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Author
Linker, Wendy

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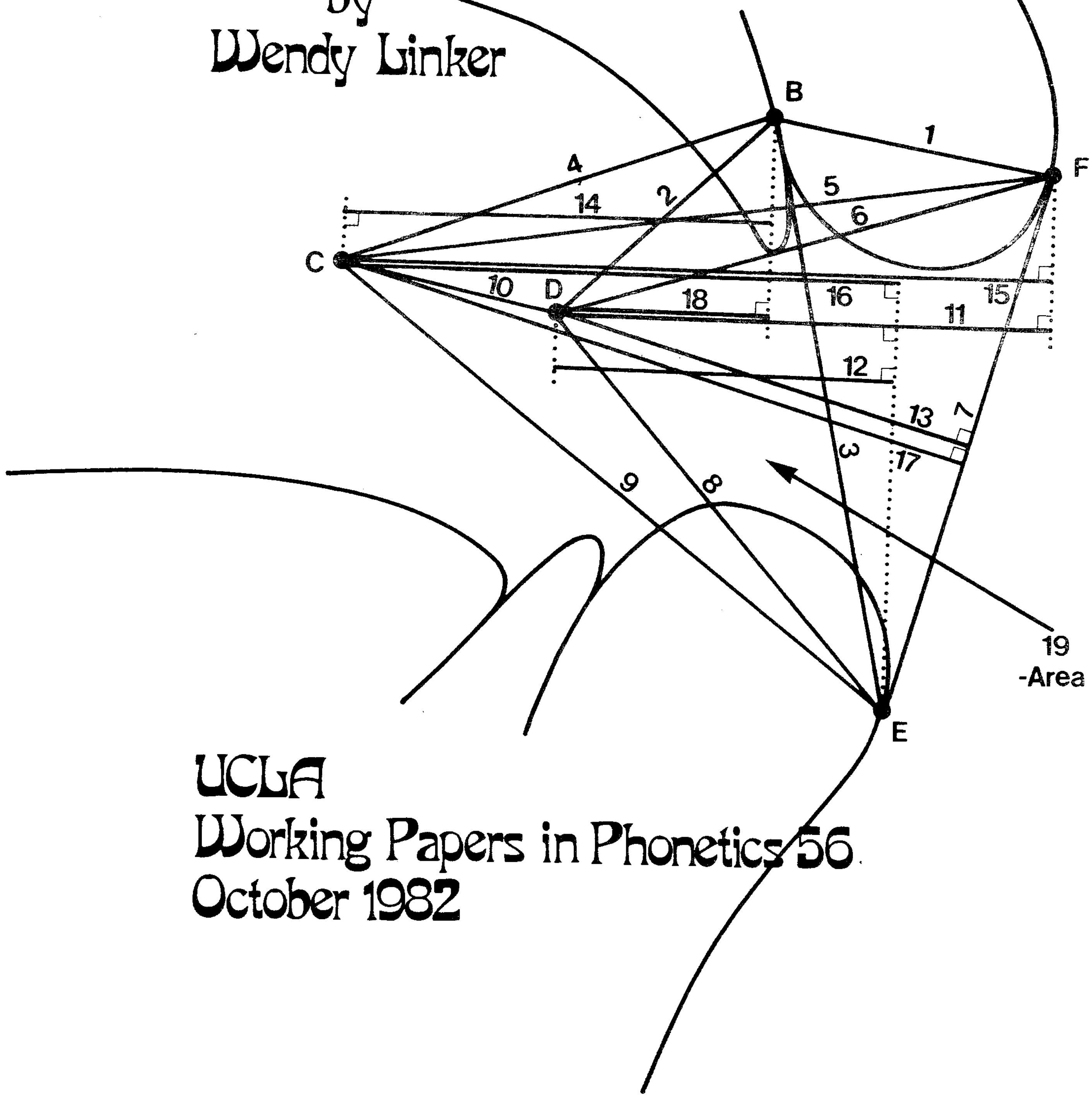
by
Wendy Linker



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As on previous occasions, the material which is presented here is simply a record for our own use, a report as required by the funding agencies which support the Phonetics Laboratory, and a preliminary account of research in progress for our colleagues in the field.

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Correspondence concerning UCLA Working Papers in Phonetics should be addressed to:

Phonetics Laboratory
Department of Linguistics
UCLA
Los Angeles CA 90024
(U.S.A.)

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[1] Goldstein, L. 1977. Three studies in speech perception: Features, relative salience and bias. <u>UCLA Working Papers in Phonetics</u> <u>39</u>, pg. iv.

Chapter 1: Introduction

It is a generally accepted fact in phonetics that one of the defining features of the production of vowels is the shape of the lips. For example, Ladefoged (1975) in A Course in Phonetics states that "vowels can be characterized mainly in terms of three features: (1) the so-called vowel height, which is inversely proportional to the frequency of the first formant; (2) the so-called degree of backness, which is directly proportional to the difference between the frequencies of the second and first formants; and (3) the degree of lip rounding, an articulatory feature that has complex acoustic correlates." (pg. 193)

It, however, remains to be established what the precise nature of the lip rounding gesture is, or even whether this gesture is the same for all languages. It is furthermore not clear that there is only one relevant type of rounding gesture. Perhaps the first observation that there may in fact be two distinguishable kinds of rounding in vowels was made by Sweet (Henderson, 1971), who differentiated between "inner" and "outer" rounding: "In outer-rounding, with which front vowels are rounded - the lips are brought together vertically...Back and mixed vowels, on the other hand, are rounded by lateral compression of the corners of the mouth and, apparently, of the cheeks as well." (pg. 63)

The phonological relevance of this observation is not obvious in perhaps the majority of languages, where a single feature [round] will adequately supplement features of vowel height and backness to account for the observed vowel patterning. However, the fact that there may exist different kinds of rounding gestures means that such gestures may have the potential to be used by the phonology to make contrasts among vowels. There exists, in fact, a real example of where a language has chosen to make use of two types of rounding to distinguish a subset of its vowels. The language in question, Swedish, has the following system of long vowels:

i: y: ɯ:	u:
e: ø:	o:
ɛ:	
	ɑ:

(The symbol [ɯ] is the one most often used for this vowel by Swedish phoneticians. It represents a high front rounded vowel, not to be confused with [ɯ], the IPA symbol for a high back unrounded vowel).

