et al.*, 1999:34).

Fourakis *et al.* (1999:40) comment that the combined effect of tempo and stress caused fast-unstressed vowels to be 50% shorter than slow-stressed vowels, thus exhibiting the effects of incomprehensibility, first proposed for English by Klatt. Concerning the influence of vowel quality on duration, the resulting pattern was expected with the exception of vowel [u], which was consistently longer than [i]. This result indicates that durations are not assigned by height only, but in the case of high vowels, by backness as well, and in this sense, Greek high vowels are different from American English (1999:38).

### 2.3.2. Unstressed high vowels

As we mentioned above, all Greek vowels are slightly longer when stressed. Mackridge (1985:18) comments that "a stressed vowel retains the same quality as, and is slightly longer than an unstressed vowel, the chief component of stress being extra loudness". Holton *et al.* (1997:7) report that there is very little vowel weakening in unstressed syllables, but the unstressed vowels may become slightly shorter and devoiced when they occur in word-final position.

The unstressed high vowels [i] and [u], however, are subject to extreme shortening, devoicing or elision in certain environments (Dauer, 1981:17). These phenomena are not purely optional, but depend mainly on the phonetic environment and position relative to the stressed syllable. Dauer recognises five "stages" in unstressed high vowel reduction (1981:17-19).

1) The normal, unreduced vowel. It occurs when preceded or followed by voiced consonants and in environments where vowel reduction does not take place. It has lower intensity and shorter duration than the corresponding stressed vowel. As far as formant structure is concerned, for [i], the second and third formant are present, and for [u] sometimes only the second formant.
2) The short vowel. It occurs after a liquid or nasal and has complete formant structure. It is perceived as a syllabic or a slightly lengthened nasal or lateral.
3) The very short, "centralised" vowel. It occurs between a voiceless and voiced consonant, or between voiceless stops and fricatives. It has low overall intensity and only the first formant is present but in a very reduced form.
4) The whispered vowel. It occurs most often between voiceless consonants and is quite common after a voiceless consonant at the end of a phrase with a falling intonation pattern. It has a very low overall intensity and there is no $F_0$ trace. The first formant is absent, but the preceding

consonant is followed by a short period of friction or voicelessness, with energy in the region of the second and third formants. Despite the above characteristics, the vowel is perceived very clearly.

5) The elided vowel. It occurs most often between two voiceless consonants, but its appearance also depends on timing. The consonant is released directly into the following consonant, so that there is no evidence of the presence of the vowel, but it is perceived through the palatalisation (in case of [i]) or non-palatalisation (in case of [u]) of the preceding consonant.

Particularly on [i] reduction, Dauer (1981:22) comments that it is most likely to occur in a completely voiceless environment, regardless of position of stress, and almost certainly will occur if this syllable is also the post-stressed one. Concerning the style of speech, she notes that a careful style seems to involve more whispering of vowels, whereas a more casual style involves more elision (1981:23). Reduction and elision also occur frequently in common verb endings and everyday words, and less frequently in words from the formal language. The position in the phrase is another important factor. At the end of the sentence said with a falling intonation pattern, unstressed high vowels placed between voiceless consonants are frequently devoiced. Finally, concerning the motivation for this reduction, Dauer (1981:26-27) discusses that there are physiological restrictions that prevent the complete realisation of vowels of very short duration (Lindblom’s undershoot hypothesis), and that, in fact, devoicing the vowel seems to make it easier to achieve the proper rhythm in Greek.

# Chapter III: Methodology

## 3.1. The subjects

This study looks at the spectral characteristics of Greek vowels produced by all three classes of speakers: adult males, females and children. Thus, the subjects who took part in the experiment were 10 adult males, 10 females and 10 children of both genders.

The adult male and female subjects were between 20 and 28 years old and were all undergraduate or postgraduate students at the University of Reading. Eight of the subjects came from Athens or central Greece, nine of the subjects came from Northern Greece (mainly Thessaloniki) and 3 subjects came from Southern Greece (Crete). All subjects spoke standard Greek[9].

All the children came from Crete and their ages ranged from five to ten. Three of them were male and seven female. They all were monolingual speakers of Greek with no reported history of speech, language or hearing problems.

## 3.2. The corpus

The corpus consisted of 30 words (Appendix 1, p. 75). The set of the first six words contained the vowel [i] in three positions: word-initially (i.e. ìrθa, imèra) word-medially (i.e. poðilato, iðikòs) and word-finally (i.e. cerì, mesimèri). The first word of each pair contained the stressed vowel, whereas the second word of the

[9] Although each area has certain "accent characteristics", these are not likely to be detected in an acoustic analysis of vowels produced by reading from a list. Hence, these differences do not constitute a limitation to this acoustic study of vowels. It might be interesting, though, to confirm this opinion. Although a number of studies on several Greek dialects have been carried out, the issue has not been examined from an acoustical perspective, to our knowledge.

pair contained the unstressed vowel. The set of the next six words contained the vowel [e] in the same positions and stress conditions, etc.

As all words had more than one syllable (up to four syllables), they contained more than one vowels in several positions, stressed or unstressed. These instances were also taken into account, so that the analysis would be based on more tokens of vowels, rather than only six for each vowel. So, the final number of tokens for each vowel was: 15 for [i], 17 for [e], 23 for [a], 19 for [o] and 6 for [u]. On total, there were 80 tokens of vowels in the aforementioned positions and stress conditions[10]. It is noteworthy that [u] did not occur in any of the other words, apart from the ones especially selected to contain it (set of last six words). This demonstrates the very low frequency of occurrence of this vowel in Greek (Dauer, 1981:20).

The chosen words were simple and common, so that even a 5-year-old would be acquainted with them and would be able to articulate them freely. These words were written in the described order (first the set for [i], then for [e], for [a], for [o], and lastly for [u]) on one sheet of paper in the format of a list[11].

## 3.3. The recording technique

Two different recording techniques were used for the adults and for the children. As far as the adults are concerned, the recordings were made in a quiet room. Most of the subjects preferred to read the list to themselves before the recording. For the recording, they were told to read the list (one column and then the other, rather than pairing the words of the two columns) at a comfortable speech rate

[10] Appendix 2 (p. 76) contains five tables, one for each vowel. Each column refers to a certain vowel position and stress condition and shows which words were used in each category.

[11] See Appendices 3 and 4 (pp. 78&79). The words in the children's list were printed in a larger font size for easier recognition.

and loudness. The recordings were made on a portable minidisc recorder. A hyper cardioid dynamic microphone was held within 30 cm from the subject's mouth and to one side, so as to avoid breathing into it.

Before the actual recording, the subjects were asked to start reading the list as loud as they would do at the recording. The recording level was then set for each individual, to make sure that the signal was not at too high a level. The level was deliberately kept considerably lower than the overload region, so that no electrical energy would be introduced but at the same time a useful signal would be captured (Lieberman & Blumstein, 1988:76). Once the experiment began, the recording level was kept constant. Each subject was recorded twice, so that the best signal would be chosen for acoustic analysis.

Concerning the children, the recordings were made on a domestic stereo recorder and saved on an audio cassette, as the minidisc was not available. A lapel microphone was used, so as to keep the distance fixed and also avoid overloading. The children who knew how to read and felt confident with their reading skills, were asked to practice reading the list at a comfortable speech rate before the recording. The children who did not know how to read or who could not read at a comfortable/normal speech rate, were asked to repeat each word after their mother or father. Two of the children, a male aged five and a female aged six, had to follow the second option. Each child was recorded twice and the best recording was chosen for analysis.

## 3.4. The measurement technique

The adults' recordings, stored on the minidisc, and the children's recordings, stored on the audio tape, were transferred to the Kay Elemetrics Computerized Speech Lab (CSL) set up at the Phonetics Laboratory of the University of Reading. The sampling rate was set at 8 kHz, as the analysis included only vowels.

The first three formants of each vowel were measured from wide-band spectrograms. Since there were 80 vowel tokens for each subject and 30 subjects were recorded, 2,400 vowels were analysed on total. Figure 19 shows the acoustic waveform (window A) and the wide-spectrogram (window B) of the word [kopáði] produced by an adult male speaker. The vibrations of the three vowels, [o], [a] and [i] are clearly visible on the waveform. The formant structure of the first vowel, [o], is not complete, as this vowel is unstressed and has a short duration. On the other hand, the first three formants of the vowel [a] are manifested clearly and were found to be 916 Hz, 1382 Hz and 2834 Hz correspondingly. The formant structure of vowel [i] can also be discerned although $F_1$ is not clearly visible. As we can see, the formant structure of the vowels was influenced by the surrounding consonants. The formants were extracted at approximately the temporal midpoint of the vowel to avoid taking into account these influences.

An FFT-derived spectrum taken at the middle of the vowel supplemented the spectrogram measurement in cases, when values of the formants could not be determined with certainty[12]. Figure 20 shows the FFT spectrum for the vowel [a] shown above. The cursor has been placed so that the middle of the vowel is analysed.

[12] For difficulties when measuring formant frequencies, see section 2.1.3.4., pp. 18ff, and for difficulties when estimating formants of high Greek vowels, see section 2.3.2., pp. 38ff.

If the value of a formant could not be estimated with a high degree of certainty, it was left blank.

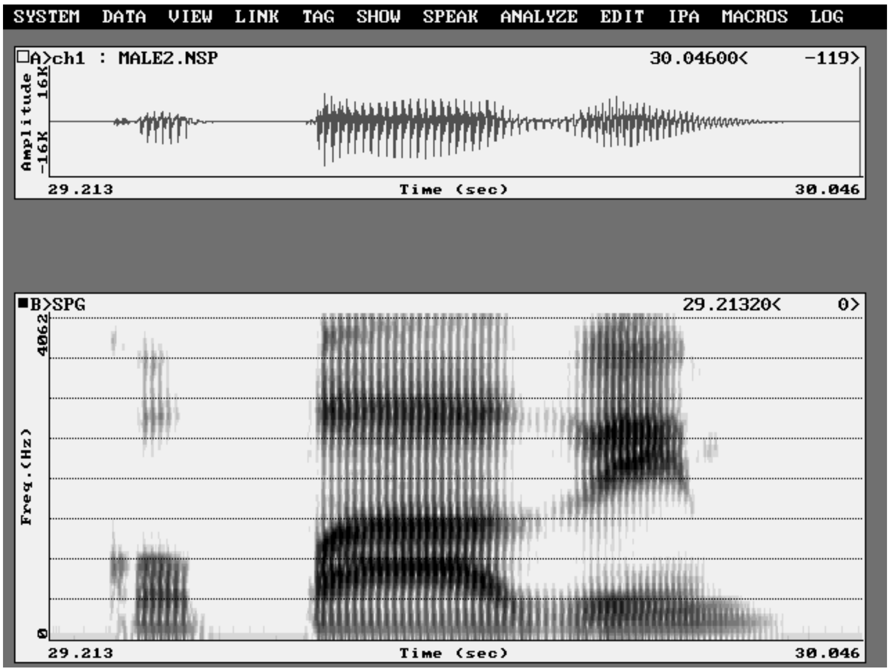



Figure 19 The acoustic waveform (window A) and the wide-spectrogram (window B) of the word [kopáði] produced by an adult male speaker.

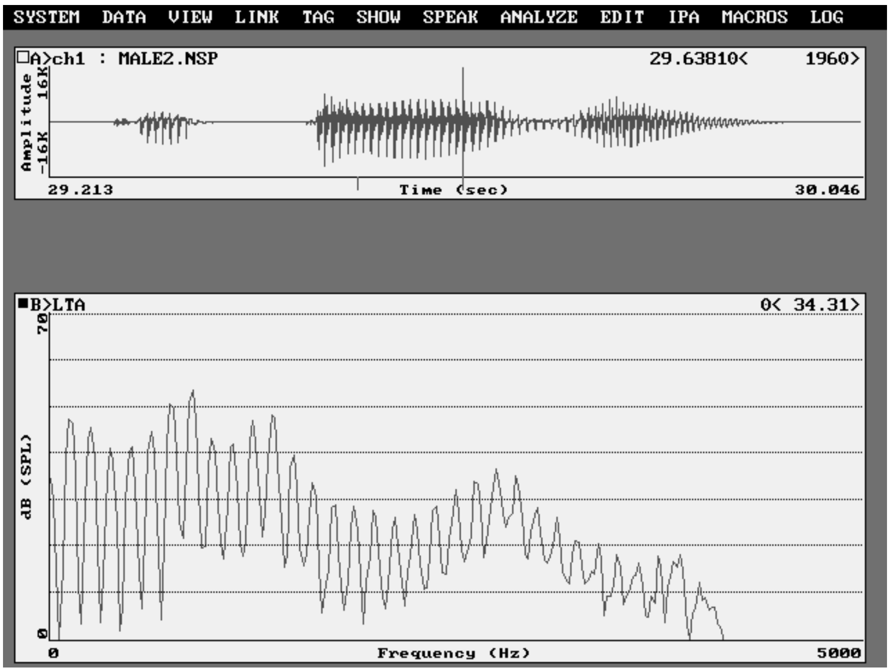



Figure 20 The acoustic waveform (window A) and the FFT spectrum (window B) for the vowel [a] of the word [kopáði] produced by an adult male speaker.

## 3.5. The methods of analysis

The data that were collected from the formant measurements were analysed statistically using the Minitab statistical software program[13]. Descriptive statistics was performed for each one of the three formants of the five vowels produced by adults and children[14]. We note that, although the vowels were divided into six categories in view of their position in the word and their stress condition, the descriptive analysis was performed for all six categories for each vowel collectively. At this point of the research we are more interested in the overall acoustic characteristics of the five vowels. As a next step, it would be very interesting to analyse each category separately and compare them, so that the role of the two aforementioned factors on the spectral characteristics of the vowels is examined.

Regression analysis was also performed, so as to find the regression equation which would predict the child formant values from the adult male and/or female formant values. The regression analysis was performed for each vowel separately and for all vowels collectively as well.

It is also important to note that although children's speech displays great variability in its acoustic characteristics mainly due to the developmental factor[15], we will not look into these differences, as here we attempt to give a more general picture of the children's speech spectral characteristics and compare them with the adult ones.

---

[13] The relative MTB file is saved on a disc. See Appendix 7 on the inside cover of the dissertation.
[14] See section 4.1., p. 47.
[15] See section 2.2., p. 26.

# Chapter IV: Presentation and Discussion of the Results

## 4.1. Male, female & child formant frequencies

The descriptive statistics provided information about the scattering of the data for each one of the first three formants of every vowel, for adult males, adult females and children separately. The results for the first formant of vowel [i] produced by children is shown as an example below. The boxplot in Figure 21 demonstrates clearly the way the data is distributed along the frequency scale.

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1cf1 | 145 | 5 | 581.43 | 587.00 | 581.35 | 81.98 | 6.81 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1cf1 | 311.00 | 795.00 | 544.00 | 622.00 |

* NOTE * N missing = 5

Boxplot of $\mathbf{F_1}$ for **child** vowel **[i]**

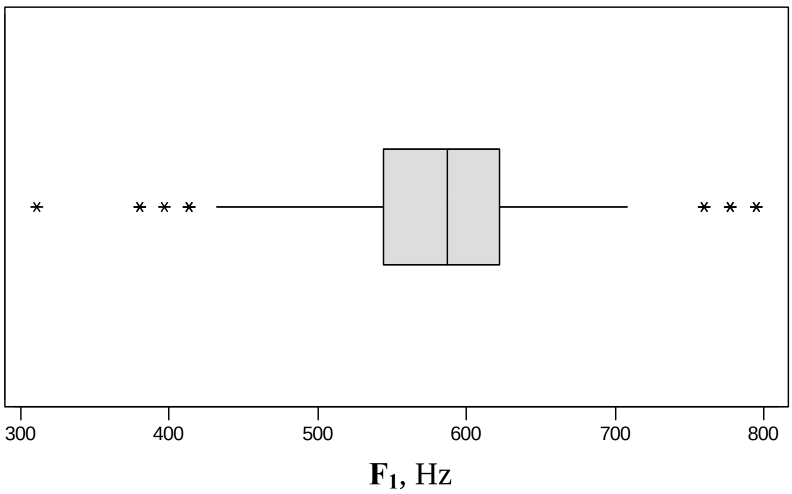



Figure 21 The boxplot for the mean value of the first formant of vowel [i] produced by children.

As we mentioned above[16], the frequencies that could not be estimated with certainty were left out. This resulted in the appearance of missing values in the data. In the above instance, which refers to $F_1$ of the vowel [i], the missing values are five. There are other instances[17], though, that the number of the missing values was quite high. The highest number of missing values involves $F_3$ of the vowels [o] and [u] produced by children (30 and 39 missing values correspondingly). This might have to do with the fact that the fundamental frequency of children's voice is high, thus creating problems in formant location (Lieberman & Blumstein, 1988:42 and Clark & Yallop, 1995:250). Additionally, $F_3$ was often low in intensity in children's speech, which made its estimation difficult. Especially concerning the vowel [u], it was observed that $F_3$ was completely absent in most cases and that, if [u] was not stressed and at a word-final position (i.e. in the word [scìlu]), then, either $F_2$ and $F_1$ were hard to discern, or there was no trace of the vowel on the waveform at all, making the analysis impossible[18].

The mean values of the formants of the five vowels produced by men, women and children are displayed on Table 1 below.

---

[16] See section 3.4., p. 44.
[17] For the rest of the Descriptive Analysis results, see Appendix 5, p. 80.
[18] For more difficulties when measuring formant frequencies, see section 2.1.3.4., pp. 18ff and for difficulties when estimating formants of high Greek vowels, see section 2.3.2., pp. 38ff.

| i | | | |
|---|---|---|---|
| | **Male** | **Female** | **Child** |
| $\mathbf{F_1}$ | 423 | 469 | 581 |
| $\mathbf{F_2}$ | 2073 | 2571 | 2873 |
| $\mathbf{F_3}$ | 2593 | 3109 | 3637 |
| e | | | |
| | **Male** | **Female** | **Child** |
| $\mathbf{F_1}$ | 601 | 687 | 719 |
| $\mathbf{F_2}$ | 1811 | 2231 | 2607 |
| $\mathbf{F_3}$ | 2560 | 3051 | 3612 |
| a | | | |
| | **Male** | **Female** | **Child** |
| $\mathbf{F_1}$ | 736 | 873 | 922 |
| $\mathbf{F_2}$ | 1466 | 1699 | 1811 |
| $\mathbf{F_3}$ | 2459 | 2713 | 3197 |
| o | | | |
| | **Male** | **Female** | **Child** |
| $\mathbf{F_1}$ | 583 | 657 | 730 |
| $\mathbf{F_2}$ | 1137 | 1219 | 1462 |
| $\mathbf{F_3}$ | 2479 | 2817 | 3240 |
| u | | | |
| | **Male** | **Female** | **Child** |
| $\mathbf{F_1}$ | 434 | 451 | 560 |
| $\mathbf{F_2}$ | 921 | 955 | 1190 |
| $\mathbf{F_3}$ | 2460 | 2804 | 3172 |

Table 1  The mean values of $F_1$, $F_2$ and $F_3$ (in Hz) of the five Greek vowels produced by men, women and children.

### 4.2. Comparisons between classes of speakers

The figures in Table 1 were fitted into plots. The first formant of each vowel was plotted against the second, so that the distribution of the values could be compared in relation to sex and most importantly age. Figure 22 is the plot of the vowel [i].

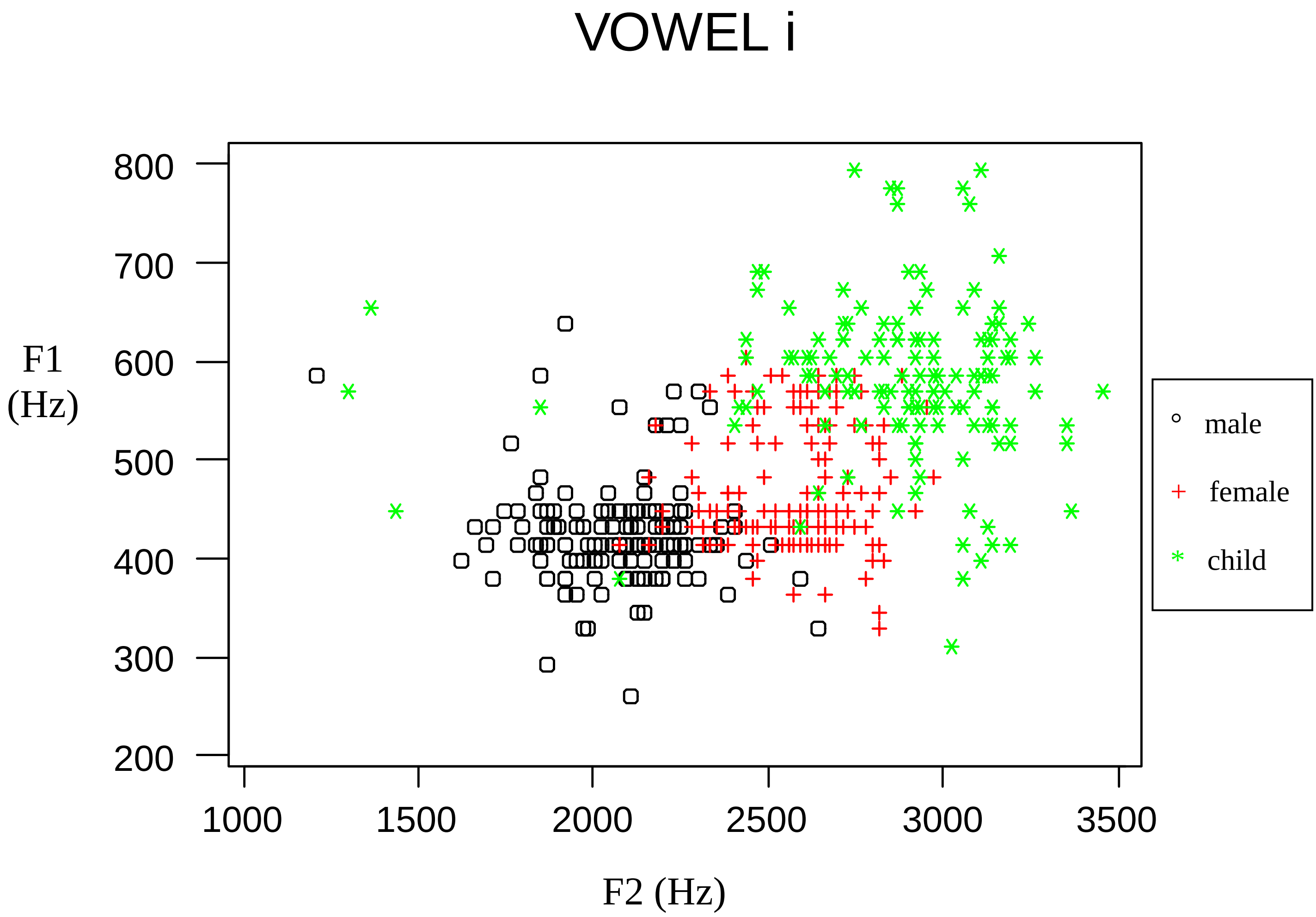



Figure 22 Plot of vowel [i], showing the distribution of the male, female and child formant frequency data.