The problem, pointed out by Lindau (1975), resides in the high vowels /i/, /y/, /ɯ / and /u/. /i/ is clearly non-round, while /y/, /ɯ /, and /u/ are clearly round. / ɯ /, derived historically from a high back rounded vowel, is now a non-back vowel, distinguished from /y/ by its kind of lip rounding. As Lindau states, "Swedish contrasts lip protrusion, [round] and lip compression, [labial], for high vowels...../y/ and / ɯ / are both non-back with decreased lip opening. The vowel /y/ is produced with lip protrusion, / ɯ / with the gesture for [labial]." (pg. 16)

Given the existence of at least two phonetically different kinds of lip rounding, as well as the existence of at least one language that is known to rely on this difference as a means of contrasting its high vowels, it seems that it would be of unquestionable value to be able to quantify the kinds of rounding gestures observable in the vowel articulations of the languages of the world. This study is directed toward this goal.

In particular, I am interested in finding answers to the following questions:

(1) Which measure or measures of lip position are the linguistically relevant ones for describing the vowels of different languages? Are the same measures relevant for all languages? Do languages such as English, with no front rounded vowels, differ in the lip gestures they use in comparison with languages that have front rounded vowels?

(2) Do similar vowels in different languages - that is, vowels that phoneticians transcribe with the same symbol - make use of measurably different lip gestures? For example, if we look at the degree of lip protrusion used in the French vowel [y] and compare it to the degree of lip protrusion used in the Swedish vowel [y], will we find a difference?

(3) What is the nature of the relationship between lip position and formant frequency in the vowels of different languages? What specific equations are necessary to predict lip position from formant frequency? Do these equations differ from language to language?

Before addressing these questions, it might be useful to review some of the research on lip position in vowels, to be used as a starting point from which the present study is undertaken.

Traditional phonetics generally embraced the view that although in principle any lip position could co-occur with any tongue position, there were in fact more "normal" or at least more probable combinations to be found in the vowels of different languages. For example, Henry Sweet writes, "Rounding can, of course be added to all the tongue positions. The degrees of rounding are infinite. As fixed points we distinguish three, corresponding to the three heights of the tongue, the general rule being that the higher the tongue position of the round vowel, the narrower the lip passage...but abnormal rounding also occurs. There is no difficulty, for instance, in combining mid position of the tongue with high rounding as in the second element of <u>ou</u> in <u>no</u>...it is also possible to under-round. The vowel in <u>good</u> is 'under-rounded' in the dialects of the North-West of England: the high position of the back of the tongue is retained, while the lips are relaxed almost to low rounding" (ibid,pg.86). As another example of "abnormal" rounding in language Sweet cites both Danish and Swedish [o], where the "lip narrowing in each case [is] a degree above the height of the tongue" (ibid, pg.64).

Daniel Jones, in his description of the cardinal vowels, also sets up an abstract system whereby tongue position and lip position are closely correlated, in a manner similar to Sweet. Jones distinguishes three kinds of lip rounding: "spread", "rounded" and "neutral", although "spread" and "neutral" are grouped together as "unrounded" (Jones, 1960, pg.39). As this system was intended to aid phoneticians in their descriptions of actual languages, it cannot be an accident that Jones set up these reference points with such close correlations between tongue height and lip position. In fact, Armstrong (1967) makes use of this system in her description of the phonetics of French, in which she also sets up direct correlations of tongue height and lip position for French vowels. Thus it is clear that both Sweet and later Jones had a strong notion of naturalness with regard to the use of lip rounding in vowels in the languages of the world; both were concerned with degrees of lip rounding, and, in the case of Sweet, with different types of rounding as well.

Fromkin's article entitled "Lip positions in American English vowels" (1964) represents one of several careful investigations into the movement of the lips in the production of vowels within a given language. This study will be described in some detail, as it is one of the most relevant to the present investigation. Simultaneous frontal and lateral photographs were taken of the production of 12 American English vowels produced by 5 subjects; in addition, for the principal subject (the author), lateral x-rays and stone casts of the lips were made. One main purpose of Fromkin's investigation was to measure a number of parameters of lip position and study the relationship among these parameters for English vowels. Seven measurements of the lips were taken: (1) the width of the lip opening, (2) the height of the lip opening, (3) the area of the lip opening, (4) the distance between the outermost points of the lips, (5) the protrusion of the upper lip, (6) the protrusion of the lower lip, and (7) the distance between the upper and lower front teeth. With respect to the present investigation, the relevant results discussed by Fromkin are the following: (1) Where four subjects were considered, the absolute values of the measurements differed greatly; however, the <u>relationships</u> among the vowels when graphed along the lip parameters remained the same. (2) Only the English [u] was distinguished by the parameters width and height of lip opening. (3) In general, lip positions do serve to distinguish <u>sets</u> of vowels in English (i.e., the front unrounded vowels from the back rounded vowels), but do not serve to distinguish vowels within particular groups ([u] being the exception). (4) upper lip protrusion was found to vary much less than lower lip protrusion for the entire range of vowels, (5) lower lip protrusion was found to be largely predictable from the width of the mouth opening, (6) No correlation was found for English between protrusion and height of lip opening. (7) A linear relationship was found to exist between the product width x height and the area of the lip opening. She concluded that "a description of vowel lip positions based on actual physiological parameters would include height, width and lower lip protrusion" (pg.225).

Along similar lines, Abry, et al (1979) measured twelve parameters of lip position for the French vowels [i], [e] and [y], [ø] as produced by five speakers. A factor analysis revealed that only two of these parameters should be retained, these being the lip area and the ratio of the lip axes (i.e., the ratio of the horizontal opening between the lips to the vertical opening between the lips). In addition, it was found that the distance from a reference point to the point of contact between the lips was correlated with the ratio of the lip axes. Of these parameters, only the lip area was capable of achieving a 100% discrimination between phonemically rounded and unrounded vowels.

Thus, both of these studies indicate that one can, in fact, quantify relationships among various parameters of lip postion in the vowels of English and French, and in addition suggest which parameters might be the relevant ones to measure in other languages.

Many other studies have been conducted investigating the activity of the lips within a single language (e.g., Fujimura, 1961, Fromkin, 1965, McAllister, Lubker & Carlson, 1974, McAllister, 1980). With regard to the present study, McAllister's work on Swedish rounded vowels is particularly relevant. Essentially, it was found that the traditional classification of the Swedish rounded vowels (i.e., inrounding vs. outrounding) was, in fact, reflected in the electromyographic activity of the orbicularis oris muscle. (This result will be discussed in more detail later, in relation to my own results). Thus it seems to be the case that one can measure differences in lip activity in vowels, using x-ray, EMG and photographic techniques, and that the results obtained from such studies are largely in agreement with traditional descriptions of lip gestures in vowel production.

The final type of investigation to be discussed involves the relationship between the acoustic nature of vowels and lip position. Recall that Sweet, for example, assumed a natural relationship between tongue position and lip position. Could it also be the case that there is some natural relation between the acoustic vowel space and the lip positions associated with points in this space? A study by Stevens and House (1955) represents a step in the direction of answering this question; they specified variations in the effect of the lips by the ratio A/l, where A represents an idealized area of the mouth opening (determined by adjusting parameters of a vocal tract analog) and l is equal to the length of an idealized vocal tract tube. They plotted this single number A/l against formant frequency, and thus found correspondences between changes in F1, F2 and F3 as A/l varied. More recent modeling studies have also investigated the relationship between acoustics and various parameters of articulation in vowels (e.g., Fant, 1962, Lindblom and Sundberg, 1971, and Atal, et al, 1978), revealing interesting correspondences between lip shape and formant frequency. For example, Atal, et al, using an extension of the three-parameter Stevens and House articulatory model found what they refer to as "fibers", articulatory regions that correspond to a single point in the acoustic space. By computing two dimensional articulatory fibers for different vowels, they were able to show that the mouth opening for the vowel [i] can vary a great deal (over 10 square centimeters) without affecting the formant frequencies, while this was not found to be the case for [u] or [a]. While modeling studies such as these provide a valuable tool for investigating the relationship between formant frequency and lip position, they do not directly address the question of how formant frequency and lip shape are related within real languages, nor whether or not this relationship can differ from language to language. For example, the parameter A/l in the Stevens and House study represents only idealized lip shapes. Thus, it is obviously still necessary to study the relation between actual measures of lip position and formant frequency in real languages, in order to approach the questions raised earlier.

The next step in this direction was to investigate the relationship between lip position and acoustic properties of vowels within a single language. Ladefoged, et al (1978) measured lateral x-rays of five speakers of American English producing ten vowels, and found that the distance between the upper and lower lips could be predicted from a particular combination of formant frequencies. The correlation between the observed lip distance and the predicted lip distance was 0.78. However, as this study was not primarily concerned with lip articulation only this single lip parameter and its relationship to formant frequency was considered.

We have seen that much research has been devoted to the study of lip activity in vowels, and that some of this research has focused on the relationship between the acoustic nature of vowels and lip position. However, most of this work has been confined to the investigation of a single language at a time, and in most cases no more than five subjects were used (usually fewer). In this investigation I would like to go a step further, and compare measurements of both lip position and formant frequency in the vowels of five languages, Cantonese, English, Finnish, French and Swedish.

The study is organized as follows. Chapter 2 describes the methods of data collection and preliminary analysis, as well as a comparison of selected lip measurements for selected vowels in the five languages. Chapter 3 discusses the problems with this approach, and attempts to solve them using a type of 3-mode factor analysis called PARAFAC (Harshman, 1970; Harshman, et al, 1977; Harshman and Berenbaum, 1980). The criteria for choosing among different PARAFAC solutions are described and applied to each language. In Chapter 4, the factors found by PARAFAC are interpreted, revealing the underlying phonetic parameters of lip position in each language. Also, the patterning of the vowels along the dimensions is discussed. Chapter 5 compares the individual PARAFAC solutions to one another, by looking at the correlations between pairs of lip measurement loading matrices and by comparing interpretations of the factors. In addition, a procedure applying a generalized type of canonical correlation (Carroll, 1965) is used to find a single canonical factor space, in which the vowels of four of the languages can be compared. Finally, Chapter 6 investigates the relationship between lip position and formant frequency in each of the five languages. In particular, the equations needed to predict the canonical factors are determined, and compared to one another in order to investigate the possibility that the relationship between lip position and formant frequency is language-specific.

Chapter 2: Data Collection, Analysis, and Preliminary Comparison

The Data Base

The languages chosen for this investigation were English, Cantonese, Finnish, French and Swedish. The rounded vowels of English can only be back, while the other four languages contain at least two front rounded vowels as well. These five languages were selected because (1) they are genetically diverse, thus maximizing the chance of discovering differences among them, (2) four of them have similar vowel systems, including front rounded vowels, so that the lip positions of the similarly transcribed vowels can be directly compared, and (3) one of them, English, has no front rounded vowels, so it will be possible to compare the linguistically relevant measures of lip position in English with those of the other four languages.

The data were collected in the following way. Wordlists were prepared containing minimal or near-minimal contrasts of stressed vowels in the five languages, long vowels in open syllables being preferred where possible. In some cases, nonsense words were used, where it was determined that the subjects had no difficulty treating them as possible words. The wordlists for each language are shown in Table 1. Eight male speakers for each language were rehearsed in reading the relevant wordlists. Subjects were instructed to sustain the vowel of each word. The English subjects, from whom the data were collected at an earlier date than the data for the other four languages, were seated in a chair that held a device with two cameras mounted on it. This device was used to keep the subject's head steady during the production of each word. The subjects for the other four languages were seated in a dentist's chair, which also held their heads in a fixed position, and the two cameras were mounted on tripods. Simultaneous frontal and lateral photographs were taken of the production of each word. The entire session was tape recorded. Measurements of the first three formants of each vowel were made on wide band spectrograms prepared from the recordings. The moment at which the photographs were taken was determined from the noise of the camera shutters, which was visible on the spectrograms. Measurements of formant frequencies were made just before that instant. In some cases in the English data, where interpretation was difficult, linear prediction analysis was used to supplement the spectrograms.