As it can be observed, male formant frequencies are lower than female frequencies and even lower than children's frequencies. There are only few $F_2$ children's values which are close to men's $F_2$ values, and a small number of children's formant frequencies close to women's frequencies. Therefore, the vowel [i], produced by a child, would most likely be more front and lower (or more open) than an adult [i].

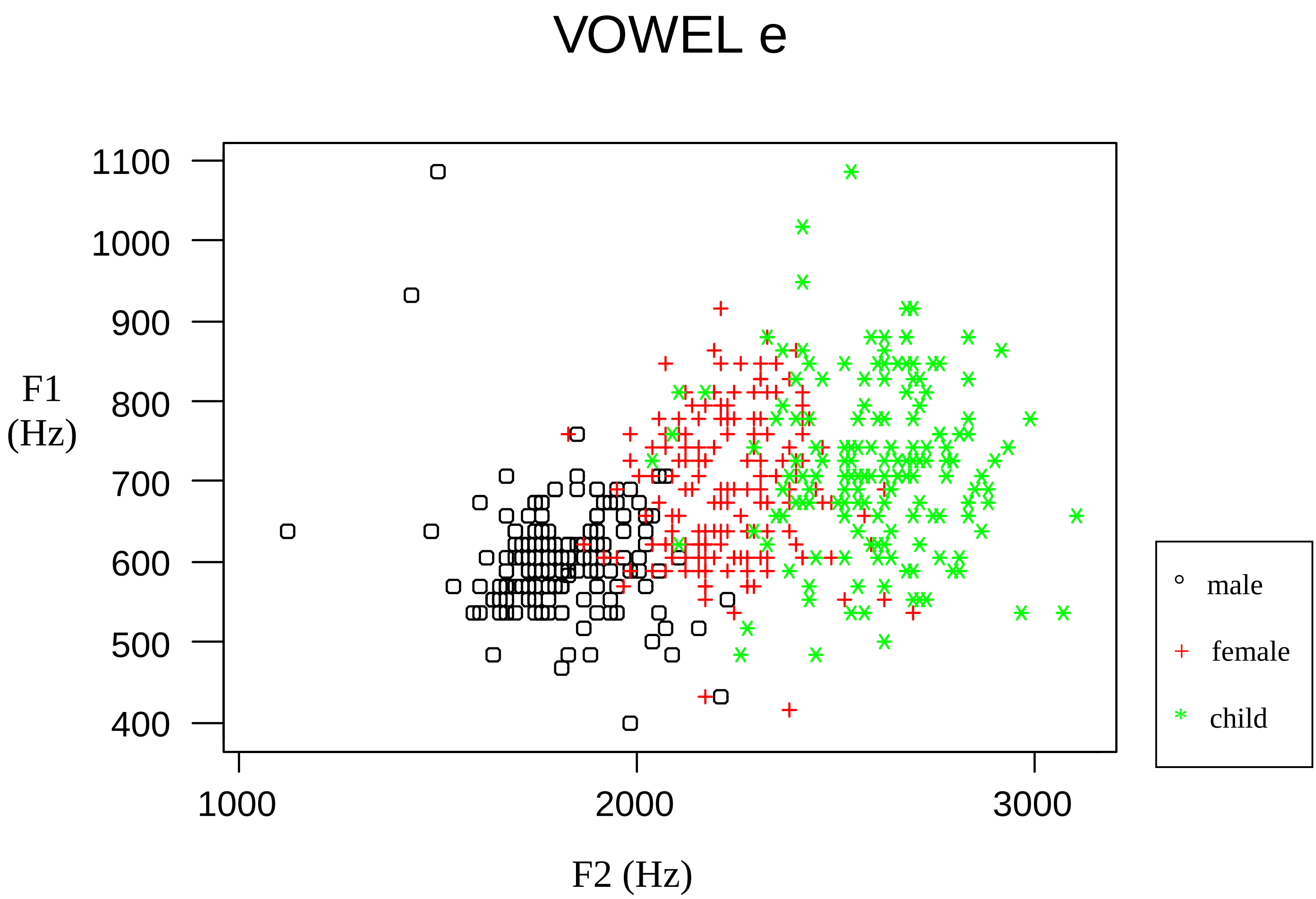



Figure 23 Plot of vowel [e], showing the distribution of the male, female and child formant frequency data.

Concerning the vowel [e] (Figure 23), we observe that children's $F_1$ and $F_2$ values are much higher than men's and only few of them are close to women's. Thus, children's [e] vowel is lower and more front (or more open) than the adult [e].

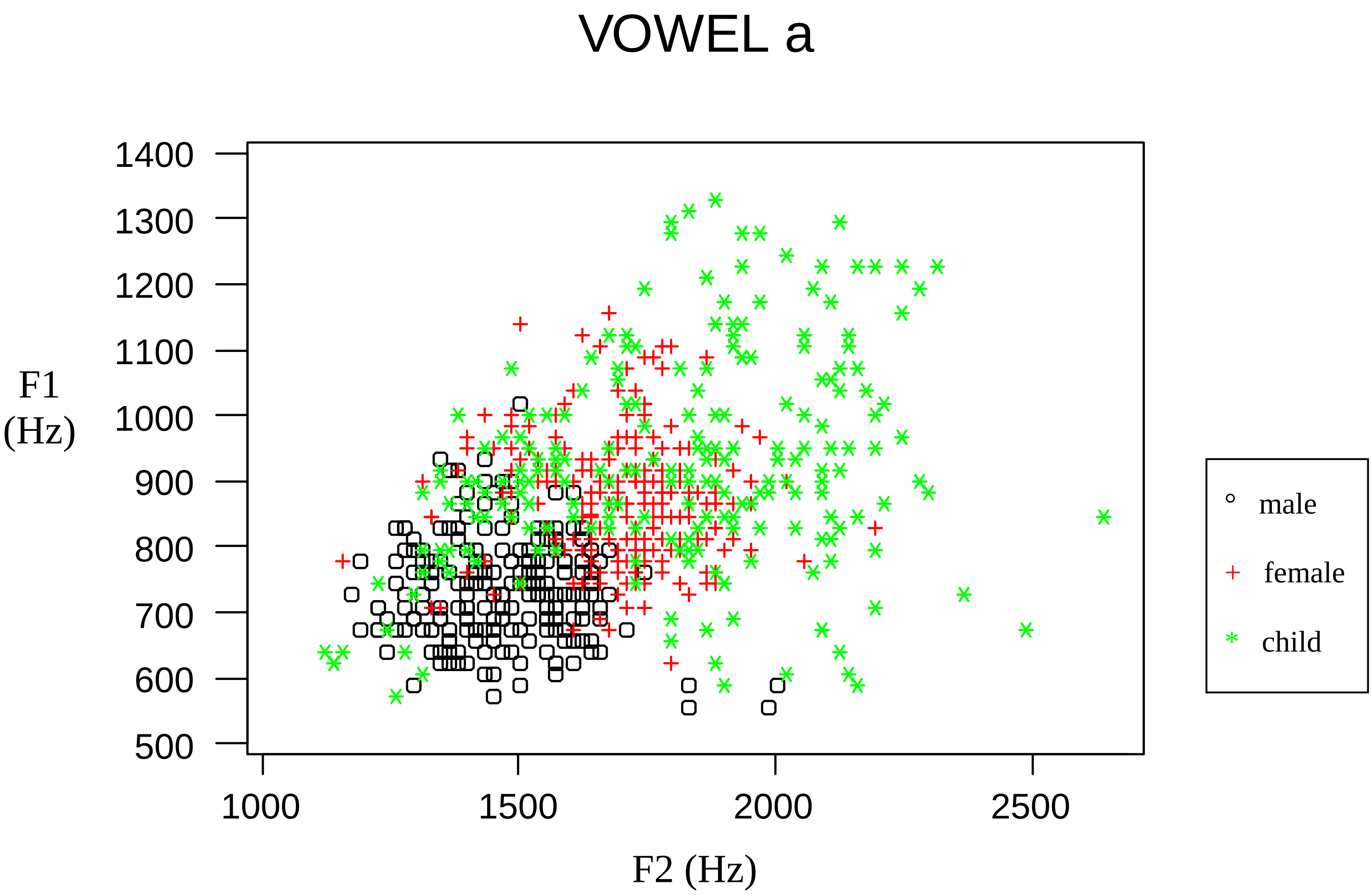



Figure 24 Plot of vowel [a], showing the distribution of the male, female and child formant frequency data.

Children's vowel [a] shows a more scattered picture than the two previous vowels (StDev for $F_1$ is 163.8 and for $F_2$ 286.4). A considerable number of children's vowel formants are amidst adult's formants . Still, a child's [a] tends to be more open and somewhat more front than an adult's [a].

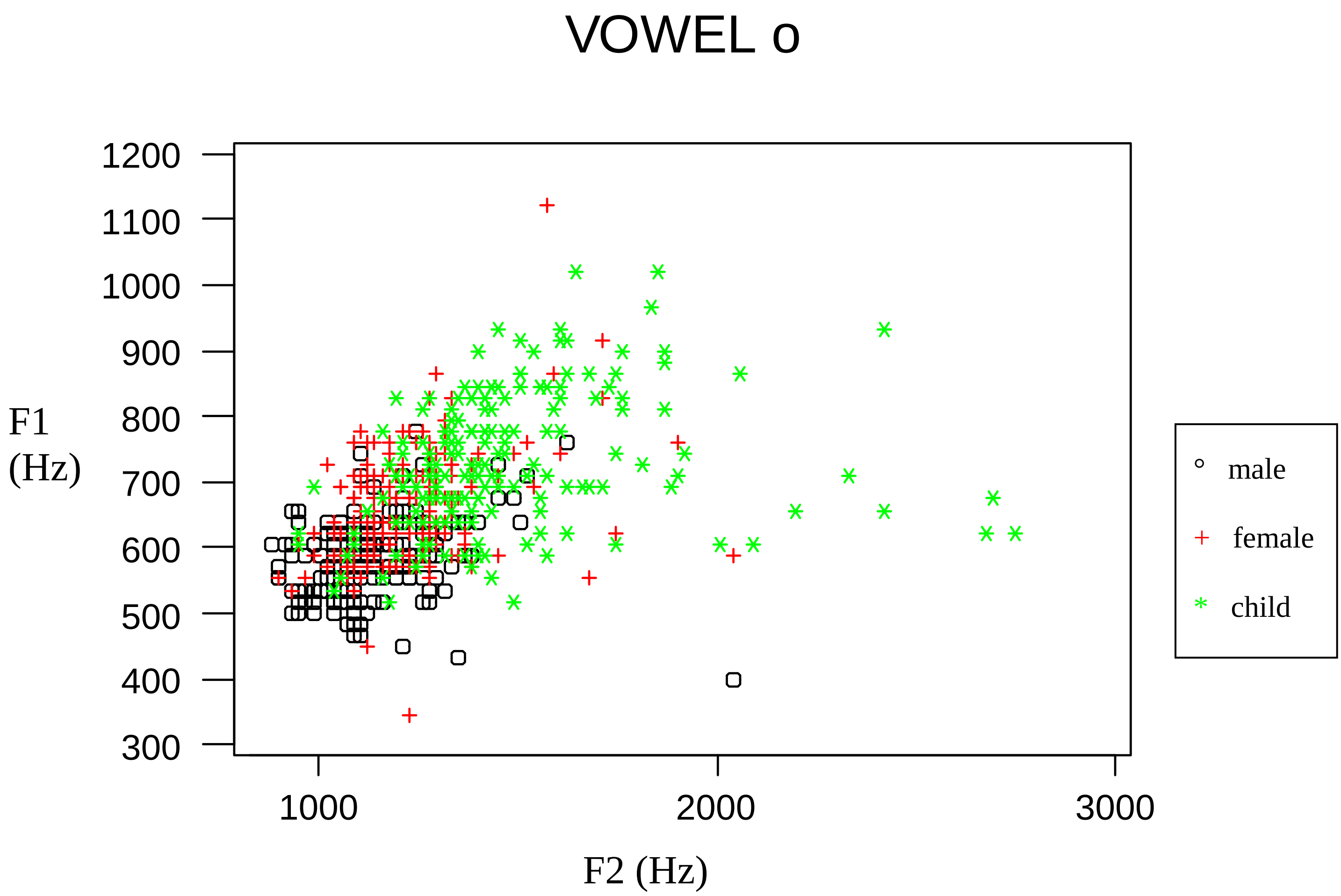



Figure 25 Plot of vowel [o], showing the distribution of the male, female and child formant frequency data.

Figure 25 shows that children's values are again quite scattered and some of children's formant frequencies are close to adults' formant frequencies. Looking at the majority of children's values, though, we draw the conclusion that children's [o] is lower and less back than adults' [o]. In addition, male and female adult values are not as far apart as it is the case with the previous vowels, a fact which possibly has to do with the intrinsic quality of the vowel [o][19].

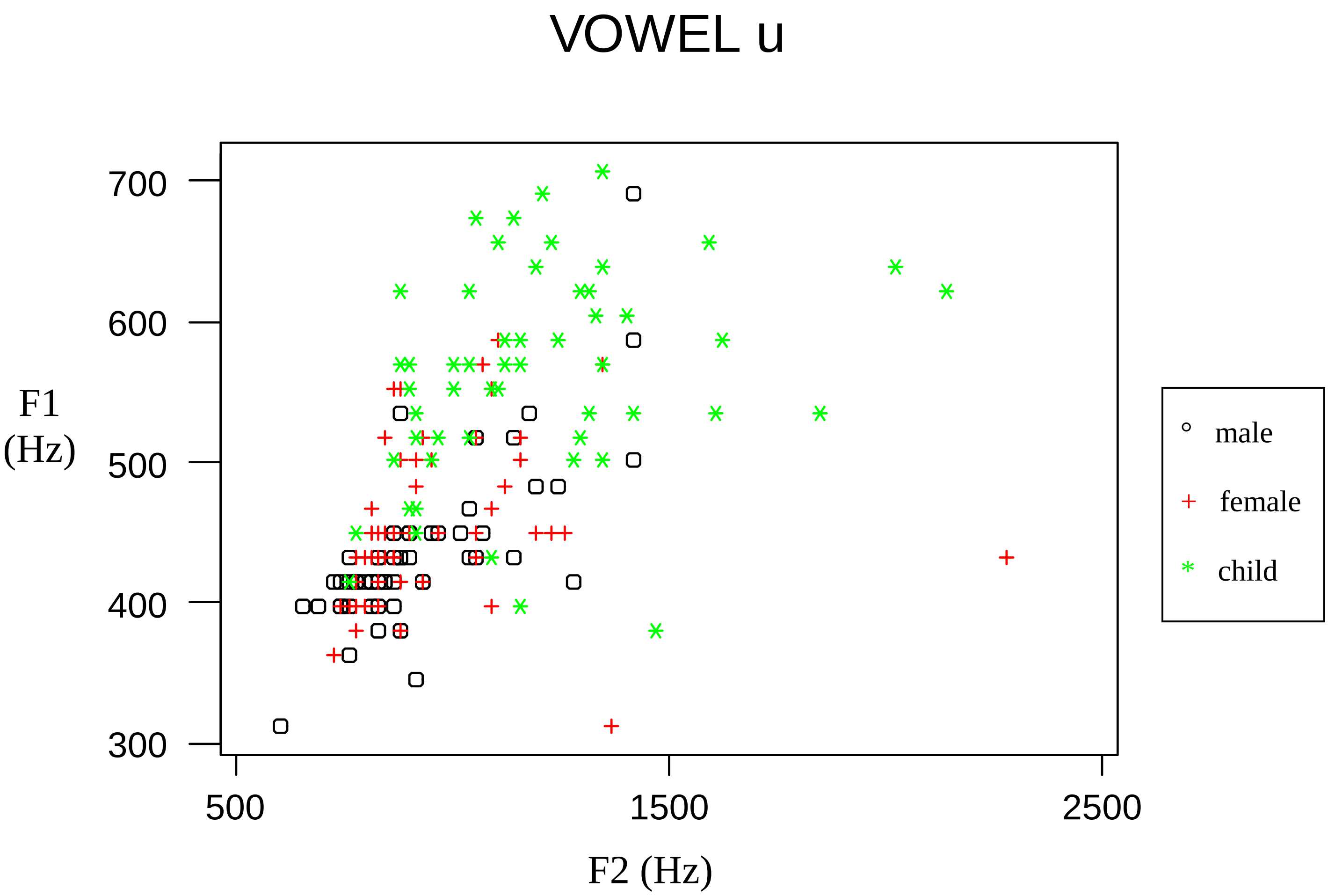



Figure 26 Plot of vowel [u], showing the distribution of the male, female and child formant frequency data.

The plot on Figure 26 demonstrates the problem we encountered with the vowel [u]. Firstly, the number of the values is distinctly lower than that of the other

[19] See section 2.1.2., p. 7.

vowels, due to the formant location difficulties[20]. Secondly, the data for all classes of speakers are quite scattered, either because of location problems or because of the nature of the vowel. Nevertheless, we can say that children's [u] is lower and less back than adults' [u].

### 4.3. Comparisons with previous studies

We saw that children's vowels seem to be more front and lower (or more open) than adults' vowels, as children values of $F_1$ and $F_2$ are higher than adult values. In addition, the front vowels display the above characteristics to a greater degree than the back vowels; that is to say, the difference/distance between the child and adult values becomes smaller as we move from front [i,e] to back [o,u] vowels.

The above observations can be demonstrated more clearly on Figure 27, which shows the vowel spaces of the three classes of speakers. $F_2$ is plotted on the horizontal axis, with values increasing from right to left, against $F_1$ on the vertical axis, with values increasing from top to bottom, in order to make it referable to the traditional auditory map (Clark & Yallop, 1995:266). It is quite clear that, according to our data, the children's vowel space is placed more "downwards and to the left", in comparison to the adults' vowel spaces. On the other hand, men's vowel space seems to be positioned more "upwards and to the right", if compared with women's and children's vowel spaces. We also observe that women's vowel space is the "broadest", followed by the children's vowel space, while the men's is the "smallest" vowel space.

[20] See section 4.1., p. 47, section 2.1.3.4., pp. 18ff and section 2.3.2., pp. 38ff.

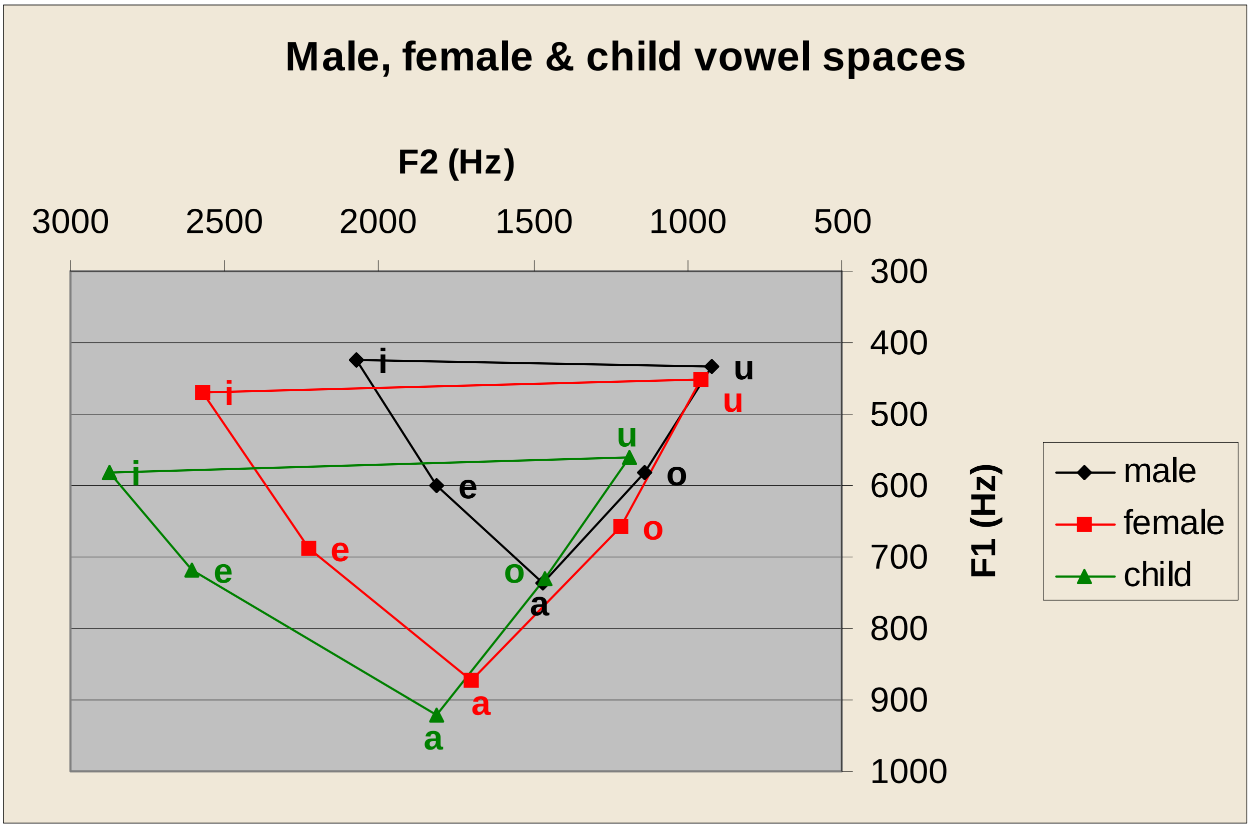



Figure 27 Greek adult male, female and child vowel spaces.