In order to measure lip protrusion, it was necessary to decide on a fixed reference point to measure from. The front surface of the upper incisors was selected, since this point is fixed by the rooting of the teeth in the skull, and hence moves less than any other structure in the front of the mouth. A narrow paper strip marked in 5 millimeter sections was attached to a very thin metal wire, and the wire was fastened between the subject's upper front teeth. From this, relevant distances to the upper teeth could be calculated. Care was taken to ensure that the stick did not touch either the upper or lower lip of the subject. In addition, a millimeter scale was placed in the frontal view in the plane of the lips.

To obtain measures of lip position, negatives of the front and side views were projected by an enlarger, and tracings were made. Exact distances were calculated from the scales using a computer program written by Lloyd Rice. With

Table 1: Wordlists

English

hid	hɑd
hɪd	hʊd
heɪd	hud
hɛd	
hæd	

French

si	so
se	su
sɛl	sy
sa	sø
sɔl	sœl

Cantonese (all words on mid level tone)

si:	ku:
sɛ:	sy:
sa:	kœ:
sɔ:	

Swedish

hi:t	hɯ:t
he:t	hɵt:
hɑ:t	hy:
ho:	hø:
hu:t	hœt:

Finnish

si:	so:
se:	su:
sæ:	sy:
sɑ:	sø:

this program it was possible to use a Grafpen connected to a PDP-12 computer to retrace the tracings of the negatives for English. (A somewhat modified version of this program, using a bitpad, was used on a Z80 CP/M computer to obtain measurements for the languages other than English). The program used the points marked by the Grafpen as input to compute 24 lip measurements. The measurements in the side view were taken with reference to the five points shown in Figure 1: (1) Point B, a fixed point on the upper front teeth, (2) Point C, the corner of the mouth, (3) Point D, the most forward point of contact between the lips, (4) Point E, the outermost point on the lower lip surface, and (5) Point F, the outermost point on the upper lip surface. Every possible direct distance from each of these five points to one another was found. In addition, as shown in Figure 1, selected perpendicular distances were taken from points B, C, and D to: (a) the line joining points E and F and (b) vertical lines drawn through points B, E, and F. Finally, the area enclosed by the inner surface of the lips was calculated.

Figure 2 shows the front view measurements that were calculated. Measures 20, 21, and 22 represent the vertical distance between the lips taken at equal intervals, with measure 21 being at the center of lips. Measure 23 is the distance between the two corners of the mouth, and measure 24 is the area of the mouth opening in the front view. (The reader may find it useful to refer to figures 1 and 2 when necessary throughout this study).

The 24 measurements of lip position and the corresponding formant frequencies taken for the eight subjects producing the vowels in each of the five languages are given in the Appendix. Measure 10, the distance between points C and D, was not used in any of the analyses, giving a total of 23 lip measurements.

Comparison of Selected Lip Measurements Across Languages

In order to see if similarly transcribed vowels in the five languages under investigation differ in the values they use for the lip measurements taken, a preliminary comparison across languages of selected lip parameters was carried out. The parameters chosen, which included both raw lip measurements and ratios of raw lip measurements, were the ones that might be expected to be relevant according to previous studies. In addition, certain parameters that had been investigated in other studies and not found to be important for a given language, as well as certain other parameters that have not previously been looked at, were investigated here for the five languages.

Recall that Fromkin (1964) measured seven parameters of lip position in English vowels, six of which correspond to measures taken in the present study. (The seventh was the distance between the upper and lower teeth). Fromkin concluded that the three necessary parameters for the description of vowel lip positions were height (i.e., measure 21, the vertical opening between the lips), width (i.e., measure 23, the horizontal opening between the lips) and lower lip protrusion (measure 3). In this preliminary analysis of the data it was decided to compare five of Fromkin's parameters across languages, these three and two others, the area of the lip opening (i.e., measure 24, the front view area), and the protrusion of the upper lip with reference to the teeth (measure 1). In the present study, the square root of the front view area was used rather than the area itself, in order to minimize the effect of the mere size of this number on the significance results. In addition, since the study by Abry, et al (1979)

Figure 1: A diagram showing the measurements taken from the side view of the lips

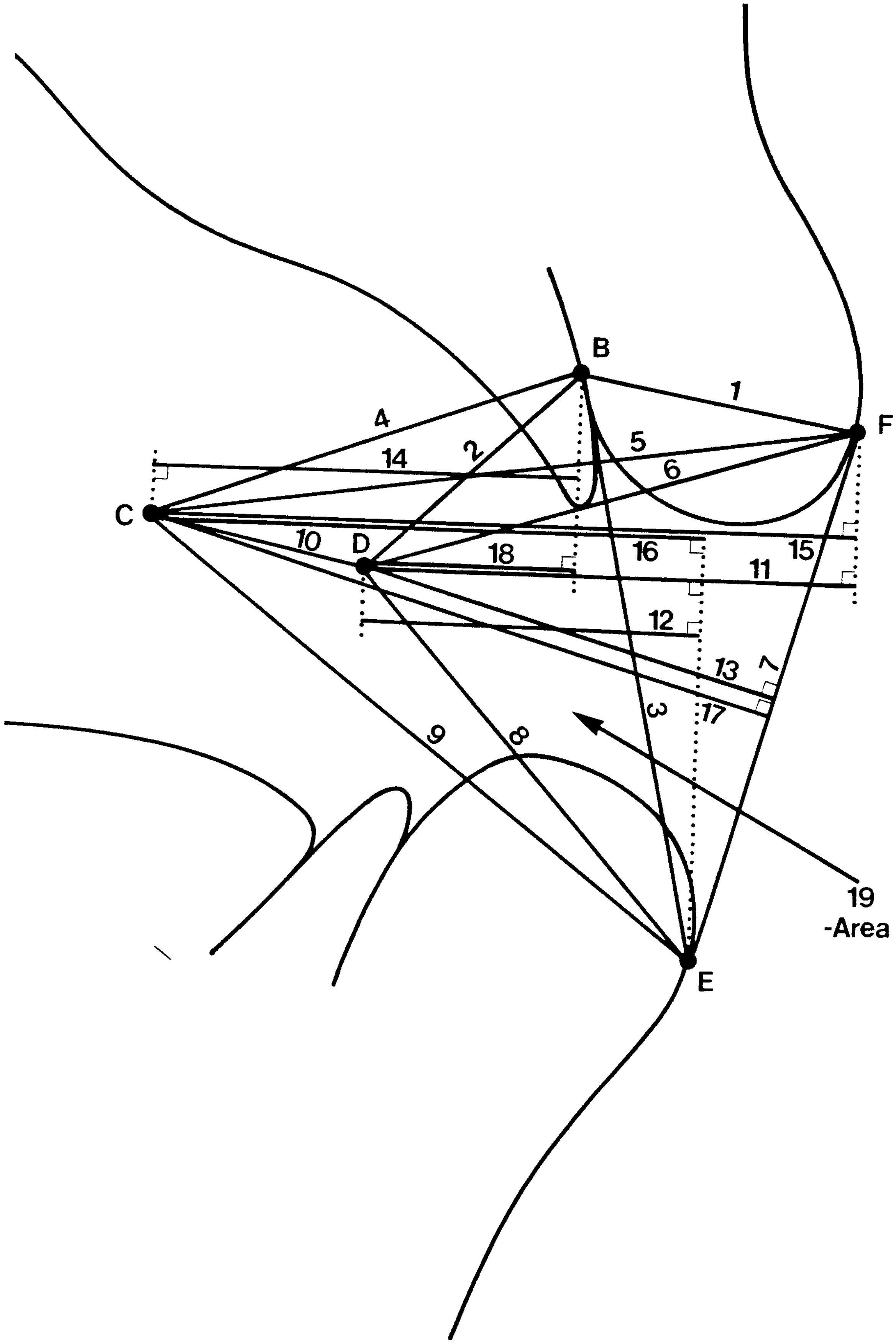
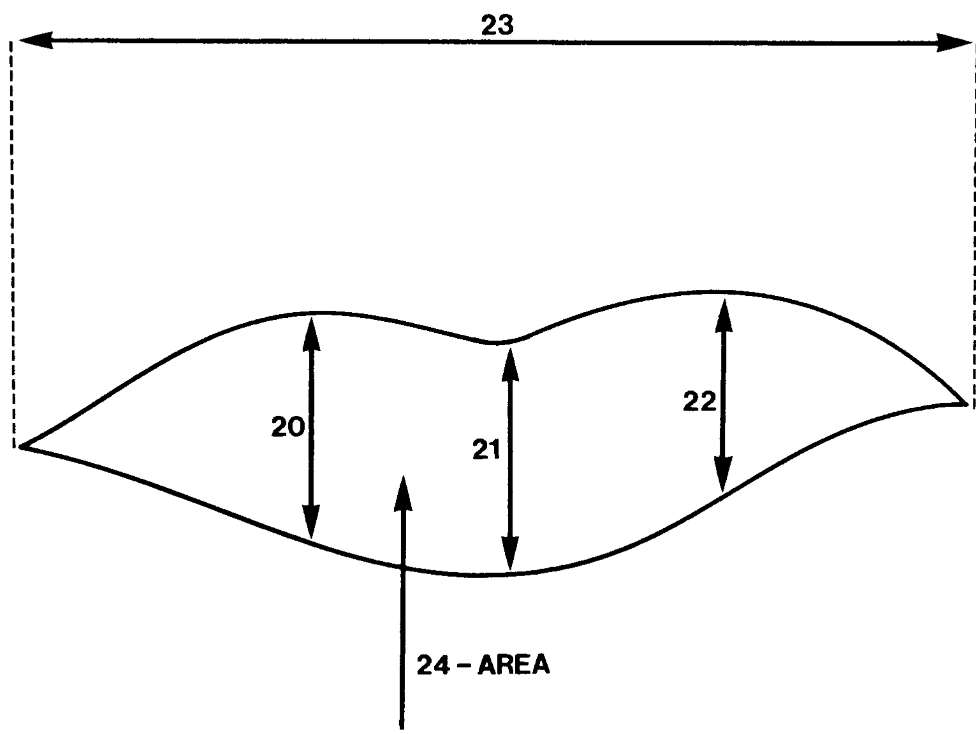


Figure 2: A diagram showing the measurements taken from the front view of the lips



revealed that the ratio of the horizontal opening between the lips to the vertical opening between the lips (measure 23/measure 21) was important for distinguishing rounded and unrounded vowels in French, this parameter was also included in the comparison. Finally, six other parameters of lip position were included for comparison across languages:

(1) The ratio of the upper lip protrusion from the teeth to the vertical opening between the lips (measure 1/measure 21)

(2) The ratio of the lower lip protrusion from the teeth to the vertical opening between the lips (measure 3/measure 21)

(3) The distance from the most forward point of contact between the lips to the outermost point on the upper lip surface (measure 6)

(4) The distance from the most forward point of contact between the lips to the outermost point on the lower lip surface (measure 8)

(5) The ratio of the horizontal opening between the lips to lower lip protrusion from the teeth (measure 23/measure 3)

(6) The ratio of the horizontal opening between the lips to the distance between the most forward point of contact between the lips and the perpendicular line through the reference point on the upper front teeth (measure 23/measure 18)

Thus, twelve parameters of lip position were selected for comparison across languages. These measures and ratios of measures were compared for the high vowels [i], [y] and [u], since these are the only vowels transcribed in the same way for all languages (with the exception of English, of course, which does not have the high front rounded vowel [y]). Table 2 lists the mean values for the twelve parameters for each of these vowels for each language.

The procedure used for comparison was a one-way analysis of variance. Each parameter was investigated across languages for a given vowel (four languages for the vowel [y], five languages for the vowels [i] and [u]). An F-ratio was obtained for each analysis, and examined for significance. Table 3 lists the results of each analysis of variance.

As Table 3 shows, certain measures were not significantly different across languages, regardless of the vowel. Such measures include upper lip protrusion (measure 1), the distance from the most forward point of contact between the lips to the outermost points on both the upper and lower lip surfaces (measures 6 and 8), and the ratio of the horizontal opening to the distance between the most forward point of contact between the lips and a perpendicular line drawn through a reference point on the upper front teeth (measure 23/measure 18). Other parameters were significantly different across languages for all three high vowels, these being measure 3, measure 21, measure 23, measure 1/measure 21, measure 3/measure 21 and measure 23/measure 3. Note that the first three of these correspond to the three parameters that Fromkin found to vary independently for English. The remaining two parameters, measure 24 and measure 23/measure 21, were significantly different across languages for some vowels but not for others.