The vowel space pattern for the three classes of Greek speakers on Figure 27 has many similarities with Deterding's findings (1990:49&51) concerning English speakers' vowel spaces (Figure 28). English men's and children's vowel spaces also seem to have a similar shift to the Greek men's and children's vowel spaces.

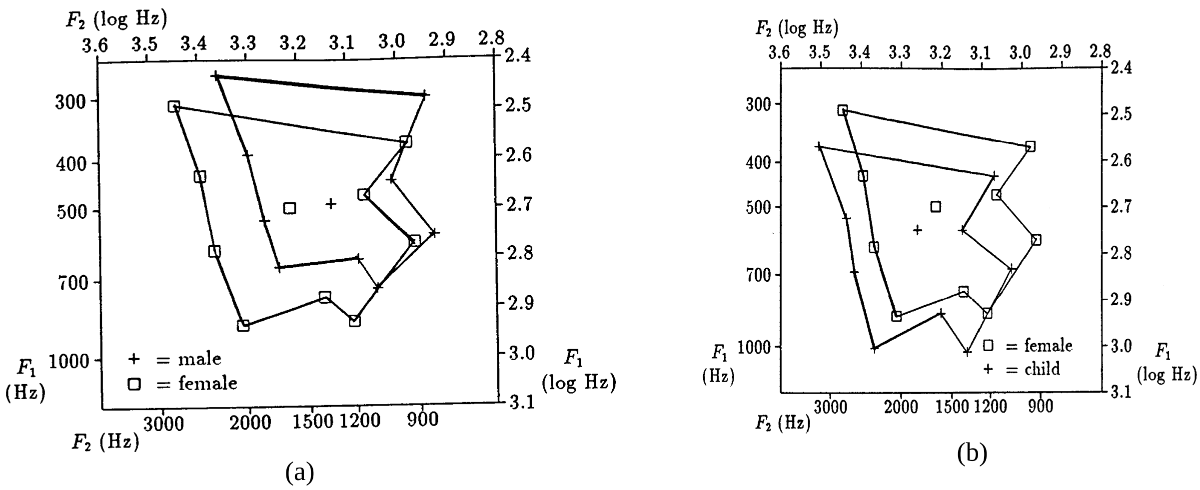



Figure 28 American English male and female (a) and child and female (b) vowel space (adopted from Deterding, 1990:49&51).

Previous Greek studies refer only to the spectral characteristics of Greek vowels produced by adults[21]. Kontosopoulos *et al.* (1988), based on the average frequency values of $F_1$ and $F_2$ of Greek vowels produced by 7 men and 7 women, construct Greek vowel spaces of i) stressed vowels produced by men, ii) stressed vowels produced by women, iii) unstressed vowels produced by men, iv) unstressed vowels produced by women, v) vowels produced by men, and vi) vowels produced by women. Vowel spaces (v) and (vi)[22] are in a condition most comparable to our study, as we study stressed and unstressed vowels collectively. No tables with frequency values are given, and hence Table 2 below is based on figures extracted from the plots[23] and was used for the comparisons.

| **Vowels** | **$F_1$** | | **$F_2$** | |
|---|---|---|---|---|
| | **Male** | **Female** | **Male** | **Female** |
| i | 300 | 320 | 2050 | 2550 |
| e | 470 | 620 | 1700 | 2200 |
| a | 730 | 800 | 1540 | 1600 |
| o | 540 | 600 | 1120 | 1000 |
| u | 400 | 350 | 1050 | 790 |

Table 2 The mean values of the first two formants of the Greek vowels (stressed and unstressed) produced by adult males and females (based on Kontosopoulos *et al.*, 1988:116).

Botinis *et al.* (1997) constructed a perceptual vowel map using synthetic stimuli, which were identified by 4 female speakers[24]. The figures in Table

[21] See also section 2.3.1.1., pp. 28ff.
[22] These vowel spaces are displayed in section 2.3.1.1., p. 29.
[23] The average values of $F_1$, $F_2$, and $F_3$ are published in Kontosopoulos, N., Ksiromeritis, N., Tsitsa, A. (1986). Ta elinika fonienta (akoustiki tous fisi) (Greek vowels (their acoustic nature)). *Lexicografikon Deltion tis Akadimias Athinon* **16.** 289-301. Unfortunately, we could not find this article.
[24] The vowel map is displayed in section 2.3.1.1., p. 32.

3 below were extracted from the vowel map and were used in the comparisons, since no tables of figures were provided in the article.

| Vowels | **$F_1$** | **$F_2$** |
|---|---|---|
| i | 220-310 | 2200-2800 |
| e | 400-650 | 1600-2300 |
| a | 700-800 | 1000-1400 |
| o | 420-600 | 400-1100 |
| u | 220-310 | 400-1050 |

Table 3 Minimum and maximum values of the $F_1$ and $F_2$ frequencies extracted from a perceptual vowel map constructed on the basis of a study using synthetic stimuli judged by four female subjects (Botinis *et al.*, 1997).

Fourakis *et al.* (1999) give tables of figures, but only for $F_1$ and $F_2$, in their study for the influence of focus, stress and tempo on the first two formants and the spectral characteristics of Greek vowels produced by five male speakers[25]. Fourakis *et al.* (1999:39) mention that "the condition most comparable to other published results is the slow, unstressed nonfocus condition", and thus this is the one we use for the comparisons (Table 4).

| Vowels | **$F_1$** | **$F_2$** |
|---|---|---|
| i | 322 | 2088 |
| e | 463 | 1745 |
| a | 692 | 1280 |
| o | 475 | 1002 |
| u | 338 | 926 |

Table 4 Means for stressed nonfocus vowels at slow tempo (adopted from Fourakis at al., 1999:32).

[25] For more information about this study, see section 2.3.1.1., pp. 32ff.

The first comparison refers to the adult male vowels (Figure 29). We compare our data (Table 1, p. 49) with the data given by Kontosopoulos *et al.* (1988) and Fourakis *et al.* (1999) (Tables 2 and 4, pp. 57&58).

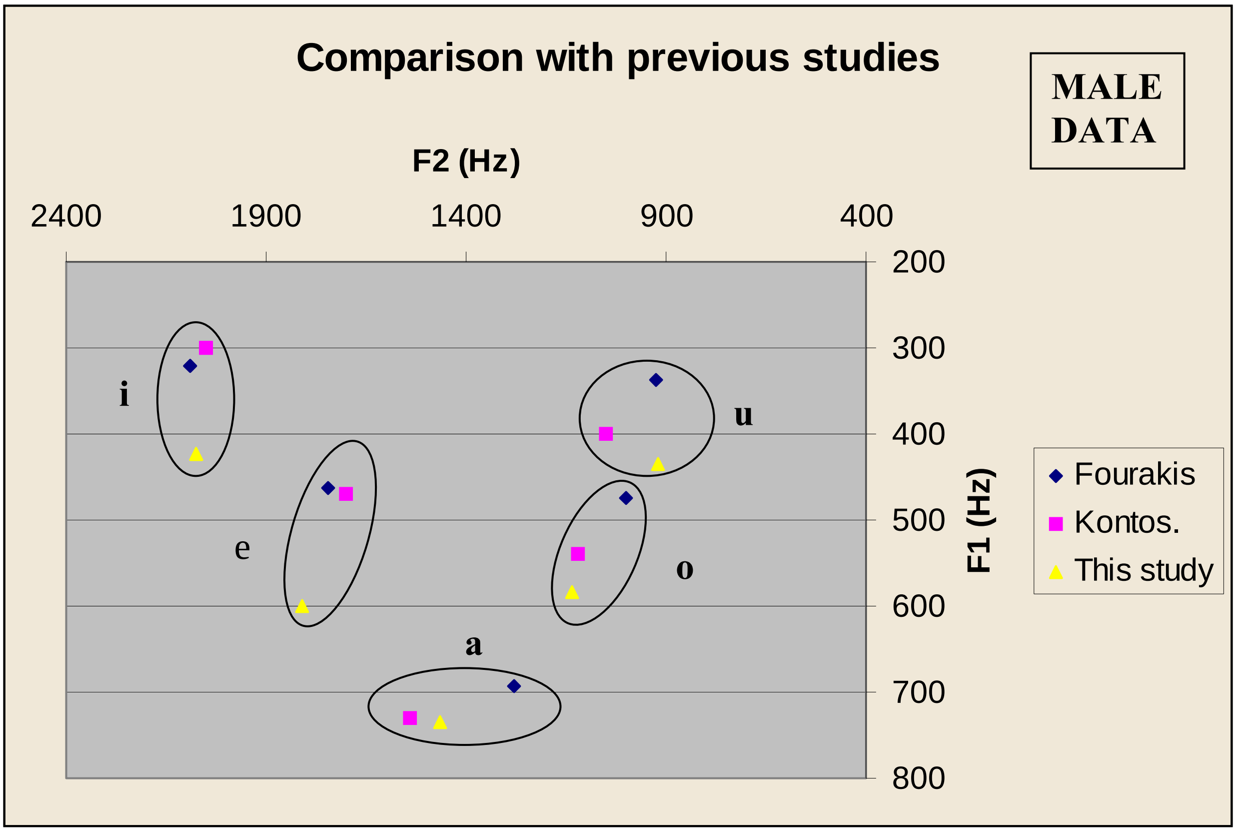



Figure 29 The vowels of Greek produced by male adults based on data from three different experiments. The ellipses group points for ease of exposition.

We observe that front vowels [i, e] are more open in our data than what the other two sources show. In addition, vowel [e] and vowel [a] are more fronted and vowel [o] is less back according to our data. Kontosopoulos *et al.* seem to agree on the front vowels' position with Fourakis *et al.*, whereas they seem to agree more with this study on the position of [a] and [o].

Concerning adult female vowels, our data are compared only with the data of Kontosopoulos *et al.*, as, to our knowledge, no other study has analysed female vowels (Figure 30).

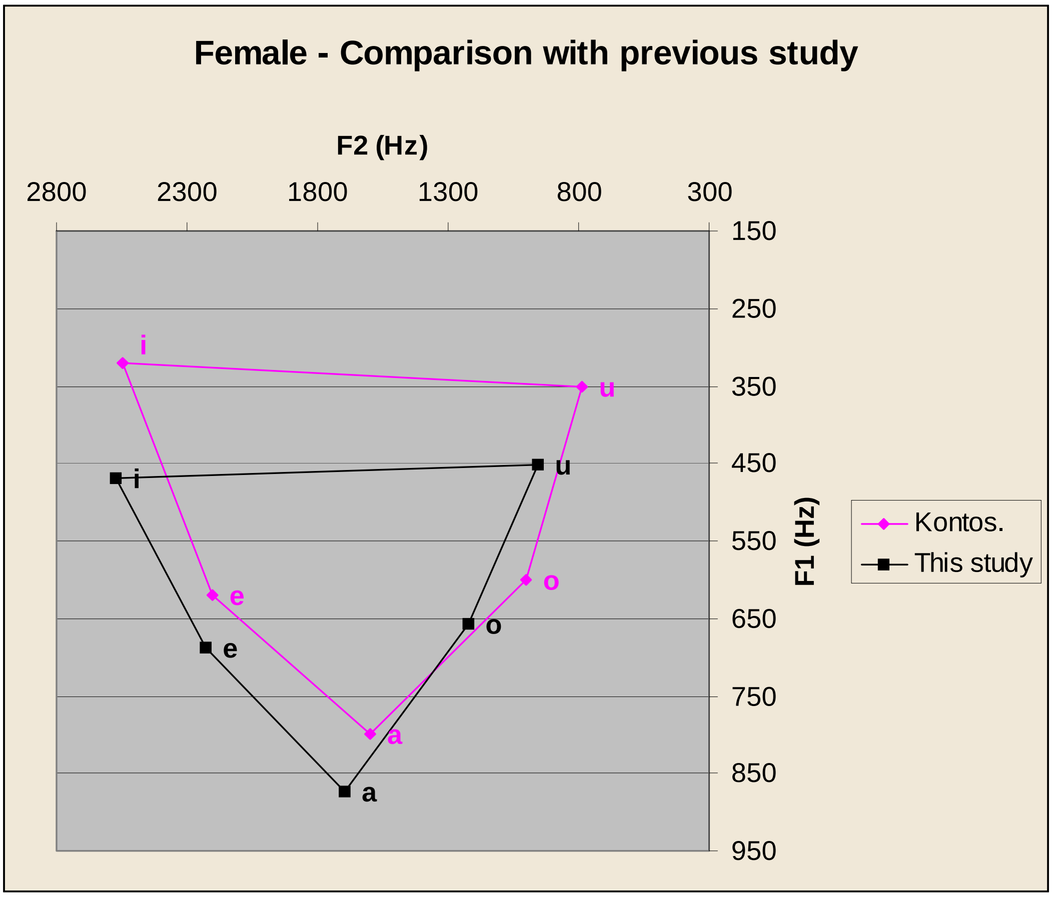



Figure 30 The vowels of Greek produced by female adults based on data from two different experiments.

Our data show that all female vowels are more fronted and more open in comparison with the previous study's data. Obviously, the first two formants were found to have higher frequencies in our study.

The differences in the results might be due to the different individuals that took part in each experiment or with the nature of the measurements themselves. Formants are difficult to locate with absolute certainty and this may cause some variation in the results.

The results of the perceptual study (Botinis *et al.*, 1997) were compared to our results, in order to see if the frequencies of $F_1$ and $F_2$ of the vowels produced by men, women and children in our study fall within the areas of the perceptual vowel map (Figure 31).

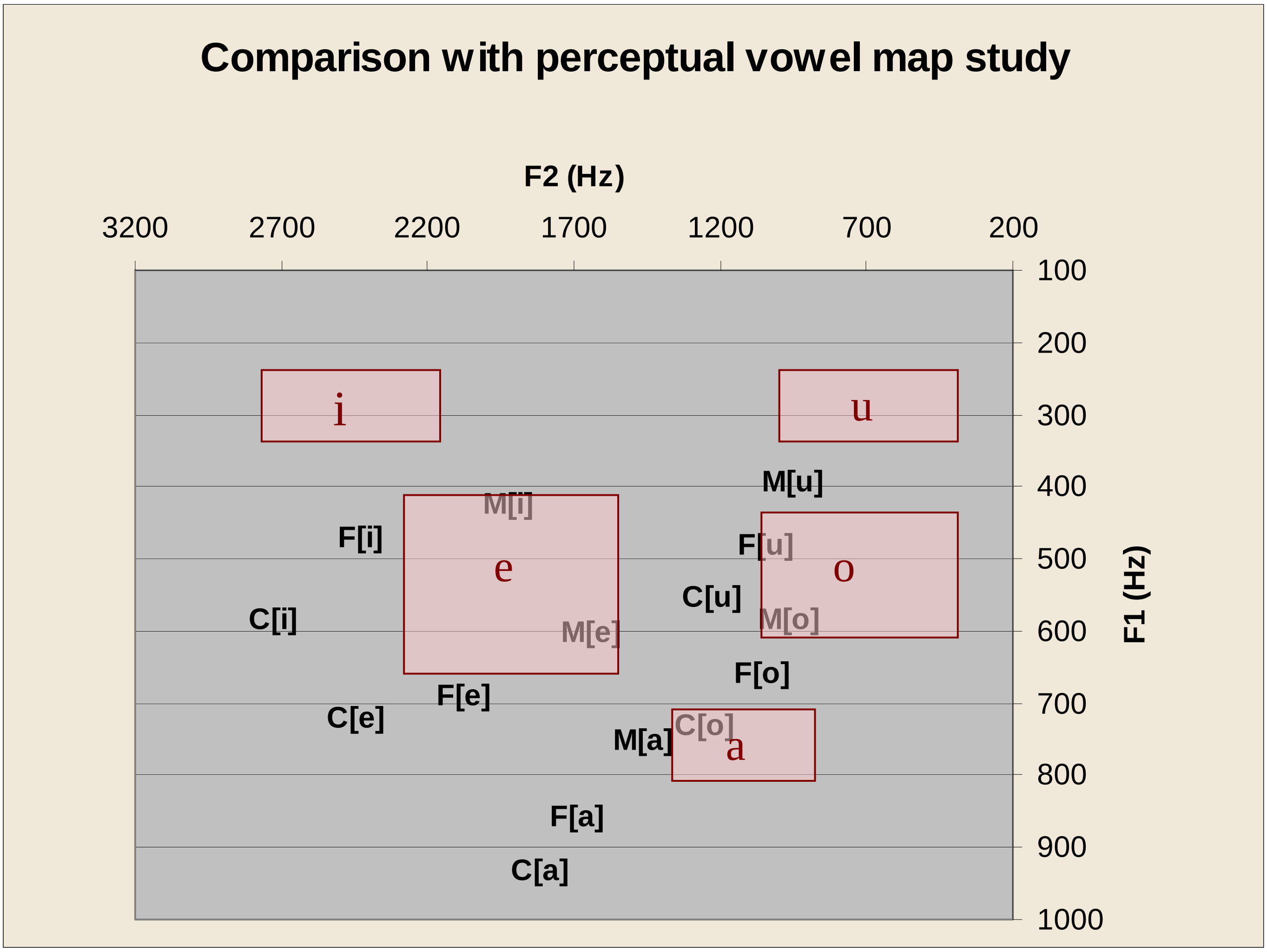



Figure 31 The vowels (average frequencies) of men, women and children (represented by pairs of letters only instead of dots, to avoid confusion), as found by our study, in comparison with the areas occupied by the Greek vowels (pink rectangles), as found by the perceptual vowel study of Botinis *et al.* (1997). The first letter of each vowel-point indicates the class of speaker (M=adult male, F=adult female and C=child) and the second indicates the vowel.

The only vowels which actually fall into the corresponding designated areas, although only marginally, are the two male mid vowels [e] and [o]. Concerning the rest of the male vowels, the back vowels [u, o] and vowel [a] are quite close to the areas, whereas vowel [i] seems to fall into the area of [e]. The female mid vowels seem to be close to their corresponding areas. Female vowels [i], [a] and [u] are more open, while [a] and [u] are more fronted as well. As far as children's vowels are concerned, we observe that all of children's vowels are quite far away from the areas; they are found more fronted and open.

In summary, we could say that male vowels and most of female vowels of our study are covered to some degree by the areas found by the above perceptual study, but children's vowels are not accounted for. The discrepancies which arose from the comparison might have to do with the different methods which were used to establish the vowel position. The reasons that these differences became highlighted in children's data might have to do with the problems in children's formants location or might suggest that the use of synthetic stimuli is not a very dependable source for establishing children's formant frequencies.

## 4.4. The relationships among adult male, adult female and children data

An interesting question is whether there is any relationship between adult male and female formant frequencies and between adult and children formant frequencies of the Greek vowels. The existence of such relationships would indicate a way in which differences between the classes of speakers could be normalised, and thus constituting the base of a methodology to achieve more accurate speech recognition programs. Nearey (as cited in Deterding, 1990:3) has suggested that a single normalising shift is sufficient to normalise for all the vowels of a speaker. Based on that, Deterding (1990:43-46) performs this first-order normalisation and observes that complete normalisation for all vowels is not a procedure quite so simple, as each vowel shift is of a different gradient[26].

In an attempt to find out what the relationship between men and women vowels and especially between adult and children vowels of the Greek language is like, we first plot male versus female formant frequencies. We observe that the data tend to create a line (Figure 32). The same trend is observed when plotting male versus child (Figure 33) and female versus child (Figure 34) formant frequencies.

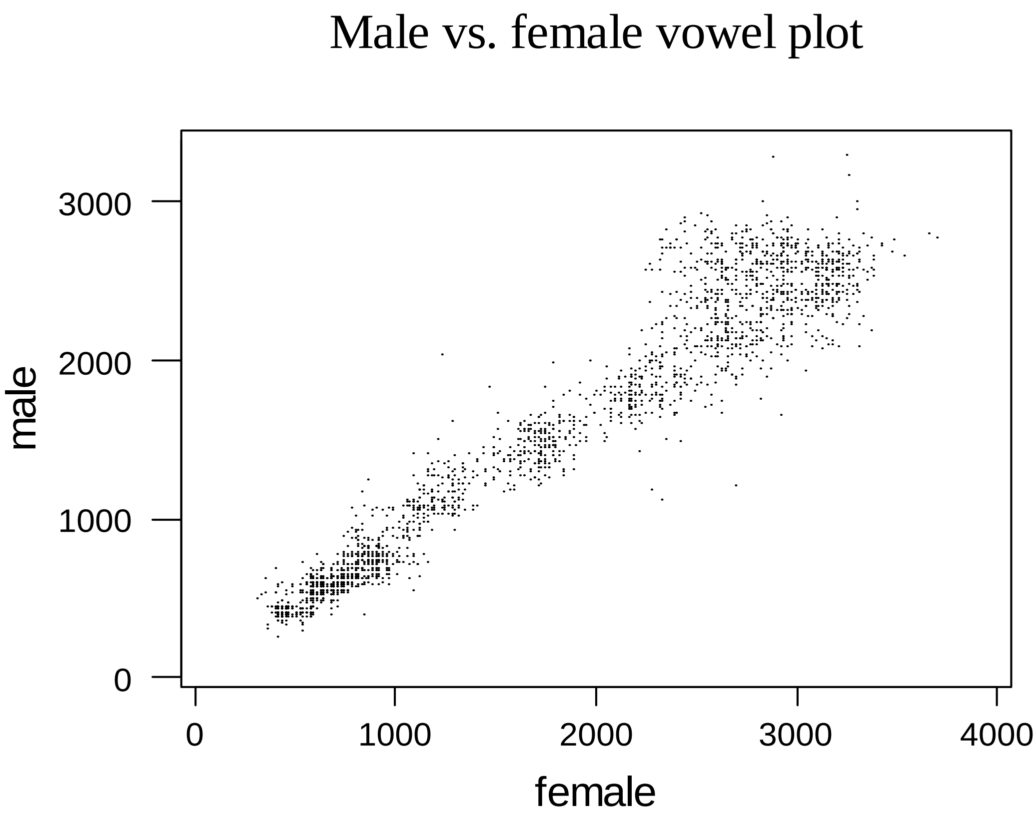



Figure 32 Male versus female vowel plot.

[26] See section 2.3., p. 23.

Male vs. child vowel plot

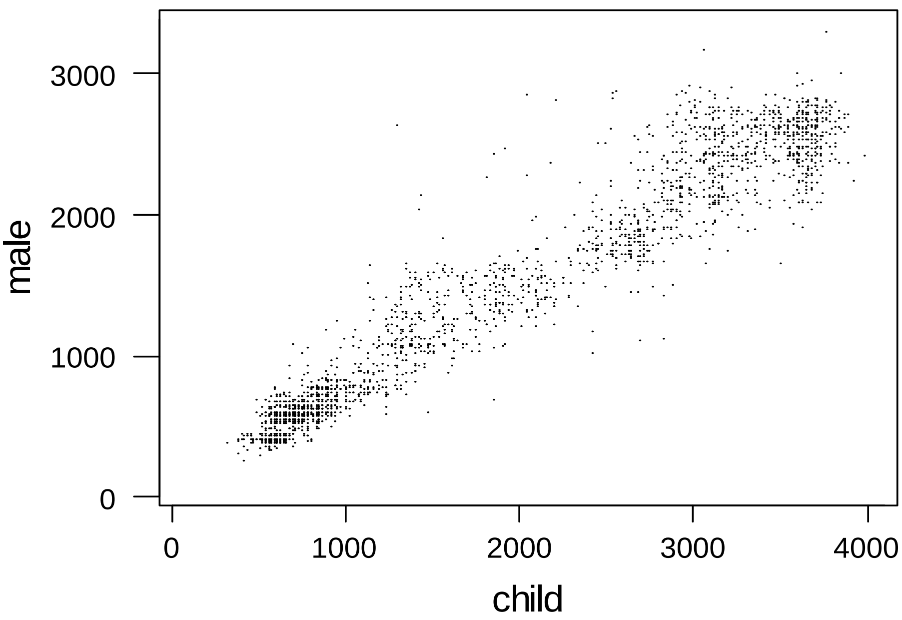



Figure 33  Male versus child vowel plot.

Female vs. child vowel plot

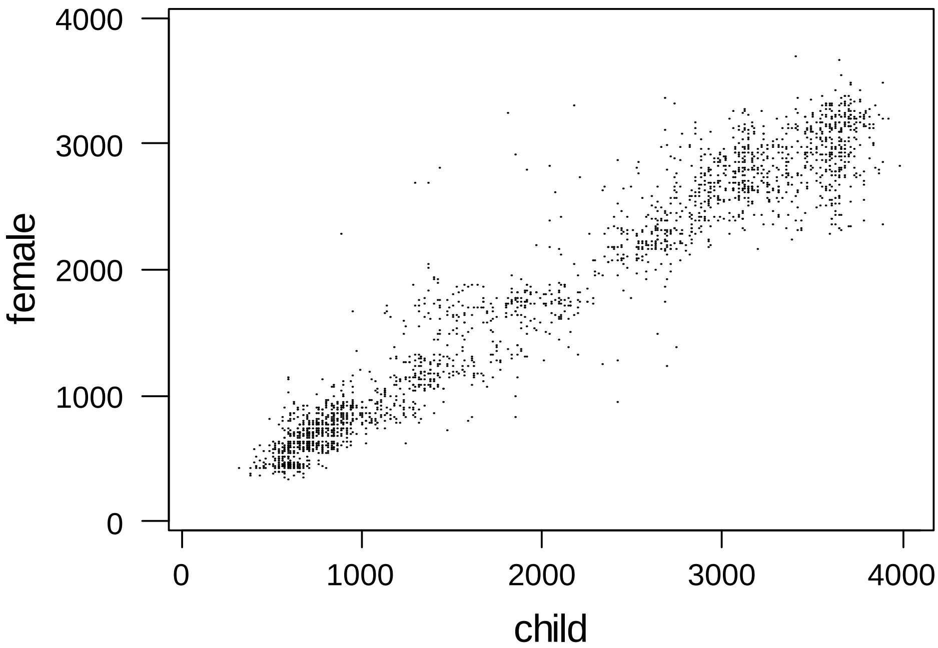



Figure 34  Female versus child vowel plot.

It is observed that there is some degree of linear relation between the variables and hence this relation can be represented quite well by a linear model (Woods *et al.*, 1986:156). We can use regression analysis to find an equation which will help to explain the variation in one variable (i.e. child formant frequencies) by using another variable (i.e. adult formant frequencies). We can also use *multiple regression*, that is, using both adult variables to predict child frequencies (Ryan & Joiner, 1994:290).

The regression equations predicting the child vowels from the adult vowels and the R-Sq values for these equations are displayed on Table 5 below[27]. It is obvious that the equations explain the variation in child vowels quite satisfactorily, as the R-Sq value is higher than 90% for all equations.

| Vowel | Equation | R-Sq |
|---|---|---|
| [i] | child[i] = 43.6 + 0.482 male[i]+ 0.731 female[i] | 96.3% |
| [e] | child[e] = - 88.7 + 0.369 male[e] + 0.891 female[e] | 97.7% |
| [a] | child[a] = - 93.4 + 0.760 male[a] + 0.506 female[a] | 90.5% |
| [o] | child[o] = 13.8 + 0.631 male[o] + 0.579 female[o] | 93.8% |
| [u] | child[u] = 42.6 + 0.963 male[u] + 0.262 female[u] | 91.1% |
| All | child[v] = - 39.4 + 0.568 male[v] + 0.678 female[v] | 94.7% |

Table 5 The regression equations and R-Sq values for predicting child vowels from adult vowels.

Lee *et al*. (1999:1455) note that the problem of automatic recognition of children's speech has gained attention in the recent years and that speech-recognition

[27] See Appendix 6, p. 110, for the complete Regression Analysis results for each vowel and for all vowels combined.

systems trained on adult speech perform unsatisfactorily when tested on children's speech. The study of the relationship between adult and children vowels could become valuable for many speech applications such as automatic recognition of children's speech, text-to-speech synthesis, etc.

# Chapter V: Conclusions and suggestions for further research

## 5.1. Main conclusions

The five Greek vowels produced by men, women and children have been analysed acoustically and their relationship according to speaker class has been investigated. A summary of the findings and observations of this study is presented in this section.

Concerning the procedure of formant location, several problems were encountered, the most prominent of which was the difficulty in locating the third formant of the back vowels; this difficulty was especially highlighted in the formant structure of the high, back vowel [u] when unstressed, in word-final position and produced by a child.

A comparison between the three classes of speakers has shown that children's vowels are generally more fronted and more open than women's vowels and even more so in comparison to men's vowels, and the difference between the children's and adults' values becomes greater as we move from back [o,u] to front [i,e] vowels. This difference is demonstrated clearly through the children's vowel space, which is placed more "downwards and to the left", in comparison to the adults' vowel spaces.

The above "speaker class pattern of the vowel space" for Greek is similar to the one for English, as described by Deterding (1990:49&51). A comparison with previous Greek studies on adults' data shows that vowels are generally found to be more fronted and open in this study, that is to say, $F_1$ and $F_2$ were found to have higher values. The fact that different individuals took part in each experiment and the difficulties in locating formants may account for the differences. As far as children's values are concerned, their formant frequency values were found not to fall within the corresponding vowel areas specified by a perceptual study of the Greek vowels (Botinis *et al.*, 1997). One possible explanation is that different methods were used to establish the vowel position.

Finally, it is suggested that children's formant frequencies can be predicted, using adults' formants. A multiple regression analysis provided equations for each vowel separately, as well as for all vowels combined, which explain the variation in children's vowels quite satisfactorily (R-Sq > 90%).

## 5.2. Suggestions for improvements

As we mentioned before, this study did not examine the effect of stress and the position of the vowel in the word, although the corpus was selected upon these criteria. Therefore, we could next investigate how the above factors have influenced the vowel formants of each speaker class.

Another issue, which has already been raised, concerns the difficulties that were encountered during the formant location procedure. These difficulties were highlighted when dealing with the two back vowels, but were also present in other cases, especially in vowels produced by women and children, as formants may not be distinctly defined for voices with high $F_0$ (Clark & Yallop, 1995:250). Many values were left out, as a consequence. Deterding (1990:97) mentions that formant trackers could be the answer to this location problem, as they allow each frame to refer to the results of previous frames and thereby make a more "intelligent" decision concerning the location of formants in the current frame. He notes, though, that this choice may be risky. Lee *et al.* (1999:1457), in an acoustic study of children's speech, also report that measuring with an automatic formant-tracking program was not the solution to the problem, as $F_2$ and $F_3$ were often inaccurate for vowels produced by young children due to poor spectral resolution at high frequencies, spurious spectral peaks, and formant-track merging. Therefore, it might be worthwhile to use both techniques, so as to locate formants with greater certainty.

The formant location problem also seems to be affected by the elicitation method. Reading a list has its drawbacks as a method of elicitation. For example, we observed that the subjects tended to increase speech rate, lower intensity and articulate "carelessly" towards the end of the list, thus giving poor samples of vowels. The last words contained the vowel [u], which was already under-represented in the rest of the corpus[28], and hence the analysis was based on a relatively small number of [u] data. This problem might be solved by randomising the list for each speaker, although it might create difficulties in processing the data. Alternatively, a different elicitation technique could be used. For example, the subject could be asked to produce sustained vowels, thus providing "clearer" tokens. It might be argued that the vowels would then not be articulated naturally. An answer to this argument is that the five Greek vowels *are* found in isolation in many linguistic contexts, as opposed to English vowels.

## 5.3. Suggestions for further research

Clark & Yallop (1995:241) comment that most research in speech acoustics has used male voices, partly for reasons of convenience in spectrographic analysis. In

[28] The reason for this has been given in section 3.3., p. 42.

addition, Henton (1995:422) underlines that in speech recognition research, it was assumed for many years that women are more difficult to recognise, a fact that she judges, based on her data, as a sexist assumption, which was fed by an "androcratic scientific heritage focusing on males' speech alone". Lass (1996:221) also emphasises the need for a more expanded database. Recent research on several languages has taken the above points into account, but unfortunately Greek does not seem to be one of them. The great majority of research has used only adult male data, neglecting women to an important extent and ignoring children. To our knowledge, research on the Greek language refers only to acoustic characteristics of adult speech.

Lass (1996:221) notes that more data are needed on women speakers and children of both genders, as acoustic theories may need to be revised to take these data into account. Potamianos *et al.* (as cited in Lee *et al.*, 1999:1455) reports that speech recognition systems trained on adults' speech degrade substantially when tested on the speech of children age twelve and younger. Without doubt the acoustic analysis of children's voices must gain attention, and this study is a small first step towards the expansion of the Greek acoustic database. As our analysis involves only vowels, a future step would include the analysis of consonants as well.

Future research could also involve more chronological detail, so as to study the effect of developmental factors in the acoustics of children's speech. Lee *et al.* (1999:1455) comment that a more chronologically detailed acoustic database obtained from a larger number of subjects with a wider range is needed, in order to better understand developmental acoustic patterns in children's speech; this knowledge would be valuable for automatic recognition of children's speech, evaluation and training of deaf children or children with speech problems, text-to-speech synthesis, and also for the construction of a better developmental model of the vocal tract for speech production research (Lee *et al*, 1997).

# References

Bladon, A. (1983). Acoustic phonetics, auditory phonetics, speaker sex and speech recognition: a thread. In Fallside, F. & Woods, W. A. (eds.) *Computer speech processing*. London: PHI. 29-38.

Botinis, A., Fourakis, M. & Hawks, J. W. (1997). A perceptual study of the Greek vowel space using synthetic stimuli. In *Eurospeech '97: Proceedings of the 5th European Conference on Speech Communication and Technology* (on CD-ROM).

Botinis, A., Fourakis, M. & Katsaiti, M. (1995). Acoustic characteristics of Greek vowels under different prosodic conditions. In *Proceedings of the XIIIth International Congress of Phonetic Sciences* (vol. 4). 404-407.

Clark, J. & Yallop, C. (1995). *An introduction to phonetics and phonology*. 2nd edition. Oxford: Blackwell.

Dauer, R. (1981). The reduction of unstressed high vowels in modern Greek. *Journal of the International Phonetic Association*. (vol. 10). 17-27.

Deterding, D. H. (1990). *Speaker normalisation for automatic speech recognition.* Ph.D. Thesis. University of Cambridge.

Farmer, A. (1984). Spectrography. In Code, C. & Ball, M. (eds.) *Experimental clinical phonetics*. London: Croom Helm. 21-40.

Fourakis, M., Botinis, A. & Katsaiti, M. (1999). Acoustic characteristics of Greek vowels. *Phonetica* **56.** 28-43.

Henton, C. (1995). Cross-language variation in the vowels of female and male speakers. In *Proceedings of the XIIIth International Congress of Phonetic Sciences* (vol. 4). 420-423.

Holton, D., Mackridge, P. & Philippaki-Warburton, I. (1997). *Greek: A comprehensive grammar of the modern language*. London: Routledge.

Joseph, B. D. & Philippaki-Warburton, I. (1987) *Modern Greek*. London: Croom Helm.

Kontosopoulos, N., Ksiromeritis, N., Tsitsa, A. (1988). Akustikes erevnes epi ton elinikon fthogon (Acoustic research on the Greek sounds). *Glossologia* **5-6.** 103-122.

Ladefoged, P. (1967). *Three areas of experimental phonetics*. Oxford: OUP.

Ladefoged, P. (1993). *A course in phonetics*. 3rd ed. Harcourt Brace College Publishers.

Lass, N. J. (ed.) (1996) *Principles of experimental phonetics*. London: Mosby.

Laver, J. (1994). *Principles of phonetics*. Cambridge: CUP.

Lee, S., Potamianos, A., Narayanan, S. (1997). Analysis of children's speech: duration, pitch and formants. In *Eurospeech '97: Proceedings of the 5th European Conference on Speech Communication and Technology* (on CD-ROM).

Lee, S., Potamianos, A., Narayanan, S. (1999). Acoustics of children's speech: Developmental changes of temporal and spectral parameters. *Acoustical Society of America*. (vol. 105). 1455-1468.

Lieberman, P. & Blumstein, S. E. (1988). *Speech physiology, speech perception, and acoustic phonetics*. Cambridge: CUP.

Mackridge, P. (1985). *The Modern Greek language: a descriptive analysis of Standard Modern Greek*. Oxford: OUP.

Peterson, G. E. & Barney, H. L. (1976). Control methods used in a study of the vowels. In Fry, D. B. (ed.) *Acoustic phonetics*. Cambridge: CUP. 104-122.

Philippaki-Warburton, I. (1992). *Isagogi sti theoritiki glosologia* (Introduction to theoretical linguistics). Athens: Nefeli.

Roach, P. (1992). *Introducing phonetics*. London: Penguin English.

Ryan, B. F. & Joiner, B. L. (1994). *Minitab Handbook*. 3rd. edition. Belmont: ITP.

Smith, B. L. & Kenney, M. K. (1998) An assessment of several acoustic parameters in children's speech production development: longitudinal data. *Journal of Phonetics* **26.** 95-108.

Stevens, K. N. (1998). *Acoustic phonetics*. Cambridge Mass.: MIT Press

Woods, A., Fletcher, P. & Hughes, A. (1986) *Statistics in language studies*. Cambridge: CUP.

# Appendix 1: The corpus

| ***Greek word*** | ***Transcription*** | ***Translation**** |
|---|---|---|
| 1. ήρθα | ìrθa | came (I) |
| 2. ημέρα | imèra | day |
| 3. ποδήλατο | poðilato | bicycle |
| 4. ειδικός | iðikòs | special |
| 5. κερί | cerì | candle |
| 6. μεσημέρι | mesimèri | noon |
| 7. αίμα | èma | blood |
| 8. εδώ | eðò | here |
| 9. σιδερένιος | siðereɲos | iron |
| 10 καφενείο | kafenìo | coffee shop |
| 11. καλέ | kalè | good (klitiki) |
| 12. έφερε | èfere | brought (he/she/it) |
| 13. άλλος | àlos | another |
| 14. ακριβός | akrivòs | expensive |
| 15. κοπάδι | kopaði | flock/herd |
| 16. καραμέλα | karamèla | candy |
| 17. καλά | kalà | well |
| 18. πέδιλα | pèðila | sandals |
| 19. όταν | òtan | when |
| 20. ωραίος | orèos | nice |
| 21. καλός | kalòs | good |
| 22. όμορφος | òmorfos | beautiful |
| 23. αβγό | avɣò | egg |
| 24. βάζο | vàzo | vase |
| 25. ούτε | ùte | neither |
| 26. ουρανός | uranòs | sky |
| 27. βούλα | vùla | spot |
| 28. μπουκάλι | bukàli | bottle |
| 29. κακού | kakù | bad (gen.) |
| 30. σκύλου | scìlu | dog (gen.) |

*The translation is broad. Some Greek words have more than one English equivalents. Also note that a Greek word may have a different rate of occurrence than its equivalent in English, which explains the fact that the word might be common for a Greek child, but not for an English child of the same age.

# Appendix 2: The data labelling

| Number | Position | Stress |
|---|---|---|
| 1 | word-initially | stressed |
| 2 | word-initially | unstressed |
| 3 | word-medially | stressed |
| 4 | word-medially | unstressed |
| 5 | word-finally | stressed |
| 6 | word-finally | unstressed |

Vowel [i]

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| ìrθa | imèra | poðilato | iðikòs | cerì | mesimèri |
| | iðikòs | kafenìo | mesimèri | | kopaði |
| | | scìlu | siðereɲos | | bukàli |
| | | | akrivòs | | |
| | | | pèðila | | |

Vowel [e]

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| èma | eðò | imèra | ceri | kale | èfere |
| èfere | | mesimèri | mesimèri | | ùte |
| | | siðereɲos | siðereɲos | | |
| | | karamèla | kafenìo | | |
| | | pèðila | èfere | | |
| | | orèos | | | |

Vowel [a]

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| àlos | akrivòs | kopaði | poðilato | kala | ìrθa |
| | avɣò | vàzo | kafenìo | | imèra |
| | | bukàli | kale | | èma |
| | | | karamèla | | karamèla |
| | | | karamèla | | pèðila |
| | | | kalà | | vùla |
| | | | òtan | | |
| | | | kalòs | | |
| | | | uranòs | | |
| | | | kaku | | |

Vowel [o]

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| òtan | orèos | iðikòs | poðilato | eðò | poðilato |
| òmorfos | | akrivòs | siðereɲos | avɣò | kafenìo |
| | | kalòs | àlos | | vàzo |
| | | uranòs | kopaði | | |
| | | | orèos | | |
| | | | òmorfos | | |
| | | | òmorfos | | |

Vowel [u]

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| ùte | uranòs | vùla | bukàli | kaku | scìlu |

## Appendix 3: The adult list

| | |
|---|---|
| ήρθα | καραμέλα |
| ημέρα | καλά |
| ποδήλατο | πέδιλα |
| ειδικός | όταν |
| κερί | ωραίος |
| μεσημέρι | καλός |
| αίμα | όμορφος |
| εδώ | αβγό |
| σιδερένιος | βάζο |
| καφενείο | ούτε |
| καλέ | ουρανός |
| έφερε | βούλα |
| άλλος | μπουκάλι |
| ακριβός | κακού |
| κοπάδι | σκύλου |

## Appendix 4: The children's list

ήρθα

ημέρα

ποδήλατο

ειδικός

κερί

μεσημέρι

αίμα

εδώ

σιδερένιος

καφενείο

καλέ

έφερε

άλλος

ακριβός

κοπάδι

καραμέλα

καλά

πέδιλα

όταν

ωραίος

καλός

όμορφος

αβγό

βάζο

ούτε

ουρανός

βούλα

μπουκάλι

κακού

σκύλου

# Appendix 5: Descriptive Statistics Results

## VOWEL [i]

### MALE

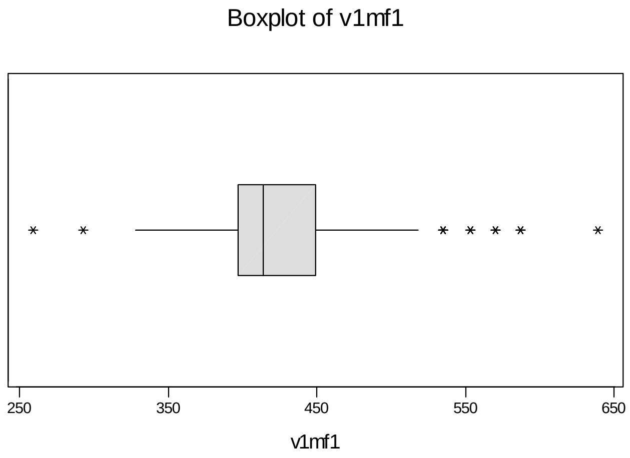
### F1

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1mf1 | 145 | 5 | 423.14 | 414.00 | 420.39 | 52.97 | 4.40 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1mf1 | 259.00 | 639.00 | 397.00 | 449.00 |

* NOTE * N missing = 5




### F2

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1mf2 | 145 | 5 | 2073.5 | 2091.0 | 2075.9 | 199.0 | 16.5 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1mf2 | 1209.0 | 2644.0 | 1926.5 | 2203.5 |

* NOTE * N missing = 5

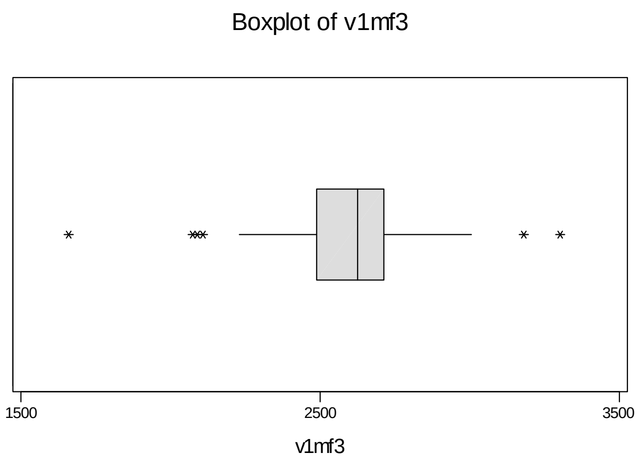

**F3**

## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1mf3 | 144 | 6 | 2593.4 | 2627.0 | 2596.9 | 201.3 | 16.8 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1mf3 | 1661.0 | 3301.0 | 2489.0 | 2713.0 |