In order to investigate the effect of each language on the significance results, a Newman-Keuls test was performed for all pairs of languages for every

Table 2: Mean values in millimeters for the twelve selected parameters of lip position in each language.

	English	Cantonese	Finnish	French	Swedish
Measure 1					
/i/	7.94	7.56	7.60	7.56	6.81
/u/	8.20	7.85	9.17	9.44	8.47
/y/	---	7.85	9.32	9.12	9.61
Measure 3					
/i/	8.02	8.05	9.26	10.18	9.75
/u/	7.88	7.48	9.53	10.37	9.87
/y/	---	7.48	9.46	10.27	10.85
Measure 6					
/i/	12.76	12.88	11.71	11.45	13.58
/u/	6.04	6.61	6.61	6.42	5.58
/y/	---	7.17	7.07	6.60	8.18
Measure 8					
/i/	10.64	10.66	9.14	9.50	10.79
/u/	5.81	5.60	6.25	5.96	5.40
/y/	---	5.99	6.28	5.91	6.38
Measure 21					
/i/	3.23	12.12	10.58	11.64	12.04
/u/	1.28	4.08	4.06	4.69	3.63
/y/	---	5.77	5.92	5.14	9.91
Measure 23					
/i/	47.16	47.41	41.68	43.30	51.07
/u/	29.75	18.89	16.19	17.23	16.14
/y/	---	22.63	19.91	18.81	26.13

Table 2, continued

Measure 24 (square root)					
/i/	10.97	20.03	18.15	18.96	20.36
/u/	4.81	7.16	6.81	7.40	6.12
/y/	---	22.63	19.91	18.81	26.13
Measure 1/Measure 21					
/i/	4.73	0.694	0.741	0.702	0.579
/u/	10.07	2.50	2.54	2.26	2.89
/y/	---	1.55	1.79	1.94	1.01
Measure 3/Measure 21					
/i/	5.21	0.718	0.909	0.912	0.838
/u/	9.58	2.31	2.59	2.42	3.32
/y/	---	1.44	1.84	2.12	1.14
Measure 23/Measure 3					
/i/	5.95	6.05	4.57	4.47	5.35
/u/	3.79	2.63	1.74	1.75	1.72
/y/	---	3.10	2.15	1.92	2.50
Measure 23/Measure 18					
/i/	10.17	9.58	52.29	13.98	10.64
/u/	16.18	48.12	6.34	6.05	4.38
/y/	---	27.65	8.41	16.60	11.54
Measure 23/Measure 21					
/i/	30.38	4.33	4.04	4.11	4.45
/u/	34.31	5.88	4.20	3.83	5.82
/y/	---	4.31	3.58	3.88	2.91

Table 3: Results of the Analysis of Variance. The numbers refer to the level of significance attained in the analysis. Non-significance is abbreviated `n.s.´.

Measure 1	
/i/	n.s.
/u/	n.s.
/y/	n.s.
Measure 3	
/i/	0.01
/u/	0.01
/y/	0.01
Measure 6	
/i/	n.s.
/u/	n.s.
/y/	n.s.
Measure 8	
/i/	n.s.
/u/	n.s.
/y/	n.s.
Measure 21	
/i/	0.01
/u/	0.01
/y/	0.01
Measure 23	
/i/	0.01
/u/	0.01
/y/	0.05
Measure 24 (square root)	
/i/	0.01
/u/	n.s.
/y/	0.01
Measure 1/Measure 21	
/i/	0.01
/u/	0.01
/y/	0.05
Measure 3/Measure 21	
/i/	0.01
/u/	0.01
/y/	0.01
Measure 23/Measure 3	
/i/	0.05
/u/	0.01
/y/	0.05
Measure 23/Measure 18	
/i/	n.s.
/u/	n.s.
/y/	n.s.
Measure 23/Measure 21	
/i/	0.01
/u/	0.01
/y/	n.s.

Table 4: Results of the Newman-Keuls Tests. Each pair of of languages for which a significant value of q was found is listed. The numbers refer to the level of significance attained in the analysis.

Measure 3

/i/	English-French	0.01
	English-Swedish	0.05
	Cantonese-Finnish	0.05
	Cantonese-French	0.01
	Cantonese-Swedish	0.01
/u/	English-Finnish	0.05
	English-French	0.01
	English-Swedish	0.05
	Cantonese-Finnish	0.05
	Cantonese-French	0.01
	Cantonese-Swedish	0.01
/y/	Cantonese-Finnish	0.05
	Cantonese-French	0.01
	Cantonese-Swedish	0.01

Measure 21

/i/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/u/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Cantonese-Swedish	0.01
	Finnish-Swedish	0.01
	French-Swedish	0.01

Measure 23

/i/	English-Finnish	0.05
	Finnish-Swedish	0.01
	French-Swedish	0.01
/u/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Finnish-Swedish	0.05
	French-Swedish	0.05

Measure 24 (square root)

/i/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Cantonese-Swedish	0.01
	Finnish-Swedish	0.01
	French-Swedish	0.01

Table 4, continued

Measure 1/Measure 21

/i/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/u/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Finnish-Swedish	0.05
	French-Swedish	0.05

Measure 3/21

/i/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/u/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Finnish-Swedish	0.05
	French-Swedish	0.01

Measure 23/Measure 3

/i/	English-Finnish	0.05
	English-French	0.05
	Cantonese-Finnish	0.05
	Cantonese-French	0.05

(only significant for /i/ using less stringent criteria; see text)

/u/	English-Cantonese	0.05
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/y/	Cantonese-French	0.05

Measure 23/Measure 21

/i/	English-Cantonese	0.01
	English-Finnish	0.01
	English-French	0.01
	English-Swedish	0.01
/u/	English-Cantonese	0.01
	English-Finnish	0.01
	English-Swedish	0.01
	English-Swedish	0.01

analysis of variance for which the F-ratio was significant. The results of these tests are given in Table 4.