* NOTE * N missing = 6



## FEMALE

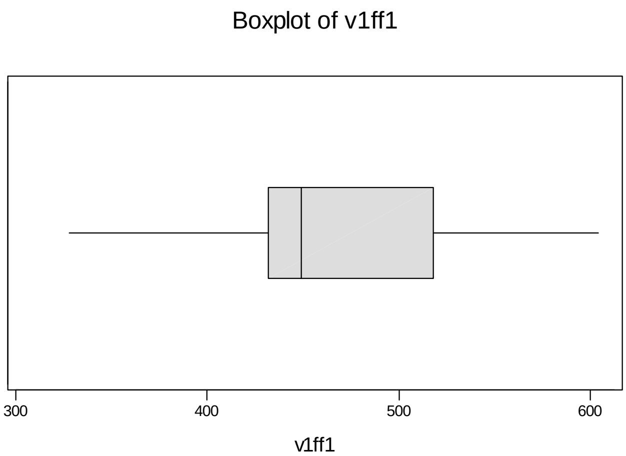
### F1

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1ff1 | 149 | 1 | 468.97 | 449.00 | 468.12 | 61.27 | 5.02 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1ff1 | 328.00 | 604.00 | 432.00 | 518.00 |

* NOTE * N missing = 1



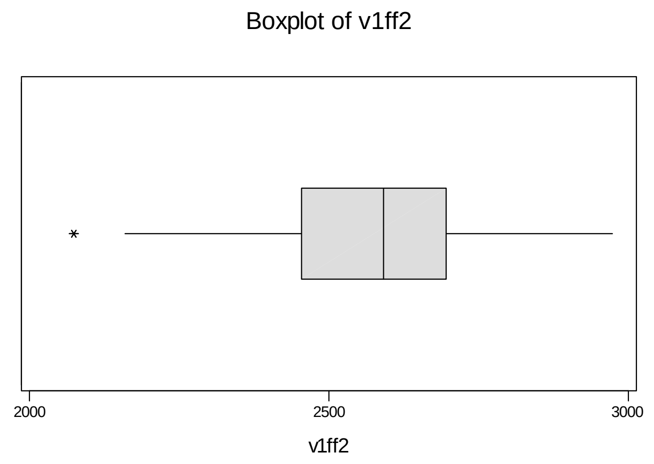

### F2

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1ff2 | 149 | 1 | 2571.2 | 2592.0 | 2576.4 | 182.5 | 15.0 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1ff2 | 2074.0 | 2973.0 | 2454.0 | 2696.0 |

* NOTE * N missing = 1



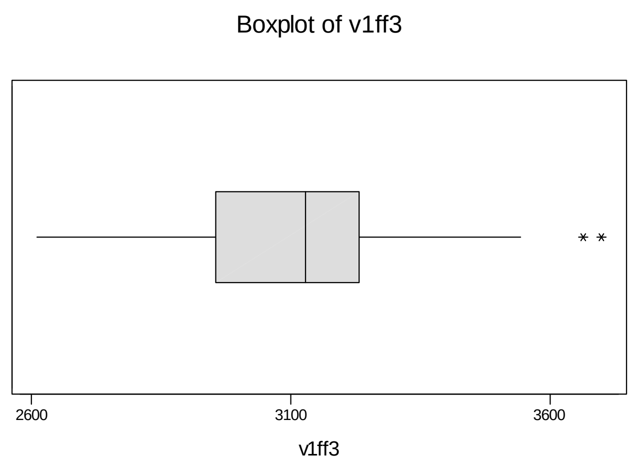

**F3**

**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1ff3 | 149 | 1 | 3109.2 | 3128.0 | 3106.9 | 199.0 | 16.3 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1ff3 | 2610.0 | 3699.0 | 2955.0 | 3232.0 |

```
* NOTE * N missing = 1
```



# CHILD

## F1

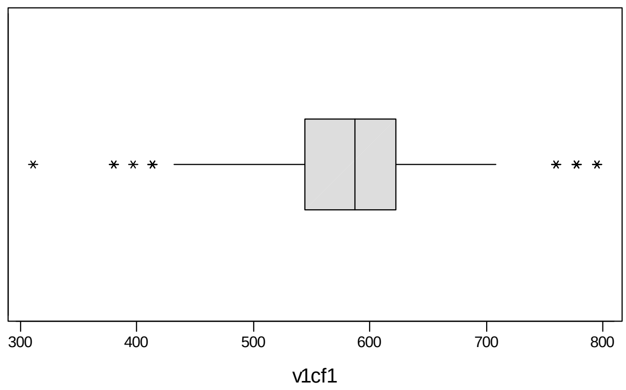
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1cf1 | 145 | 5 | 581.43 | 587.00 | 581.35 | 81.98 | 6.81 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1cf1 | 311.00 | 795.00 | 544.00 | 622.00 |

* NOTE * N missing = 5

Boxplot of v1cf1



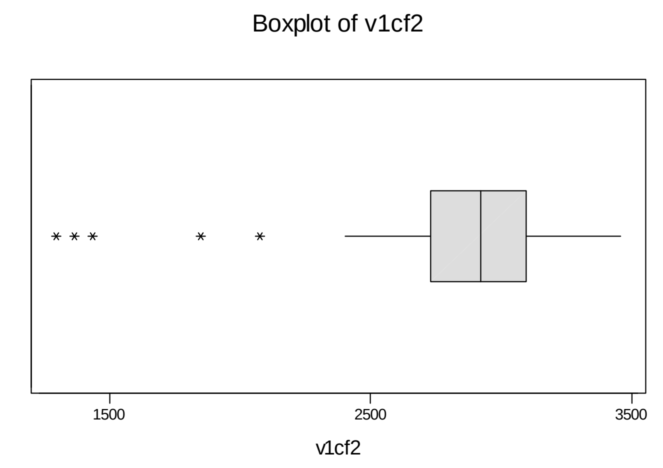

## F2

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1cf2 | 143 | 7 | 2873.1 | 2921.0 | 2904.7 | 333.5 | 27.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1cf2 | 1296.0 | 3457.0 | 2731.0 | 3094.0 |

* NOTE * N missing = 7



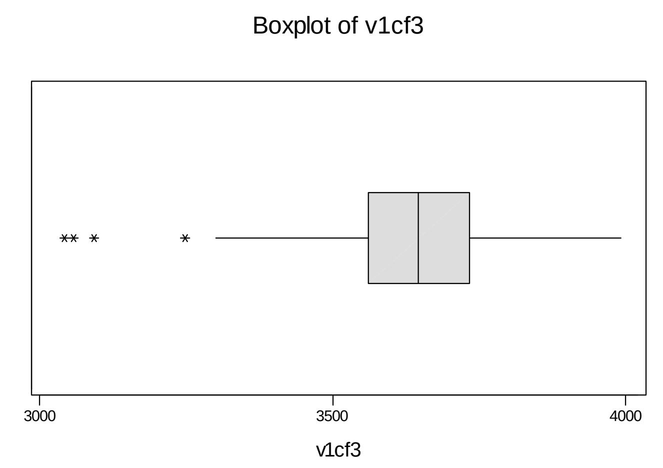

**F3**

## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v1cf3 | 141 | 9 | 3637.2 | 3647.0 | 3647.6 | 153.7 | 12.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v1cf3 | 3042.0 | 3992.0 | 3560.0 | 3733.0 |

* NOTE * N missing = 9



# VOWEL [e]

## MALE

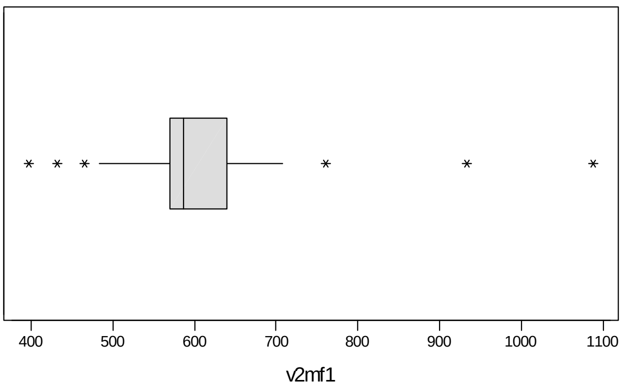
### F1

### Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2mf1 | 170 | 601.37 | 587.00 | 598.63 | 72.00 | 5.52 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2mf1 | 397.00 | 1088.00 | 570.00 | 639.00 |

Boxplot of v2mf1

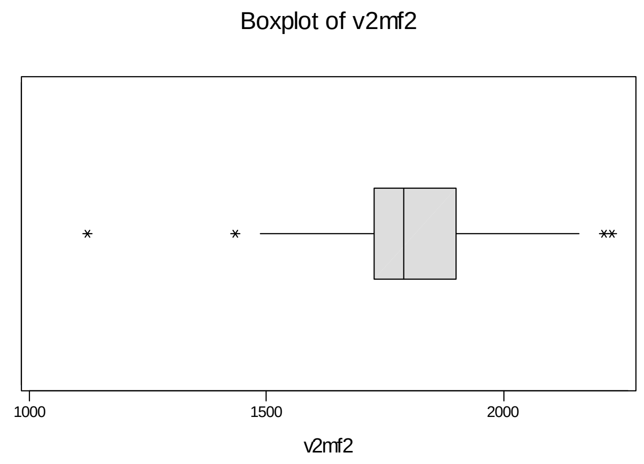



### F2

### Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2mf2 | 170 | 1811.1 | 1788.5 | 1811.4 | 145.7 | 11.2 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2mf2 | 1123.0 | 2229.0 | 1728.0 | 1901.0 |

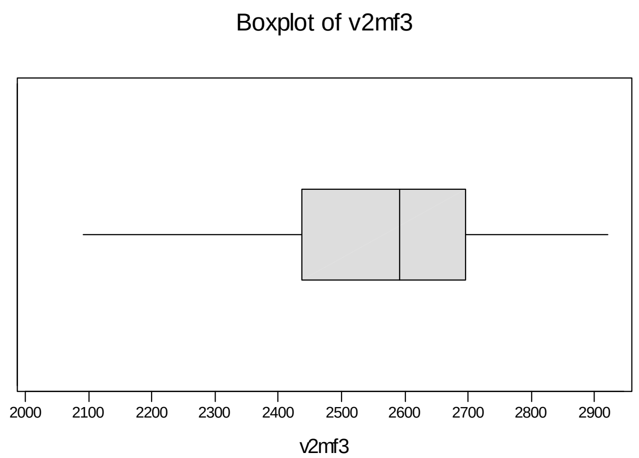



**F3**

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2mf3 | 170 | 2560.4 | 2592.0 | 2566.0 | 168.7 | 12.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2mf3 | 2091.0 | 2921.0 | 2437.0 | 2696.0 |



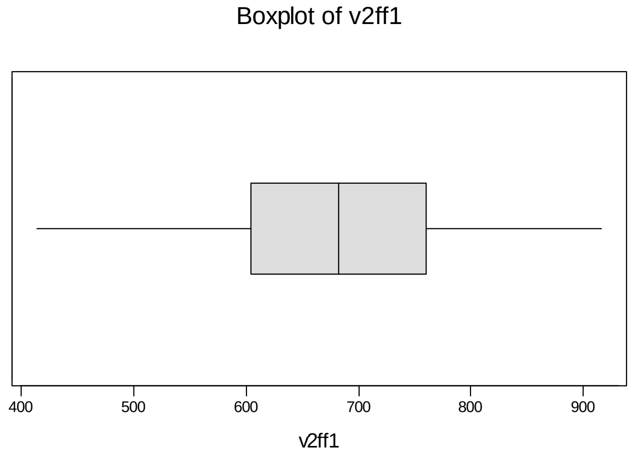
# FEMALE

## F1

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2ff1 | 170 | 687.38 | 682.50 | 686.74 | 90.27 | 6.92 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2ff1 | 414.00 | 916.00 | 604.00 | 760.00 |

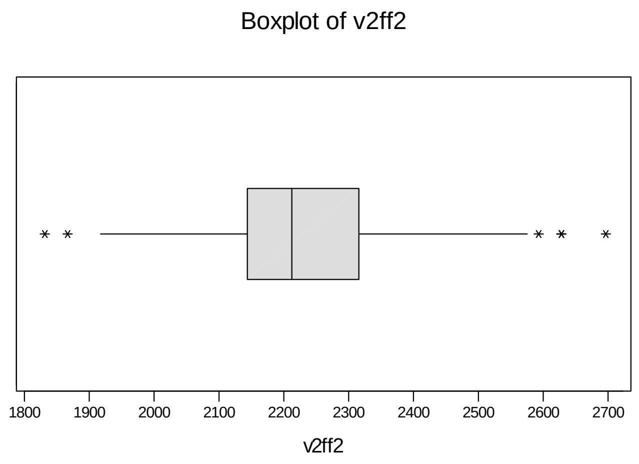



## F2

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2ff2 | 170 | 2230.5 | 2212.0 | 2228.3 | 147.9 | 11.3 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2ff2 | 1832.0 | 2696.0 | 2143.0 | 2316.0 |

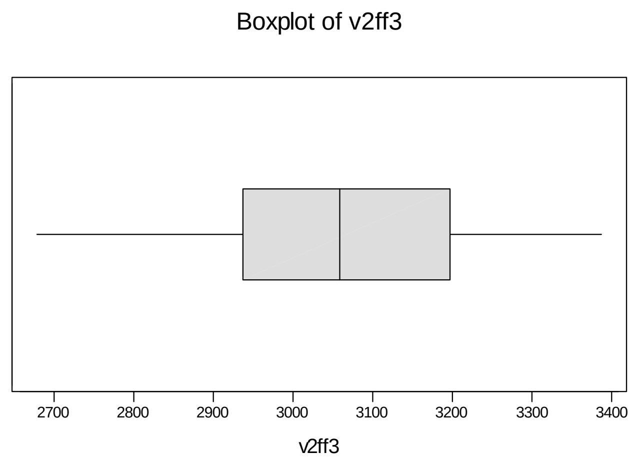



**F3**

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2ff3 | 170 | 3050.6 | 3059.0 | 3053.2 | 159.6 | 12.2 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2ff3 | 2679.0 | 3387.0 | 2938.0 | 3197.0 |



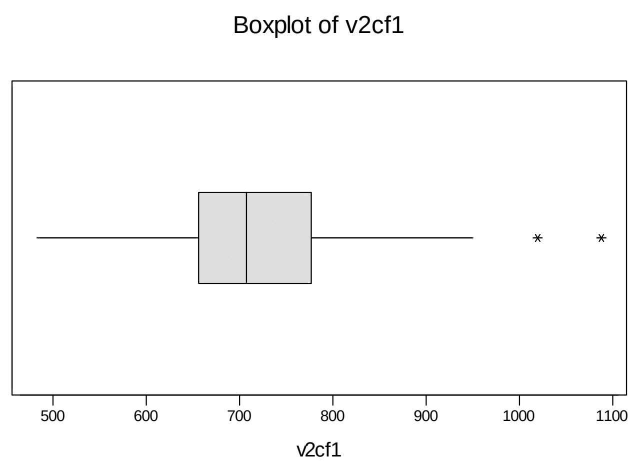
# CHILD

## F1

### Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2cf1 | 170 | 719.27 | 708.00 | 718.32 | 102.55 | 7.87 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2cf1 | 483.00 | 1088.00 | 656.00 | 777.00 |



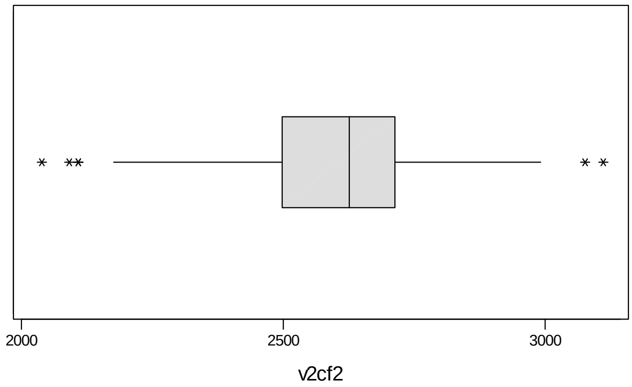

## F2

### Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2cf2 | 170 | 2607.3 | 2627.0 | 2611.2 | 183.7 | 14.1 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2cf2 | 2039.0 | 3111.0 | 2497.2 | 2713.0 |

Boxplot of v2cf2



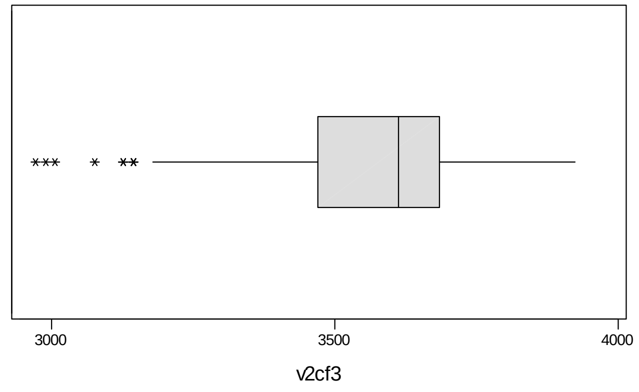

**F3**

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v2cf3 | 170 | 3558.0 | 3612.0 | 3569.1 | 190.5 | 14.6 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v2cf3 | 2973.0 | 3923.0 | 3469.8 | 3685.5 |

Boxplot of v2cf3



# VOWEL [a]

## MALE

## F1

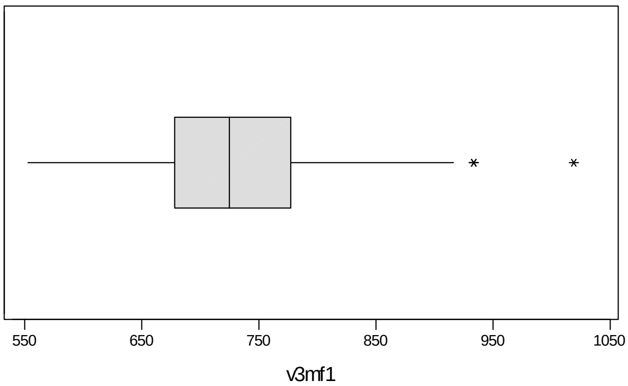
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3mf1 | 228 | 2 | 735.89 | 725.00 | 734.24 | 77.15 | 5.11 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3mf1 | 553.00 | 1019.00 | 678.25 | 777.00 |

* NOTE * N missing = 2

Boxplot of v3mf1




## F2

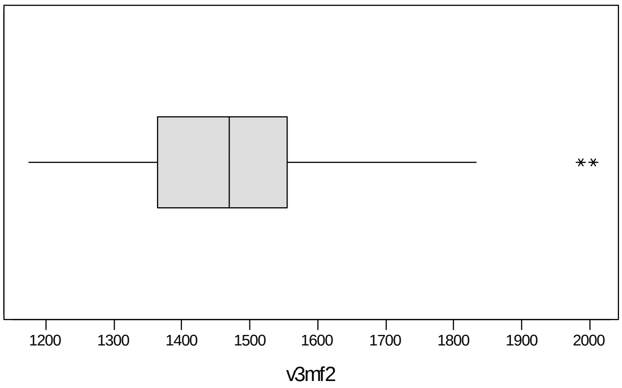
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3mf2 | 228 | 2 | 1465.7 | 1469.0 | 1462.4 | 133.2 | 8.8 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3mf2 | 1175.0 | 2005.0 | 1365.0 | 1555.0 |

* NOTE * N missing = 2

Boxplot of v3mf2




**F3**

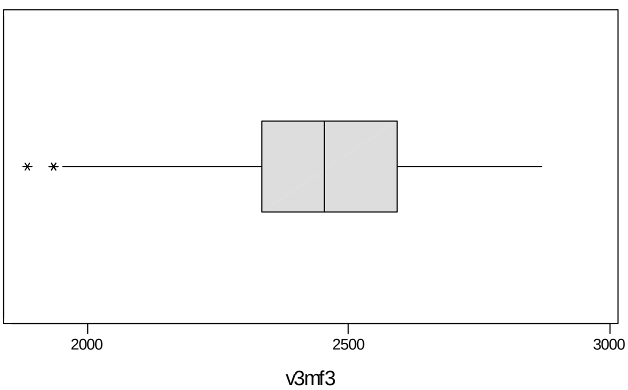
## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3mf3 | 217 | 3 | 2459.1 | 2454.0 | 2463.0 | 205.3 | 13.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3mf3 | 1884.0 | 2869.0 | 2333.0 | 2592.0 |

* NOTE * N missing = 3

Boxplot of v3mf3



**FEMALE**

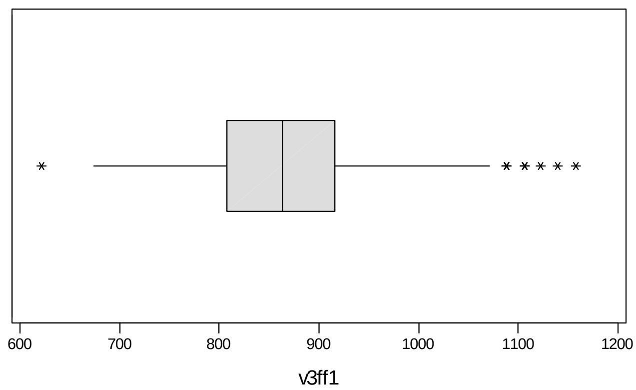
**F1**

**Descriptive Statistics**

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v3ff1 | 230 | 872.55 | 864.00 | 869.38 | 94.01 | 6.20 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3ff1 | 622.00 | 1158.00 | 807.75 | 916.00 |

Boxplot of v3ff1

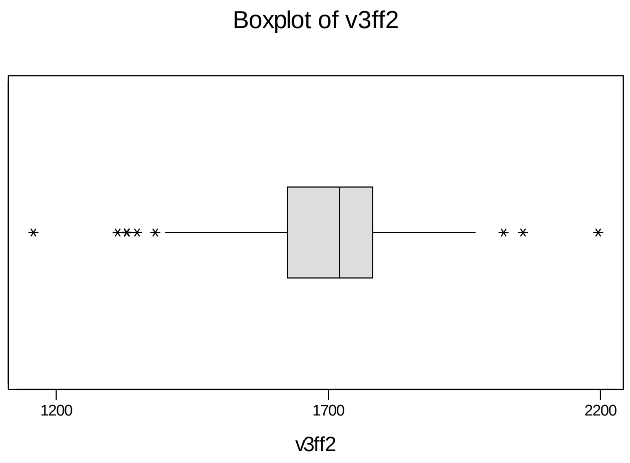



**F2**

**Descriptive Statistics**

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v3ff2 | 230 | 1698.8 | 1719.5 | 1703.3 | 145.2 | 9.6 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3ff2 | 1158.0 | 2195.0 | 1624.0 | 1780.0 |

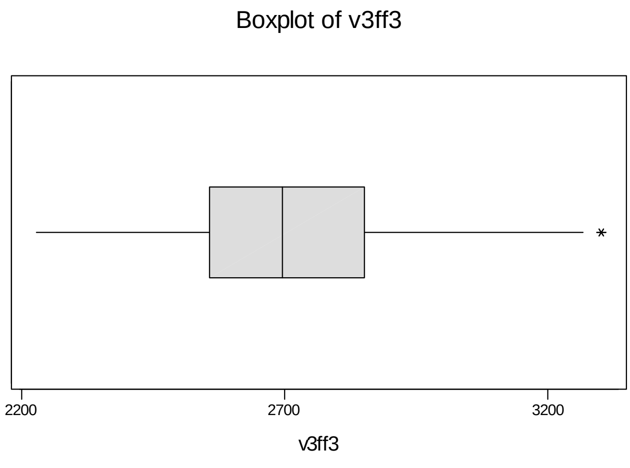



**F3**

## Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v3ff3 | 220 | 2712.8 | 2696.0 | 2708.6 | 237.3 | 16.0 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3ff3 | 2229.0 | 3301.0 | 2558.0 | 2852.0 |



**CHILD**

**F1**

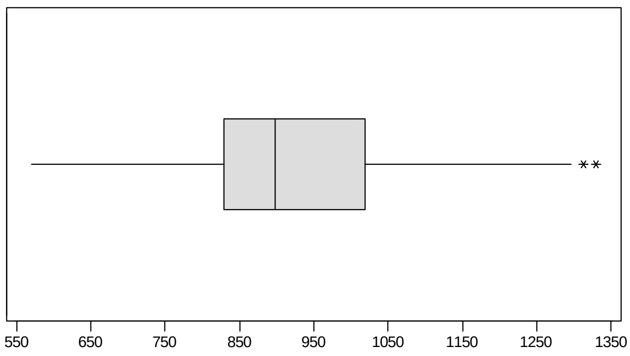
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3cf1 | 228 | 2 | 921.9 | 898.0 | 919.9 | 163.8 | 10.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3cf1 | 570.0 | 1330.0 | 829.0 | 1019.0 |

* NOTE * N missing = 2

Boxplot of v3cf1




**F2**

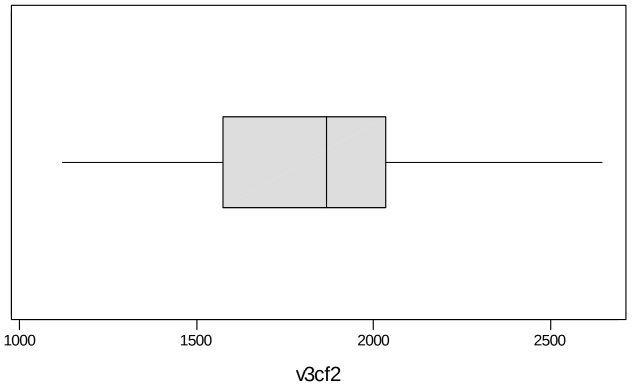
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3cf2 | 228 | 2 | 1811.3 | 1866.0 | 1814.9 | 286.4 | 19.0 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3cf2 | 1123.0 | 2644.0 | 1576.5 | 2034.8 |

* NOTE * N missing = 2

Boxplot of v3cf2




**F3**

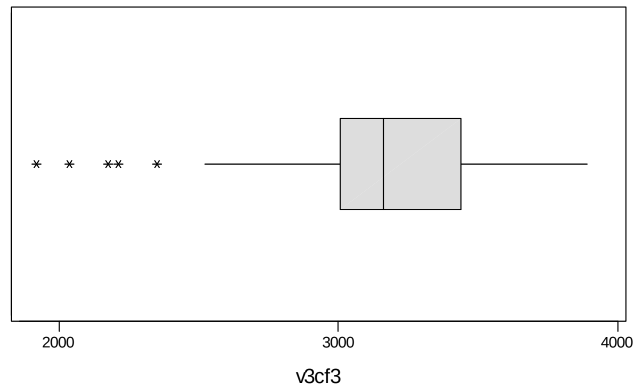
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v3cf3 | 215 | 5 | 3196.8 | 3163.0 | 3214.6 | 332.1 | 22.7 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v3cf3 | 1918.0 | 3889.0 | 3007.0 | 3439.0 |

* NOTE * N missing = 5

Boxplot of v3cf3



# VOWEL [o]

## MALE

### F1

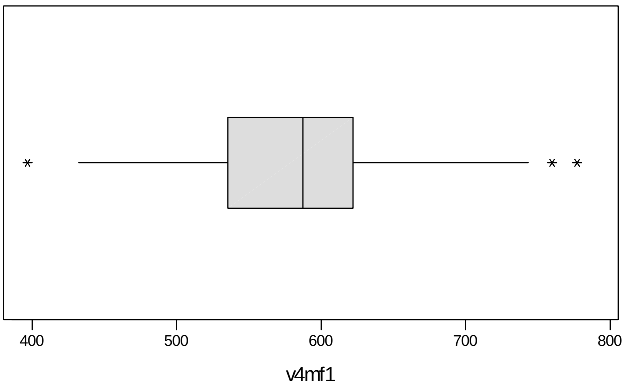
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4mf1 | 177 | 13 | 583.02 | 587.00 | 581.70 | 61.52 | 4.62 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4mf1 | 397.00 | 777.00 | 535.00 | 622.00 |

* NOTE * N missing = 13

Boxplot of v4mf1




### F2

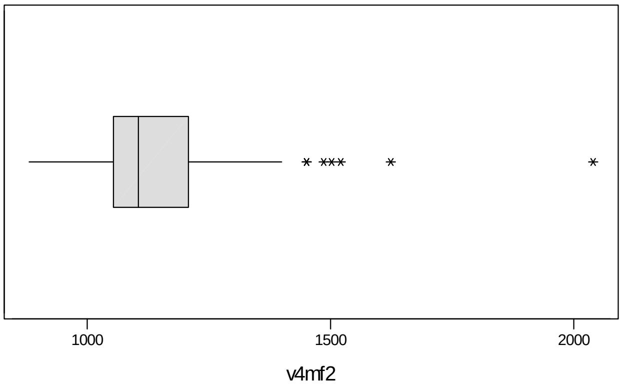
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4mf2 | 177 | 13 | 1137.3 | 1106.0 | 1127.2 | 148.8 | 11.2 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4mf2 | 881.0 | 2039.0 | 1054.0 | 1209.0 |

* NOTE * N missing = 13

Boxplot of v4mf2




**F3**

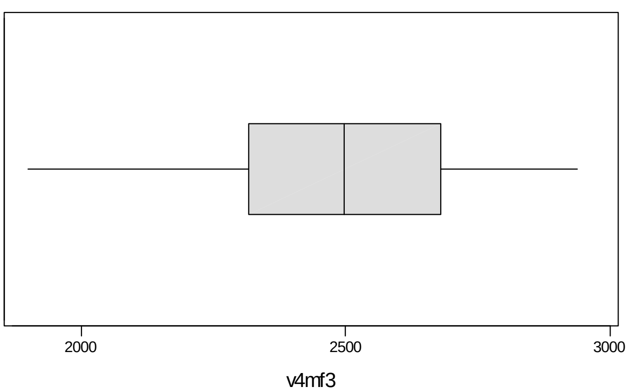
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4mf3 | 168 | 22 | 2479.3 | 2497.5 | 2483.1 | 243.5 | 18.8 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4mf3 | 1901.0 | 2938.0 | 2316.0 | 2679.0 |

* NOTE * N missing = 22

Boxplot of v4mf3



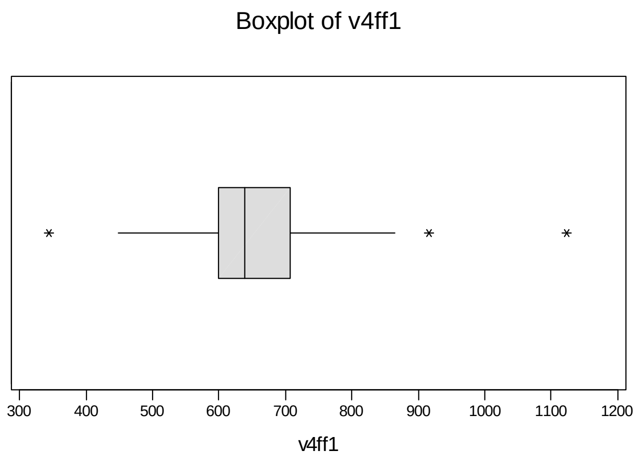
## FEMALE

### F1

### Descriptive Statistics

| Variable | N | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|
| v4ff1 | 190 | 657.32 | 639.00 | 653.67 | 84.54 | 6.13 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4ff1 | 345.00 | 1123.00 | 599.75 | 708.00 |



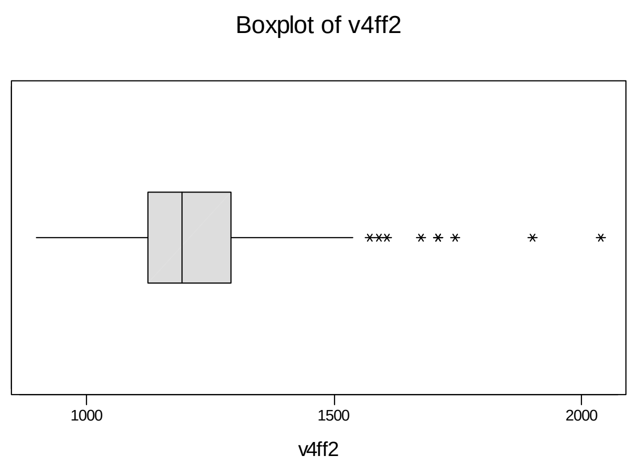

### F2

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4ff2 | 188 | 2 | 1219.1 | 1192.0 | 1205.7 | 163.6 | 11.9 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4ff2 | 898.0 | 2039.0 | 1123.0 | 1291.8 |

* NOTE * N missing = 2



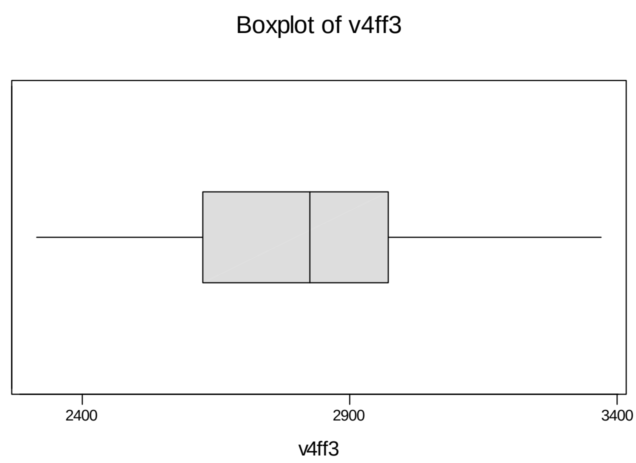

**F3**

**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4ff3 | 188 | 2 | 2816.9 | 2825.5 | 2817.2 | 230.0 | 16.8 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4ff3 | 2316.0 | 3370.0 | 2627.0 | 2973.0 |

* NOTE * N missing = 2



# CHILD

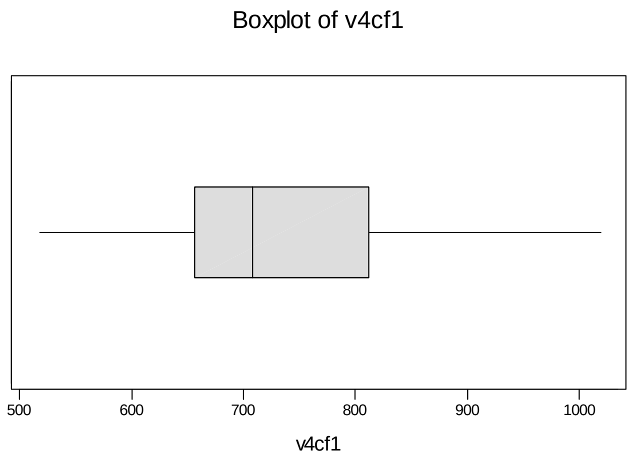
## F1

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4cf1 | 186 | 4 | 729.66 | 708.00 | 727.73 | 102.45 | 7.51 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4cf1 | 518.00 | 1019.00 | 656.00 | 812.00 |

* NOTE * N missing = 4




## F2

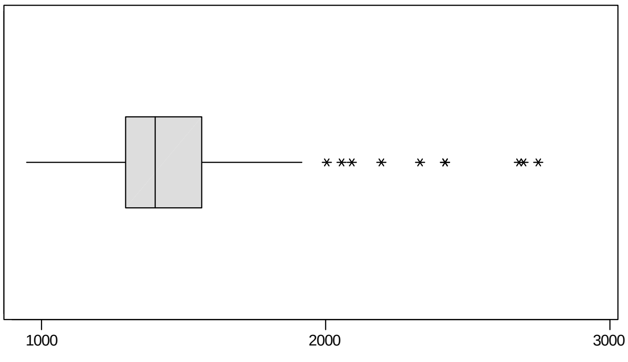
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4cf2 | 185 | 5 | 1462.0 | 1400.0 | 1434.5 | 295.4 | 21.7 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4cf2 | 950.0 | 2748.0 | 1296.0 | 1563.5 |

* NOTE * N missing = 5

Boxplot of v4cf2




**F3**

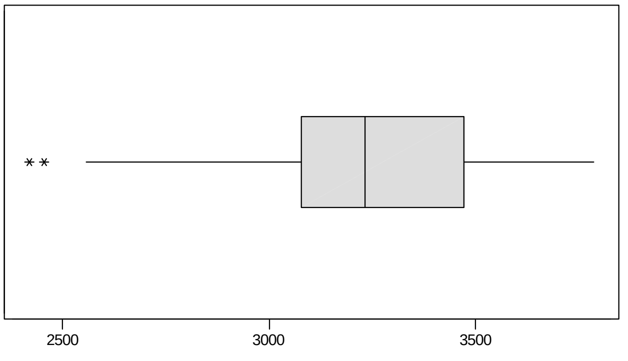
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v4cf3 | 160 | 30 | 3239.8 | 3232.0 | 3245.9 | 287.6 | 22.7 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v4cf3 | 2419.0 | 3785.0 | 3076.0 | 3469.8 |

* NOTE * N missing = 30

Boxplot of v4cf3



# VOWEL [u]

## MALE

## F1

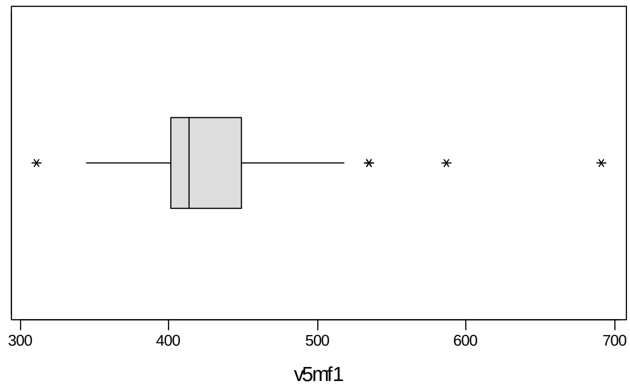
## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5mf1 | 56 | 4 | 434.36 | 414.00 | 429.86 | 58.75 | 7.85 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5mf1 | 311.00 | 691.00 | 401.25 | 449.00 |

* NOTE * N missing = 4

Boxplot of v5mf1




## F2

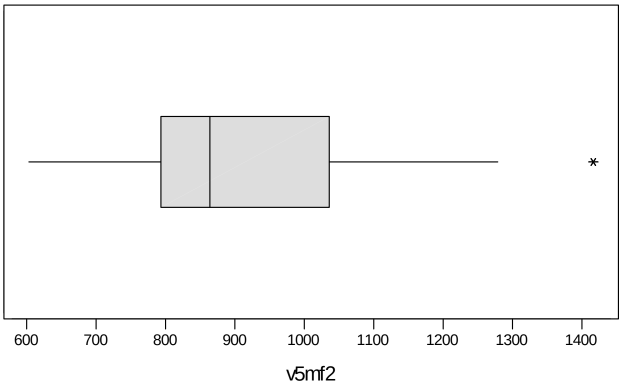
## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5mf2 | 55 | 5 | 920.6 | 864.0 | 906.8 | 189.1 | 25.5 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5mf2 | 604.0 | 1417.0 | 795.0 | 1037.0 |

* NOTE * N missing = 5

Boxplot of v5mf2




**F3**

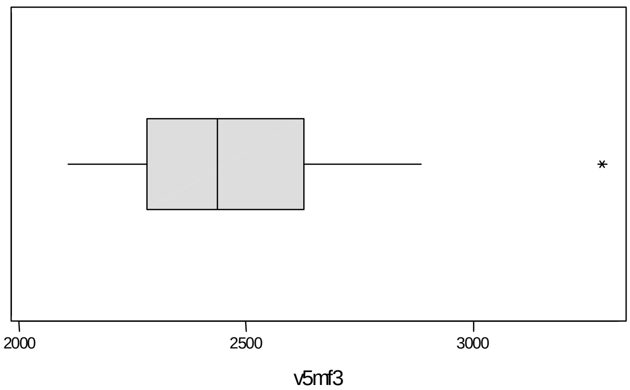
**Descriptive Statistics**

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5mf3 | 52 | 18 | 2459.7 | 2437.0 | 2446.5 | 239.0 | 33.1 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5mf3 | 2108.0 | 3284.0 | 2281.0 | 2627.0 |

* NOTE * N missing = 18

Boxplot of v5mf3



# FEMALE

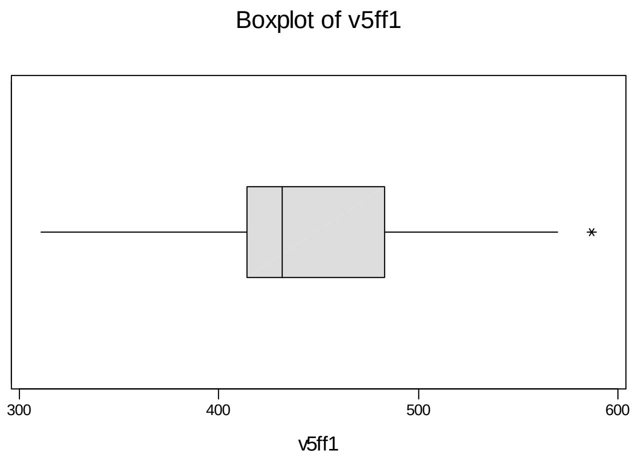
## F1

## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5ff1 | 59 | 1 | 451.34 | 432.00 | 449.98 | 55.47 | 7.22 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5ff1 | 311.00 | 587.00 | 414.00 | 483.00 |

* NOTE * N missing = 1



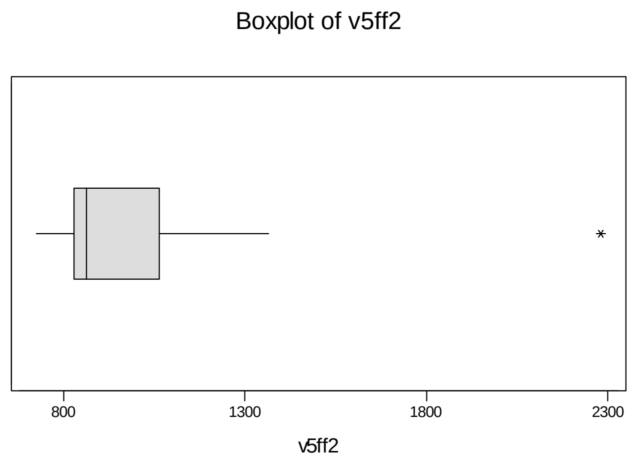

## F2

## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5ff2 | 57 | 3 | 954.7 | 864.0 | 925.4 | 237.7 | 31.5 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5ff2 | 725.0 | 2281.0 | 829.0 | 1062.5 |

* NOTE * N missing = 3



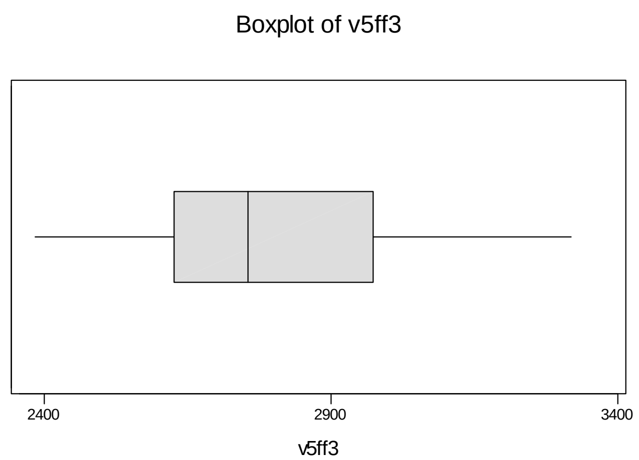

**F3**

## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5ff3 | 58 | 12 | 2803.6 | 2756.5 | 2799.7 | 227.0 | 29.8 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5ff3 | 2385.0 | 3318.0 | 2627.0 | 2973.0 |

* NOTE * N missing = 12



# CHILD

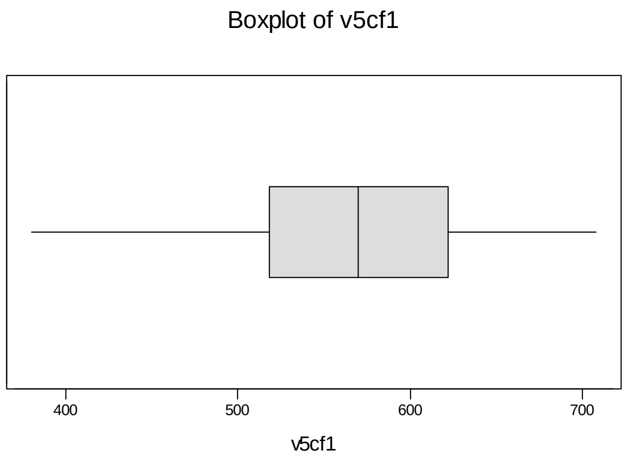
## F1

### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5cf1 | 56 | 4 | 560.3 | 570.0 | 562.3 | 77.2 | 10.3 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5cf1 | 380.0 | 708.0 | 518.0 | 622.0 |