Examination of Tables 2 and 4 leads us to the following conclusions:

(1) Cantonese differs significantly from French and Swedish, and to a lesser degree from Finnish, in its use of measure 3 (lower lip protrusion) for the vowels [i], [y], and [u]. English also differs in the use of this measure from Finnish, French, and Swedish for the vowel [u], and from French and Swedish for the vowel [i]. Thus, it seems that Cantonese and English speakers for the most part use significantly less lower lip protrusion for the vowels investigated than do the other three languages.

(2) English has significantly less vertical opening for the vowels [i] and [u] than do the other four languages. In addition, Swedish has significantly greater vertical opening for the vowel [y] than do the other languages with this vowel.

(3) Regarding measure 23 (horizontal opening), the following observations can be made: (a) for [i], English uses a significantly greater horizontal lip opening than does Finnish, and Swedish uses a significantly greater horizontal lip opening than do Finnish and French, (b) for [u], English uses a greater horizontal opening than do the other four languages, and (c) for [y], Swedish again uses significantly more horizontal opening than do Finnish and French.

(4) The only significant differences for the square root of measure 24 (front view area) pertain to the vowels [i] and [y]. For [i], English uses significantly less front view area than do the other four languages. For [y], Swedish is found to use a significantly greater front view area than do the other three languages with this vowel.

(5) The Swedish [y] differs significantly from the Finnish and French [y] in its value for the ratios measure 1/measure 21 and measure 3/measure 21 (the ratio of upper and lower lip protrusion, respectively, to vertical opening). The English [i] and [u] differ significantly along these two parameters from the [i] and [u] of the other four languages. Similarly, English [i] and [u] differ significantly along the parameter measure 23/measure 21 (the ratio of horizontal opening to vertical opening) from the [i] and [u] of the other four languages. These facts result primarily from the effect of measure 21, for which English has extremely low values and for which the Swedish [y] has a relatively high value. Thus, this result simply duplicates the results detailed under (2) above.

(6) For the ratio measure 23/measure 3 (horizontal opening/lower lip protrusion), (a) the English [u] has significantly higher values than the [u] of the other four languages, (b) the Cantonese [y] differs significantly, at the 0.05 level, from the French [y], in having higher values. No significant difference was found for any language pairs using the most conservative form of the Newman-Keuls test for the vowel [i], as was used for all the other vowels along all parameters (i.e., with the ordering of the means taken into account); when the means are treated as unordered, it is found that the English and Cantonese [i] use a significantly larger amount of measure 23/measure 3 than do the French and Finnish [i], at the 0.05 level.

In using analysis of variance and the Newman-Keuls test we have been able to approach one of the questions raised in the introduction to this study, namely, whether or not similarly transcribed vowels in different languages make use of significantly different values of various parameters of lip position. For those parameters where the analysis of variance revealed a significant language (between-groups) effect, we have been able to ascertain the source of the significant difference, by comparing selected vowels across pairs of languages. It turns out to be the case that for eight out of the twelve chosen parameters of lip position, there are in fact significant differences between certain pairs of languages for certain vowels.

Although the findings show important differences in the use of lip gestures by different languages, it is not possible to answer all of the questions raised in the Introduction by examination of results of this kind alone. It is, for example, not clear how one is to interpret those analyses of variance where the F-ratio turns out to be statistically non-significant. This issue is particularly crucial regarding the first question raised in Chapter 1: what are the linguistically relevant parameters of lip position in the vowel systems of different languages? There seem to be three possible categories that a non-significant result could belong to:

(1) A particular parameter of lip position simply does not vary very much across the entire range of vowels. In this case, the parameter would not be expected to be important in distinguishing the vowels of a given system, and would similarly not be expected to differ significantly from language to language (assuming that the sizes of the speaker's mouths were roughly equivalent).

(2) A particular parameter of lip position might be important in distinguishing the vowels of a given system or of several systems, and a non-significant result for a particular vowel across languages simply means that the languages in question do not differ in the values they use for this parameter in the production of the vowel.

(3) A particular parameter of lip position might be important in distinguishing the vowels of a given system, but a large amount of individual speaker variation in the absolute values of this parameter might obscure its importance. Such a situation would also give rise to a non-significant F-ratio when comparing this parameter across languages.

Measure 1, upper lip protrusion, is a likely candidate for the first category, given Fromkin's result that this parameter varied much less than lower lip protrusion over the entire range of English vowels investigated. However, it is not a priori clear that measure 1 does not also belong to the third category, i.e., there may be a lot of individual speaker variation in the absolute values of measure 1 across vowels, but the <u>relationships</u> of the vowels along this parameter may be similar from speaker to speaker. Thus, it is possible that measure 1 is, in fact, a linguistically relevant parameter of lip position for a given vowel system but that the analysis of variance is not capable of shedding light on the issue.

A pilot study, also using analysis of variance, is worth describing in light of this problem. In this study, five measurements of lip position for English vowels were investigated: (1) measure 1 (upper lip protrusion), (2) measure 3 (lower lip protrusion), (3) measure 7 (the distance between the outermost points on the upper and lower lips), (4) measure 23 (horizontal opening) and (5) measure

24 (front view area). This analysis was carried out to see if the estimate of the variance among the vowels would be greater than the estimate of the variance among the individual subjects. If this were the case, then we could be confident that at least the subjects vary more in their lip positions along these five measures from vowel to vowel than they vary among themselves in the production of any given vowel. Examination of the F-ratios for measures 3, 7, 23, and 24 showed, in fact, that the between-group variation (i.e., the variation from vowel to vowel) was significantly greater than the within-group variation (i.e., the variation from subject to subject). However, the F-ratio for measure 1 was not significant at either the 0.01 or the 0.05 level.

Again, this result could be interpreted to mean that measure 1 is not a linguistically relevant parameter of lip position for English vowels. However, it could be the case that the individual variation from speaker to speaker along measure 1 is obscuring a linguistically relevant parameter that would become evident if a more sophisticated tool were used to abstract away the noise in the data.

With respect to the question of determining the linguistically relevant parameters of lip position in the vowel systems of different languages, there is an additional, perhaps more serious problem, with attempting to compare lip positions based on the raw data measurements alone. Thus far all that has been done is to select twelve parameters of lip position and compare them, for three vowels, across languages. But clearly, simply choosing measurements that appear to be relevant does not address the question of the appropriateness of these measures for linguistic purposes. In order to approach this issue, a more powerful analytical method is necessary. Fortunately, it turns out that this same method is capable of dealing effectively with the aforementioned problem of individual speaker variation. This method will be discussed in the next chapter.