* NOTE * N missing = 4




## F2

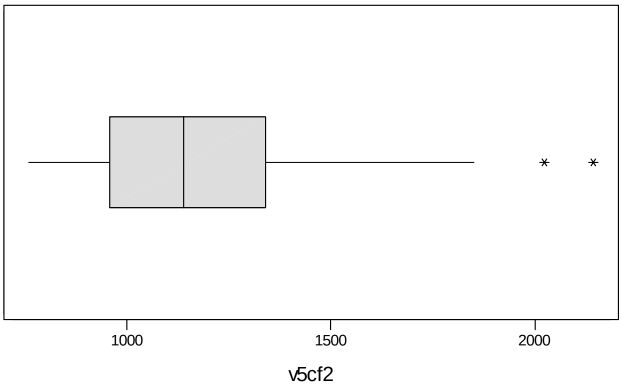
### Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5cf2 | 53 | 7 | 1189.9 | 1140.0 | 1162.8 | 292.2 | 40.1 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5cf2 | 760.0 | 2143.0 | 958.5 | 1339.0 |

* NOTE * N missing = 7

Boxplot of v5cf2




**F3**

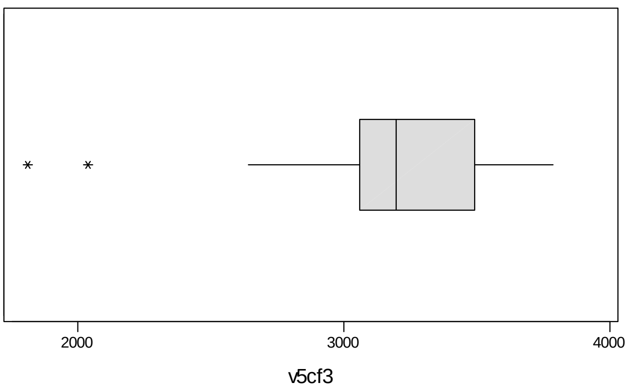
## Descriptive Statistics

| Variable | N | N* | Mean | Median | Tr Mean | StDev | SE Mean |
|---|---|---|---|---|---|---|---|
| v5cf3 | 31 | 39 | 3172.2 | 3197.0 | 3224.1 | 441.4 | 79.3 |

| Variable | Min | Max | Q1 | Q3 |
|---|---|---|---|---|
| v5cf3 | 1814.0 | 3785.0 | 3059.0 | 3491.0 |

* NOTE * N missing = 39

Boxplot of v5cf3



# Appendix 6: Regression Analysis Results

## VOWEL [i]

**Regression Analysis**

The regression equation is

**cfreqv1 = 43.6 + 0.482 mfreqv1 + 0.731 ffreqv1**

410 cases used 40 cases contain missing values

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 43.56 | 25.68 | 1.70 | 0.091 |
| mfreqv1 | 0.48197 | 0.07324 | 6.58 | 0.000 |
| ffreqv1 | 0.73106 | 0.05975 | 12.24 | 0.000 |

S = 253.9    R-Sq = 96.3%    R-Sq(adj) = 96.3%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 688588487 | 344294244 | 5339.53 | 0.000 |
| Error | 407 | 26243440 | 64480 | | |
| Total | 409 | 714831928 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mfreqv1 | 1 | 678934075 |
| ffreqv1 | 1 | 9654413 |

Unusual Observations

| Obs | mfreqv1 | cfreqv1 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 20 | 1763 | 3094.0 | 2952.7 | 42.8 | 141.3 | 0.56 X |
| 21 | 2281 | 3733.0 | 3581.8 | 37.7 | 151.2 | 0.60 X |
| 50 | 2437 | 1849.0 | 3353.6 | 16.1 | -1504.6 | -5.94R |
| 51 | 2782 | 3405.0 | 4088.6 | 27.9 | -683.6 | -2.71R |
| 87 | 3007 | 3595.0 | 3564.7 | 52.3 | 30.3 | 0.12 X |
| 95 | 2506 | 2489.0 | 3196.7 | 27.5 | -707.7 | -2.80R |
| 96 | 2903 | 3042.0 | 3779.9 | 27.6 | -737.9 | -2.92R |
| 141 | 3301 | 3768.0 | 4009.8 | 50.6 | -241.8 | -0.97 X |
| 149 | 1970 | 2074.0 | 2901.1 | 18.9 | -827.1 | -3.27R |
| 162 | 1661 | 3508.0 | 2979.5 | 55.9 | 528.5 | 2.13RX |
| 275 | 2143 | 1434.0 | 3135.8 | 19.4 | -1701.8 | -6.72R |
| 299 | 1209 | 1365.0 | 2597.2 | 74.9 | -1232.2 | -5.08RX |
| 300 | 2229 | 3681.0 | 3543.5 | 40.0 | 137.5 | 0.55 X |
| 365 | 2644 | 1296.0 | 3288.8 | 34.7 | -1992.8 | -7.92R |
| 366 | 3180 | 3059.0 | 3963.9 | 41.6 | -904.9 | -3.61RX |
| 437 | 1745 | 3197.0 | 2463.7 | 12.9 | 733.3 | 2.89R |
| 438 | 2419 | 3992.0 | 3281.3 | 16.7 | 710.7 | 2.81R |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

# VOWEL [e]

**Regression Analysis**

The regression equation is

**cfreqv2 = - 88.7 + 0.369 mfreqv2 + 0.891 ffreqv2**

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -88.74 | 18.03 | -4.92 | 0.000 |
| mfreqv2 | 0.36913 | 0.04471 | 8.26 | 0.000 |
| ffreqv2 | 0.89054 | 0.03699 | 24.07 | 0.000 |

S = 179.8 R-Sq = 97.7% R-Sq(adj) = 97.7%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 707069229 | 353534615 | 10932.21 | 0.000 |
| Error | 507 | 16395775 | 32339 | | |
| Total | 509 | 723465005 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mfreqv2 | 1 | 688329076 |
| ffreqv2 | 1 | 18740154 |

Unusual Observations

| Obs | mfreqv2 | cfreqv2 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 44 | 1676 | 2731.00 | 2869.36 | 24.13 | -138.36 | -0.78 X |
| 59 | 1918 | 2264.00 | 2650.56 | 8.38 | -386.56 | -2.15R |
| 60 | 2627 | 3889.00 | 3420.77 | 16.14 | 468.23 | 2.61R |
| 61 | 691 | 483.00 | 889.44 | 12.40 | -406.44 | -2.27R |
| 72 | 2713 | 3871.00 | 3406.21 | 20.67 | 464.79 | 2.60R |
| 81 | 2817 | 3768.00 | 3398.29 | 26.43 | 369.71 | 2.08RX |
| 87 | 2800 | 3595.00 | 3330.57 | 27.92 | 264.43 | 1.49 X |
| 90 | 2782 | 3681.00 | 3370.23 | 25.52 | 310.77 | 1.75 X |
| 101 | 1814 | 2679.00 | 2242.60 | 13.98 | 436.40 | 2.43R |
| 102 | 2696 | 3871.00 | 3368.77 | 21.02 | 502.23 | 2.81R |
| 104 | 1676 | 2765.00 | 2376.89 | 8.30 | 388.11 | 2.16R |
| 108 | 2713 | 3076.00 | 3529.10 | 17.01 | -453.10 | -2.53R |
| 111 | 2852 | 3128.00 | 3611.58 | 21.12 | -483.58 | -2.71R |
| 114 | 2748 | 3145.00 | 3588.33 | 16.96 | -443.33 | -2.48R |
| 117 | 2834 | 3128.00 | 3588.91 | 20.94 | -460.91 | -2.58R |
| 123 | 2748 | 3232.00 | 3634.64 | 15.84 | -402.64 | -2.25R |
| 126 | 2765 | 3145.00 | 3563.44 | 18.40 | -418.44 | -2.34R |
| 129 | 2748 | 3128.00 | 3542.02 | 18.23 | -414.02 | -2.31R |
| 135 | 2834 | 3197.00 | 3573.77 | 21.41 | -376.77 | -2.11R |
| 138 | 2748 | 2990.00 | 3526.88 | 18.66 | -536.88 | -3.00R |
| 140 | 1676 | 2713.00 | 2299.42 | 8.02 | 413.58 | 2.30R |
| 150 | 2921 | 2973.00 | 3529.30 | 27.46 | -556.30 | -3.13RX |
| 153 | 2782 | 3007.00 | 3523.41 | 20.41 | -516.41 | -2.89R |
| 165 | 2575 | 3145.00 | 3601.06 | 11.96 | -456.06 | -2.54R |
| 177 | 2713 | 3215.00 | 3575.41 | 15.83 | -360.41 | -2.01R |
| 183 | 2696 | 3145.00 | 3522.83 | 16.44 | -377.83 | -2.11R |
| 206 | 1763 | 2091.00 | 2485.59 | 8.21 | -394.59 | -2.20R |
| 227 | 1693 | 2039.00 | 2474.89 | 9.62 | -435.89 | -2.43R |

| | | | | | | |
|---|---|---|---|---|---|---|
| 234 | 2368 | 3699.00 | 3325.17 | 10.58 | 373.83 | 2.08R |
| 243 | 2177 | 3681.00 | 3238.64 | 12.75 | 442.36 | 2.47R |
| 255 | 2281 | 3664.00 | 3261.89 | 10.57 | 402.11 | 2.24R |
| 308 | 1849 | 2938.00 | 2548.51 | 8.21 | 389.49 | 2.17R |
| 319 | 1088 | 691.00 | 1066.26 | 19.96 | -375.26 | -2.10R |
| 323 | 1123 | 2834.00 | 2403.42 | 37.27 | 430.58 | 2.45RX |
| 329 | 1486 | 2765.00 | 2614.00 | 24.75 | 151.00 | 0.85 X |
| 330 | 2091 | 3716.00 | 3637.91 | 31.55 | 78.09 | 0.44 X |
| 333 | 2748 | 3750.00 | 3357.68 | 24.13 | 392.32 | 2.20RX |
| 344 | 1434 | 2834.00 | 2410.46 | 19.79 | 423.54 | 2.37R |
| 383 | 1866 | 2696.00 | 2308.10 | 14.33 | 387.90 | 2.16R |
| 404 | 1745 | 2333.00 | 2894.83 | 21.33 | -561.83 | -3.15R |
| 405 | 2298 | 3215.00 | 3668.01 | 21.77 | -453.01 | -2.54R |
| 473 | 1763 | 2108.00 | 2716.24 | 13.85 | -608.24 | -3.39R |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

## VOWEL [a]

### Regression Analysis

The regression equation is

**cfreqv3 = - 93.4 + 0.760 mfreqv3 + 0.506 ffreqv3**

664 cases used 16 cases contain missing values

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -93.44 | 28.90 | -3.23 | 0.001 |
| mfreqv3 | 0.75957 | 0.05549 | 13.69 | 0.000 |
| ffreqv3 | 0.50607 | 0.05197 | 9.74 | 0.000 |

S = 299.2     R-Sq = 90.5%     R-Sq(adj) = 90.5%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 562762920 | 281381460 | 3143.82 | 0.000 |
| Error | 661 | 59161468 | 89503 | | |
| Total | 663 | 621924388 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mfreqv3 | 1 | 554276432 |
| ffreqv3 | 1 | 8486488 |

Unusual Observations

| Obs | mfreqv3 | cfreqv3 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 3 | 2454 | 3560.0 | 3441.1 | 37.4 | 118.9 | 0.40 X |
| 29 | 2281 | 3163.0 | 3248.5 | 39.0 | -85.5 | -0.29 X |
| 50 | 2108 | 3439.0 | 3012.3 | 36.8 | 426.7 | 1.44 X |
| 58 | 1417 | 1140.0 | 1831.1 | 12.1 | -691.1 | -2.31R |

| | | | | | | |
|---|---|---|---|---|---|---|
| 59 | 2368 | 2177.0 | 3375.8 | 41.0 | -1198.8 | -4.05RX |
| 68 | 1935 | 3111.0 | 2915.8 | 48.3 | 195.2 | 0.66 X |
| 71 | 2834 | * | 3353.7 | 35.8 | * | * X |
| 77 | 2817 | 3664.0 | 3279.6 | 39.8 | 384.4 | 1.30 X |
| 85 | 2713 | 3094.0 | 3191.5 | 35.3 | -97.5 | -0.33 X |
| 88 | 2713 | 3629.0 | 3165.7 | 37.4 | 463.3 | 1.56 X |
| 91 | 2644 | 3439.0 | 3086.9 | 36.0 | 352.1 | 1.19 X |
| 94 | 2834 | 3716.0 | 3248.5 | 44.4 | 467.5 | 1.58 X |
| 103 | 2869 | 2955.0 | 3310.0 | 43.2 | -355.0 | -1.20 X |
| 106 | 2679 | 3353.0 | 3122.1 | 37.1 | 230.9 | 0.78 X |
| 112 | 2852 | 3422.0 | 3332.5 | 39.4 | 89.5 | 0.30 X |
| 115 | 2713 | 3889.0 | 3165.7 | 37.4 | 723.3 | 2.44RX |
| 118 | 2713 | 3405.0 | 3174.3 | 36.7 | 230.7 | 0.78 X |
| 121 | 2765 | 3422.0 | 3178.8 | 42.3 | 243.2 | 0.82 X |
| 124 | 2765 | 3647.0 | 3187.4 | 41.5 | 459.6 | 1.55 X |
| 127 | 2748 | 3612.0 | 3192.2 | 39.1 | 419.8 | 1.42 X |
| 130 | 2765 | 3612.0 | 3222.4 | 38.6 | 389.6 | 1.31 X |
| 133 | 2713 | 3439.0 | 3147.9 | 38.8 | 291.1 | 0.98 X |
| 136 | 2575 | 3387.0 | 2999.6 | 35.4 | 387.4 | 1.30 X |
| 139 | 2869 | 2540.0 | 3529.1 | 27.8 | -989.1 | -3.32R |
| 141 | 1659 | 1348.0 | 2041.2 | 13.8 | -693.2 | -2.32R |
| 142 | 2852 | 2039.0 | 3507.1 | 27.6 | -1468.1 | -4.93R |
| 167 | 1521 | 1123.0 | 1901.4 | 12.1 | -778.4 | -2.60R |
| 168 | 2471 | 1918.0 | 3200.5 | 19.9 | -1282.5 | -4.30R |
| 171 | 2817 | 2212.0 | 3428.4 | 29.0 | -1216.4 | -4.09R |
| 183 | 2834 | 2540.0 | 3458.5 | 28.7 | -918.5 | -3.08R |
| 227 | 2610 | 2523.0 | 3034.8 | 36.5 | -511.8 | -1.72 X |
| 275 | 2281 | 3578.0 | 2977.2 | 18.3 | 600.8 | 2.01R |
| 281 | 2177 | 3647.0 | 2740.8 | 16.0 | 906.2 | 3.03R |
| 298 | 2212 | 3647.0 | 2942.5 | 20.5 | 704.5 | 2.36R |
| 301 | 2298 | 3647.0 | 2963.8 | 17.4 | 683.2 | 2.29R |
| 304 | 2316 | 3716.0 | 3012.4 | 18.3 | 703.6 | 2.36R |
| 313 | 2229 | 3612.0 | 2894.2 | 17.1 | 717.8 | 2.40R |
| 322 | 2368 | 3612.0 | 2982.0 | 18.2 | 630.0 | 2.11R |
| 328 | 2229 | 3647.0 | 2911.4 | 17.8 | 735.6 | 2.46R |
| 331 | 2177 | 3595.0 | 2915.9 | 21.4 | 679.1 | 2.28R |
| 334 | 2229 | 3647.0 | 2981.7 | 21.8 | 665.3 | 2.23R |
| 340 | 2056 | 3439.0 | 2675.2 | 15.5 | 763.8 | 2.56R |
| 365 | 1451 | 2644.0 | 1760.7 | 14.6 | 883.3 | 2.96R |
| 410 | 1642 | 1140.0 | 2019.7 | 13.8 | -879.7 | -2.94R |
| 411 | 2143 | 3232.0 | 3125.9 | 43.5 | 106.1 | 0.36 X |
| 431 | 1953 | 3128.0 | 2841.9 | 38.8 | 286.1 | 0.96 X |
| 436 | 1590 | 1400.0 | 2093.5 | 13.7 | -693.5 | -2.32R |
| 439 | 1538 | 1400.0 | 2045.4 | 14.7 | -645.4 | -2.16R |
| 446 | 1884 | 3318.0 | 2570.9 | 21.9 | 747.1 | 2.50R |
| 451 | 1590 | 1365.0 | 2137.6 | 16.5 | -772.6 | -2.59R |
| 455 | 2091 | 3612.0 | 3121.8 | 49.3 | 490.2 | 1.66 X |
| 467 | 2074 | 2852.0 | 3064.9 | 45.8 | -212.9 | -0.72 X |
| 496 | 2558 | 2661.0 | 3354.1 | 22.5 | -693.1 | -2.32R |
| 499 | 2195 | 3094.0 | 3148.2 | 39.5 | -54.2 | -0.18 X |
| 535 | 2091 | 2782.0 | 3051.5 | 42.5 | -269.5 | -0.91 X |
| 553 | 2350 | 3612.0 | 2959.8 | 17.9 | 652.2 | 2.18R |
| 594 | 2350 | 3612.0 | 2907.1 | 19.7 | 704.9 | 2.36R |
| 597 | 2247 | 3629.0 | 2942.8 | 18.4 | 686.2 | 2.30R |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

# **VOWEL [o]**

## Regression Analysis

The regression equation is

**cfreqv4 = 13.8 + 0.631 mfreqv4 + 0.579 ffreqv4**

485 cases used 85 cases contain missing values

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 13.81 | 23.27 | 0.59 | 0.553 |
| mfreqv4 | 0.63128 | 0.05743 | 10.99 | 0.000 |
| ffreqv4 | 0.57888 | 0.05039 | 11.49 | 0.000 |

S = 261.9    R-Sq = 93.8%    R-Sq(adj) = 93.8%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 498220247 | 249110123 | 3632.03 | 0.000 |
| Error | 482 | 33058961 | 68587 | | |
| Total | 484 | 531279208 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mfreqv4 | 1 | 489169152 |
| ffreqv4 | 1 | 9051095 |

Unusual Observations

| Obs | mfreqv4 | cfreqv4 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 17 | 1106 | 2696.0 | 1422.3 | 12.4 | 1273.7 | 4.87R |
| 27 | 2177 | * | 3149.1 | 36.4 | * | * X |
| 35 | 1227 | 2195.0 | 1558.3 | 12.1 | 636.7 | 2.43R |
| 51 | 2298 | 3163.0 | 3285.1 | 35.7 | -122.1 | -0.47 X |
| 63 | 2834 | * | 3303.3 | 37.3 | * | * X |
| 71 | 1348 | 2333.0 | 1584.9 | 17.4 | 748.1 | 2.86R |
| 84 | 2765 | * | 3149.8 | 41.1 | * | * X |
| 87 | 2817 | 3716.0 | 3262.5 | 38.4 | 453.5 | 1.75 X |
| 90 | 2748 | 3457.0 | 3169.1 | 38.2 | 287.9 | 1.11 X |
| 99 | 2886 | 3094.0 | 3246.4 | 46.0 | -152.4 | -0.59 X |
| 108 | 2938 | 3629.0 | 3329.0 | 45.3 | 300.0 | 1.16 X |
| 111 | 2782 | 3785.0 | 3250.8 | 35.9 | 534.2 | 2.06RX |
| 114 | 2903 | 3215.0 | 3257.2 | 46.9 | -42.2 | -0.16 X |
| 128 | 1486 | 1365.0 | 2132.2 | 23.1 | -767.2 | -2.94R |
| 144 | 2886 | 2938.0 | 3526.6 | 29.5 | -588.6 | -2.26R |
| 198 | 2713 | * | 3086.8 | 40.5 | * | * X |
| 200 | 1019 | 2419.0 | 1207.0 | 15.8 | 1212.0 | 4.64R |
| 201 | 2921 | 3595.0 | 3338.6 | 43.0 | 256.4 | 0.99 X |
| 207 | 2506 | 2454.0 | 3126.4 | 22.2 | -672.4 | -2.58R |
| 212 | 1054 | 1849.0 | 1249.4 | 15.8 | 599.6 | 2.29R |
| 222 | 2886 | 2558.0 | 3326.3 | 40.5 | -768.3 | -2.97RX |
| 228 | 2765 | 3266.0 | 3229.7 | 35.8 | 36.3 | 0.14 X |
| 231 | 2039 | 3681.0 | 2891.8 | 29.5 | 789.2 | 3.03R |
| 237 | 1918 | 3629.0 | 2635.3 | 21.6 | 993.7 | 3.81R |

| | | | | | | |
|---|---|---|---|---|---|---|
| 240 | 2195 | 3681.0 | 3030.2 | 26.3 | 650.8 | 2.50R |
| 252 | 1935 | 3578.0 | 2756.1 | 28.6 | 821.9 | 3.16R |
| 258 | 2091 | 3733.0 | 2924.6 | 27.4 | 808.4 | 3.10R |
| 261 | 2091 | 3664.0 | 2674.5 | 16.5 | 989.5 | 3.79R |
| 270 | 2126 | 2938.0 | 3147.0 | 41.0 | -209.0 | -0.81 X |
| 276 | 1901 | 3353.0 | 2864.9 | 40.4 | 488.1 | 1.89 X |
| 279 | 2091 | 3612.0 | 2924.6 | 27.4 | 687.4 | 2.64R |
| 320 | 1175 | 2419.0 | 1496.0 | 12.2 | 923.0 | 3.53R |
| 342 | 2264 | 3648.0 | 2853.8 | 18.7 | 794.2 | 3.04R |
| 345 | 2126 | * | 3196.8 | 45.0 | * | * X |
| 348 | 2108 | 2852.0 | 3185.4 | 45.8 | -333.4 | -1.29 X |
| 353 | 2039 | 1417.0 | 2011.3 | 54.3 | -594.3 | -2.32RX |
| 381 | 2056 | 3560.0 | 2972.5 | 34.0 | 587.5 | 2.26R |
| 387 | 2108 | * | 3175.6 | 45.0 | * | * X |
| 393 | 2039 | 2903.0 | 2991.9 | 37.1 | -88.9 | -0.34 X |
| 434 | 1244 | 950.0 | 1769.3 | 19.0 | -819.3 | -3.14R |
| 453 | 2454 | 2696.0 | 3293.8 | 24.9 | -597.8 | -2.29R |
| 456 | 2195 | 2679.0 | 3350.3 | 50.6 | -671.3 | -2.61RX |
| 501 | 2160 | 3180.0 | 3158.0 | 38.6 | 22.0 | 0.08 X |
| 527 | 1451 | 2679.0 | 1940.0 | 13.8 | 739.0 | 2.83R |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

## VOWEL [u]

## Regression Analysis

The regression equation is

**cfreqv5 = 42.6 + 0.963 mfreqv5 + 0.262 ffreqv5**

126 cases used 64 cases contain missing values

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 42.58 | 44.56 | 0.96 | 0.341 |
| mfreqv5 | 0.9627 | 0.1510 | 6.37 | 0.000 |
| ffreqv5 | 0.2623 | 0.1243 | 2.11 | 0.037 |

S = 289.4   R-Sq = 91.1%   R-Sq(adj) = 91.0%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 105991631 | 52995816 | 632.85 | 0.000 |
| Error | 123 | 10300144 | 83741 | | |
| Total | 125 | 116291775 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mfreqv5 | 1 | 105618767 |
| ffreqv5 | 1 | 372865 |

Unusual Observations

| Obs | mfreqv5 | cfreqv5 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 13 | 3284 | * | 3961.0 | 142.6 | * | * X |
| 20 | 2281 | 2039.0 | 2864.0 | 60.5 | -825.0 | -2.92R |
| 35 | 2679 | * | 3337.9 | 79.4 | * | * X |
| 39 | 2264 | 1814.0 | 3074.3 | 97.1 | -1260.3 | -4.62RX |
| 42 | 2834 | * | 3523.3 | 86.8 | * | * X |
| 45 | 2886 | * | 3573.4 | 92.7 | * | * X |
| 48 | 2834 | * | 3491.6 | 96.1 | * | * X |
| 57 | 2627 | * | 3260.6 | 81.1 | * | * X |
| 61 | 2696 | 3145.0 | 3331.4 | 87.9 | -186.4 | -0.68 X |
| 64 | 2748 | * | 3377.0 | 95.7 | * | * X |
| 67 | 2627 | * | 3246.9 | 85.1 | * | * X |
| 70 | 2610 | * | 3235.0 | 81.8 | * | * X |
| 75 | 604 | 1469.0 | 814.2 | 31.2 | 654.8 | 2.28R |
| 80 | 2160 | 3612.0 | 2819.9 | 54.9 | 792.1 | 2.79R |
| 83 | 2108 | 3629.0 | 2801.6 | 66.7 | 827.4 | 2.94R |
| 86 | 2247 | 3629.0 | 2917.3 | 55.1 | 711.7 | 2.51R |
| 88 | 691 | 1849.0 | 925.2 | 30.0 | 923.8 | 3.21R |
| 99 | 2696 | 3629.0 | 3358.7 | 80.1 | 270.3 | 0.97 X |
| 124 | 2281 | * | 3072.5 | 88.3 | * | * X |
| 134 | 2627 | 2731.0 | 3441.8 | 74.2 | -710.8 | -2.54R |
| 146 | 2160 | * | 2901.8 | 79.7 | * | * X |
| 151 | 1192 | 881.0 | 1788.4 | 121.4 | -907.4 | -3.45RX |
| 153 | 2143 | 3094.0 | 2876.2 | 77.9 | 217.8 | 0.78 X |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

## ALL VOWELS

## Regression Analysis

The regression equation is

**cvowels = - 39.4 + 0.568 mvowels + 0.678 fvowels**

2195 cases used 205 cases contain missing values

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -39.36 | 11.89 | -3.31 | 0.001 |
| mvowels | 0.56763 | 0.02821 | 20.12 | 0.000 |
| fvowels | 0.67832 | 0.02387 | 28.42 | 0.000 |

S = 266.1       R-Sq = 94.7%     R-Sq(adj) = 94.7%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 2 | 2756517156 | 1378258578 | 19470.56 | 0.000 |
| Error | 2192 | 155164655 | 70787 | | |
| Total | 2194 | 2911681811 | | | |

| Source | DF | Seq SS |
|---|---|---|
| mvowels | 1 | 2699341709 |
| fvowels | 1 | 57175447 |

Unusual Observations

| Obs | mvowels | cvowels | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 20 | 1763 | 3094.00 | 2872.21 | 19.41 | 221.79 | 0.84 X |
| 21 | 2281 | 3733.00 | 3518.29 | 18.41 | 214.71 | 0.81 X |
| 26 | 1659 | 3076.00 | 2520.14 | 12.43 | 555.86 | 2.09R |
| 50 | 2437 | 1849.00 | 3325.33 | 8.89 | -1476.33 | -5.55R |
| 51 | 2782 | 3405.00 | 4048.90 | 15.63 | -643.90 | -2.42R |
| 87 | 3007 | 3595.00 | 3589.87 | 19.16 | 5.13 | 0.02 X |
| 95 | 2506 | 2489.00 | 3188.14 | 10.48 | -699.14 | -2.63R |
| 96 | 2903 | 3042.00 | 3777.06 | 11.70 | -735.06 | -2.77R |
| 141 | 3301 | 3768.00 | 4038.25 | 18.97 | -270.25 | -1.02 X |
| 149 | 1970 | 2074.00 | 2849.29 | 10.20 | -775.29 | -2.92R |
| 162 | 1661 | 3508.00 | 2884.85 | 24.44 | 623.15 | 2.35RX |
| 275 | 2143 | 1434.00 | 3087.90 | 10.79 | -1653.90 | -6.22R |
| 299 | 1209 | 1365.00 | 2475.66 | 31.34 | -1110.66 | -4.20RX |
| 300 | 2229 | 3681.00 | 3476.56 | 19.22 | 204.44 | 0.77 X |
| 365 | 2644 | 1296.00 | 3290.21 | 12.85 | -1994.21 | -7.50R |
| 366 | 3180 | 3059.00 | 3981.10 | 15.98 | -922.10 | -3.47R |
| 437 | 1745 | 3197.00 | 2416.33 | 6.75 | 780.67 | 2.94R |
| 438 | 2419 | 3992.00 | 3256.10 | 8.48 | 735.90 | 2.77R |
| 494 | 1676 | 2731.00 | 2693.94 | 17.32 | 37.06 | 0.14 X |
| 600 | 2921 | 2973.00 | 3553.26 | 16.70 | -580.26 | -2.19R |
| 693 | 2177 | 3681.00 | 3118.74 | 10.50 | 562.26 | 2.11R |
| 773 | 1123 | 2834.00 | 2180.62 | 25.23 | 653.38 | 2.47RX |
| 774 | 2229 | 3716.00 | 3418.22 | 17.35 | 297.78 | 1.12 X |
| 779 | 1486 | 2765.00 | 2445.00 | 17.51 | 320.00 | 1.21 X |
| 780 | 2091 | 3716.00 | 3398.23 | 22.56 | 317.77 | 1.20 X |
| 794 | 1434 | 2834.00 | 2275.07 | 14.23 | 558.93 | 2.10R |
| 978 | 777 | 587.00 | 1174.98 | 9.35 | -587.98 | -2.21R |
| 1018 | 1417 | 1140.00 | 1901.84 | 5.76 | -761.84 | -2.86R |
| 1019 | 2368 | 2177.00 | 3543.93 | 15.77 | -1366.93 | -5.15R |
| 1027 | 1330 | 1158.00 | 1817.18 | 6.11 | -659.18 | -2.48R |
| 1028 | 1935 | 3111.00 | 3122.46 | 20.18 | -11.46 | -0.04 X |
| 1031 | 2834 | * | 3304.45 | 20.09 | * | * X |
| 1034 | 2800 | 3629.00 | 3296.68 | 18.87 | 332.32 | 1.25 X |
| 1037 | 2817 | 3664.00 | 3212.72 | 22.13 | 451.28 | 1.70 X |
| 1042 | 2575 | 3595.00 | 2969.54 | 18.94 | 625.46 | 2.36RX |
| 1045 | 2713 | 3094.00 | 3141.48 | 19.74 | -47.48 | -0.18 X |
| 1048 | 2713 | 3629.00 | 3106.89 | 20.80 | 522.11 | 1.97 X |
| 1051 | 2644 | 3439.00 | 3032.45 | 20.04 | 406.55 | 1.53 X |
| 1054 | 2834 | 3716.00 | 3163.36 | 24.44 | 552.64 | 2.09RX |
| 1063 | 2869 | 2955.00 | 3230.03 | 23.91 | -275.03 | -1.04 X |
| 1066 | 2679 | 3353.00 | 3063.85 | 20.62 | 289.15 | 1.09 X |
| 1069 | 2817 | 3560.00 | 3306.33 | 19.31 | 253.67 | 0.96 X |
| 1072 | 2852 | 3422.00 | 3267.86 | 21.99 | 154.14 | 0.58 X |
| 1075 | 2713 | 3889.00 | 3106.89 | 20.80 | 782.11 | 2.95RX |
| 1078 | 2713 | 3405.00 | 3118.42 | 20.44 | 286.58 | 1.08 X |
| 1081 | 2765 | 3422.00 | 3101.13 | 23.30 | 320.87 | 1.21 X |
| 1084 | 2765 | 3647.00 | 3112.66 | 22.93 | 534.34 | 2.02RX |
| 1087 | 2748 | 3612.00 | 3126.75 | 21.73 | 485.25 | 1.83 X |
| 1090 | 2765 | 3612.00 | 3159.47 | 21.48 | 452.53 | 1.71 X |
| 1093 | 2713 | 3439.00 | 3083.15 | 21.53 | 355.85 | 1.34 X |
| 1096 | 2575 | 3387.00 | 2946.48 | 19.65 | 440.52 | 1.66 X |
| 1099 | 2869 | 2540.00 | 3523.74 | 15.46 | -983.74 | -3.70R |
| 1101 | 1659 | 1348.00 | 2074.48 | 7.42 | -726.48 | -2.73R |
| 1102 | 2852 | 2039.00 | 3501.88 | 15.36 | -1462.88 | -5.51R |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1127 | 1521 | 1123.00 | 1949.34 | 6.22 | -826.34 | -3.11R |
| 1128 | 2471 | 1918.00 | 3262.56 | 8.79 | -1344.56 | -5.06R |
| 1130 | 1555 | 1365.00 | 1968.64 | 6.66 | -603.64 | -2.27R |
| 1131 | 2817 | 2212.00 | 3412.15 | 16.33 | -1200.15 | -4.52R |
| 1136 | 1486 | 1313.00 | 1941.01 | 5.80 | -628.01 | -2.36R |
| 1140 | 2782 | 2921.00 | 3310.21 | 17.72 | -389.21 | -1.47 X |
| 1143 | 2834 | 2540.00 | 3444.86 | 16.13 | -904.86 | -3.41R |
| 1148 | 1417 | 1227.00 | 1772.96 | 6.88 | -545.96 | -2.05R |
| 1154 | 1365 | 1313.00 | 1896.07 | 6.49 | -583.07 | -2.19R |
| 1155 | 2247 | 2523.00 | 3146.94 | 9.23 | -623.94 | -2.35R |
| 1180 | 1590 | 1607.00 | 2141.13 | 5.78 | -534.13 | -2.01R |
| 1187 | 2610 | 2523.00 | 2977.88 | 20.23 | -454.88 | -1.71 X |
| 1198 | 1659 | 1521.00 | 2168.09 | 5.93 | -647.09 | -2.43R |
| 1207 | 1624 | 1555.00 | 2125.16 | 5.86 | -570.16 | -2.14R |
| 1208 | 2627 | 3318.00 | 3092.66 | 17.48 | 225.34 | 0.85 X |
| 1211 | 2852 | 2903.00 | 3443.55 | 16.88 | -540.55 | -2.04R |
| 1241 | 2177 | 3647.00 | 2778.90 | 8.51 | 868.10 | 3.26R |
| 1249 | 2402 | 3578.00 | 3023.96 | 10.53 | 554.04 | 2.08R |
| 1258 | 2212 | 3647.00 | 3033.46 | 7.98 | 613.54 | 2.31R |
| 1261 | 2298 | 3647.00 | 3023.26 | 7.98 | 623.74 | 2.35R |
| 1264 | 2316 | 3716.00 | 3080.29 | 7.93 | 635.71 | 2.39R |
| 1273 | 2229 | 3612.00 | 2961.04 | 7.53 | 650.96 | 2.45R |
| 1282 | 2368 | 3612.00 | 3016.19 | 9.63 | 595.81 | 2.24R |
| 1288 | 2229 | 3647.00 | 2984.10 | 7.52 | 662.90 | 2.49R |
| 1291 | 2177 | 3595.00 | 3013.60 | 8.24 | 581.40 | 2.19R |
| 1294 | 2229 | 3647.00 | 3078.39 | 8.37 | 568.61 | 2.14R |
| 1297 | 2437 | 3647.00 | 3090.63 | 10.27 | 556.37 | 2.09R |
| 1300 | 2056 | 3439.00 | 2745.49 | 6.80 | 693.51 | 2.61R |
| 1305 | 1642 | 1572.00 | 2170.65 | 5.77 | -598.65 | -2.25R |
| 1317 | 2575 | 3128.00 | 2993.28 | 18.21 | 134.72 | 0.51 X |
| 1325 | 1451 | 2644.00 | 1792.26 | 7.42 | 851.74 | 3.20R |
| 1370 | 1642 | 1140.00 | 2053.30 | 7.37 | -913.30 | -3.43R |
| 1371 | 2143 | 3232.00 | 3310.39 | 17.44 | -78.39 | -0.30 X |
| 1376 | 1521 | 1417.00 | 2019.89 | 5.68 | -602.89 | -2.27R |
| 1377 | 2229 | 2350.00 | 3030.90 | 7.78 | -680.90 | -2.56R |
| 1396 | 1590 | 1400.00 | 2175.73 | 6.10 | -775.73 | -2.92R |
| 1399 | 1538 | 1400.00 | 2134.68 | 6.51 | -734.68 | -2.76R |
| 1402 | 1486 | 1417.00 | 2105.16 | 7.31 | -688.16 | -2.59R |
| 1403 | 2316 | 2679.00 | 3385.53 | 13.05 | -706.53 | -2.66R |
| 1406 | 1884 | 3318.00 | 2683.13 | 8.71 | 634.87 | 2.39R |
| 1411 | 1590 | 1365.00 | 2234.74 | 7.10 | -869.74 | -3.27R |
| 1414 | 1555 | 1400.00 | 2015.45 | 5.97 | -615.45 | -2.31R |
| 1415 | 2091 | 3612.00 | 3328.36 | 20.23 | 283.64 | 1.07 X |
| 1417 | 1451 | 1313.00 | 1980.15 | 5.99 | -667.15 | -2.51R |
| 1426 | 1486 | 1348.00 | 2011.55 | 5.83 | -663.55 | -2.49R |
| 1427 | 2074 | 2852.00 | 3259.70 | 18.70 | -407.70 | -1.54 X |
| 1429 | 1538 | 1434.00 | 1982.06 | 6.09 | -548.06 | -2.06R |
| 1435 | 1434 | 1365.00 | 2017.31 | 6.95 | -652.31 | -2.45R |
| 1456 | 2558 | 2661.00 | 3429.29 | 9.17 | -768.29 | -2.89R |
| 1477 | 2558 | 2765.00 | 3358.74 | 9.38 | -593.74 | -2.23R |
| 1480 | 2454 | 2731.00 | 3311.24 | 8.70 | -580.24 | -2.18R |
| 1495 | 2091 | 2782.00 | 3234.07 | 17.15 | -452.07 | -1.70 X |
| 1513 | 2350 | 3612.00 | 2994.45 | 9.51 | 617.55 | 2.32R |
| 1518 | 2471 | 3629.00 | 3039.39 | 12.62 | 589.61 | 2.22R |
| 1554 | 2350 | 3612.00 | 2923.90 | 11.02 | 688.10 | 2.59R |
| 1557 | 2247 | 3629.00 | 3018.06 | 7.63 | 610.94 | 2.30R |
| 1603 | 1313 | 1279.00 | 1983.90 | 10.33 | -704.90 | -2.65R |
| 1636 | 1503 | 1434.00 | 2009.67 | 5.70 | -575.67 | -2.16R |
| 1657 | 1106 | 2696.00 | 1420.74 | 6.51 | 1275.26 | 4.79R |
| 1675 | 1227 | 2195.00 | 1559.29 | 6.46 | 635.71 | 2.39R |
| 1703 | 2834 | * | 3327.51 | 19.41 | * | * X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1711 | 1348 | 2333.00 | 1569.64 | 9.65 | 763.36 | 2.87R |
| 1715 | 2748 | 3249.00 | 3267.17 | 17.53 | -18.17 | -0.07 X |
| 1721 | 2713 | 3647.00 | 3212.03 | 17.64 | 434.97 | 1.64 X |
| 1724 | 2765 | * | 3159.47 | 21.48 | * | * X |
| 1727 | 2817 | 3716.00 | 3282.59 | 20.01 | 433.41 | 1.63 X |
| 1730 | 2748 | 3457.00 | 3185.09 | 19.95 | 271.91 | 1.02 X |
| 1733 | 2852 | 3474.00 | 3408.28 | 17.85 | 65.72 | 0.25 X |
| 1739 | 2886 | 3094.00 | 3251.89 | 23.99 | -157.89 | -0.60 X |
| 1748 | 2938 | 3629.00 | 3339.74 | 23.58 | 289.26 | 1.09 X |
| 1751 | 2782 | 3785.00 | 3274.93 | 18.74 | 510.07 | 1.92 X |
| 1754 | 2903 | 3215.00 | 3261.54 | 24.45 | -46.54 | -0.18 X |
| 1766 | 2800 | 2973.00 | 3507.64 | 13.36 | -534.64 | -2.01R |
| 1768 | 1486 | 1365.00 | 2187.24 | 9.40 | -822.24 | -3.09R |
| 1784 | 2886 | 2938.00 | 3580.20 | 14.72 | -642.20 | -2.42R |
| 1799 | 2817 | 3007.00 | 3564.09 | 12.75 | -557.09 | -2.10R |
| 1835 | 2679 | 3111.00 | 3157.45 | 17.80 | -46.45 | -0.17 X |
| 1838 | 2713 | * | 3094.68 | 21.17 | * | * X |
| 1840 | 1019 | 2419.00 | 1183.46 | 8.76 | 1235.54 | 4.65R |
| 1841 | 2921 | 3595.00 | 3353.83 | 22.40 | 241.17 | 0.91 X |
| 1847 | 2506 | 2454.00 | 3176.60 | 10.70 | -722.60 | -2.72R |
| 1852 | 1054 | 1849.00 | 1227.07 | 8.75 | 621.93 | 2.34R |
| 1853 | 2748 | 3405.00 | 3278.70 | 17.20 | 126.30 | 0.48 X |
| 1862 | 2886 | 2558.00 | 3345.50 | 21.12 | -787.50 | -2.97RX |
| 1868 | 2765 | 3266.00 | 3253.07 | 18.65 | 12.93 | 0.05 X |
| 1871 | 2039 | 3681.00 | 2982.07 | 11.47 | 698.93 | 2.63R |
| 1877 | 1918 | 3629.00 | 2702.43 | 8.17 | 926.57 | 3.48R |
| 1880 | 2195 | 3681.00 | 3117.42 | 9.93 | 563.58 | 2.12R |
| 1892 | 1935 | 3578.00 | 2840.96 | 11.23 | 737.04 | 2.77R |
| 1898 | 2091 | 3733.00 | 3011.58 | 10.48 | 721.42 | 2.71R |
| 1901 | 2091 | 3664.00 | 2718.55 | 7.35 | 945.45 | 3.55R |
| 1919 | 2091 | 3612.00 | 3011.58 | 10.48 | 600.42 | 2.26R |
| 1960 | 1175 | 2419.00 | 1495.18 | 6.51 | 923.82 | 3.47R |
| 1982 | 2264 | 3648.00 | 2898.83 | 8.79 | 749.17 | 2.82R |
| 1985 | 2126 | * | 3324.49 | 18.61 | * | * X |
| 1988 | 2108 | 2852.00 | 3314.27 | 19.04 | -462.27 | -1.74 X |
| 1993 | 2039 | 1417.00 | 1950.34 | 27.85 | -533.34 | -2.02RX |
| 2027 | 2108 | * | 3302.74 | 18.66 | * | * X |
| 2051 | 2385 | 2852.00 | 3400.96 | 11.25 | -548.96 | -2.07R |
| 2074 | 1244 | 950.00 | 1803.64 | 8.08 | -853.64 | -3.21R |
| 2084 | 2402 | 2817.00 | 3352.27 | 9.79 | -535.27 | -2.01R |
| 2093 | 2454 | 2696.00 | 3381.79 | 9.37 | -685.79 | -2.58R |
| 2096 | 2195 | 2679.00 | 3492.53 | 21.18 | -813.53 | -3.07RX |
| 2167 | 1451 | 2679.00 | 1967.94 | 5.87 | 711.06 | 2.67R |
| 2223 | 3284 | * | 3782.37 | 25.34 | * | * X |
| 2230 | 2281 | 2039.00 | 2873.20 | 9.80 | -834.20 | -3.14R |
| 2249 | 2264 | 1814.00 | 3449.62 | 16.93 | -1635.62 | -6.16R |
| 2285 | 604 | 1469.00 | 795.27 | 8.46 | 673.73 | 2.53R |
| 2290 | 2160 | 3612.00 | 2991.74 | 8.20 | 620.26 | 2.33R |
| 2293 | 2108 | 3629.00 | 3044.30 | 10.78 | 584.70 | 2.20R |
| 2296 | 2247 | 3629.00 | 3076.39 | 8.08 | 552.61 | 2.08R |
| 2298 | 691 | 1849.00 | 915.20 | 8.03 | 933.80 | 3.51R |
| 2344 | 2627 | 2731.00 | 3702.48 | 11.71 | -971.48 | -3.65R |
| 2361 | 1192 | 881.00 | 2184.51 | 22.16 | -1303.51 | -4.92RX |
| 2365 | 881 | 1590.00 | 999.99 | 9.12 | 590.01 | 2.22R |

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.