Chapter 3: Factor Analysis of Lip Shapes: Methods

In the preceding chapter we saw that it is possible to select parameters of lip position, compare them for different vowels across languages, and discover those parameters which are significantly different for a given vowel from language to language. We were able to arrive at some interesting results in this way, in that certain parameters that might be expected to be important in a given language were shown to differ in specific ways for some vowels for some pairs of languages. However, we also saw that there are two basic problems with the approach taken in Chapter 2. First, a parameter that is, in fact, significant in accounting for the variance in a particular data set may have its significance obscured by the presence of a large amount of variation in the absolute values of the lip measurements from speaker to speaker. Thus, it could be the case that a particular parameter actually does serve to distinguish the vowels of a given system in terms of their lip shapes, but that an analysis of variance will turn out a result of non-significance. Second, the decision regarding which parameters to compare across languages is by its very nature an arbitrary one. Although it is likely that at least some of the parameters investigated in Chapter 2 are important for distinguishing the vowels in the systems in question, there is no way to know which ones are, in fact, the relevant ones simply by comparing them across languages. There may even be combinations of lip measurements other than those that we have looked at that account for more of the variance in an individual data set. It is clear that we need a more powerful tool than that discussed so far, in order to deal with these problems.

Richard Harshman's PARAFAC (Harshman, 1970; Harshman, Ladefoged and Goldstein, 1977; Harshman and Berenbaum, 1980), a type of three-mode factor analysis, provides such a tool. As shown below, PARAFAC gives as a result three sets of weightings, also referred to as 'loadings'. If we apply PARAFAC to the lip measurement data for a given language, the first set (m) represents the weighting of each of the lip measures on the extracted factors; the second set (v) represents the weightings of the individual vowels on the factors, and the third set (s) represents the weightings of the individual speakers with respect to the extracted factors. Each set of weightings relates to a "mode".

THE PARAFAC EQUATION

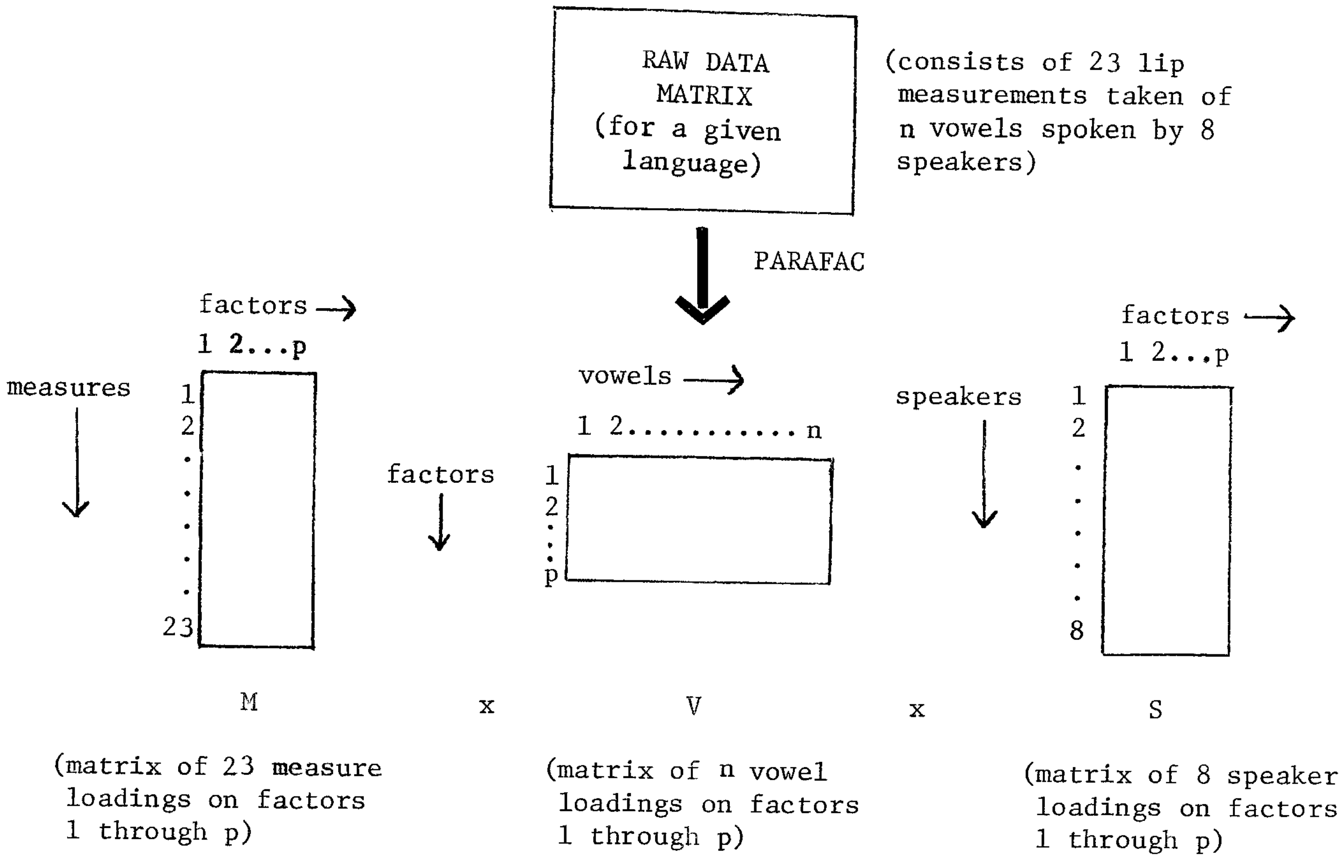
$$d_{ijk}=m_{i1}v_{j1}s_{k1} + m_{i2}v_{j2}s_{k2} + \cdots + m_{ip}v_{jp}s_{kp} + e_{ijk}$$

where d_{ijk} = a single data point for lip measure i for vowel j as spoken by speaker k;

m,v,s = the loadings (weightings) of lip measure, vowel, and speaker respectively on factors 1 through p.

e = an error term

Schematically, we are breaking down the raw data matrix in the following way:



(That is, the raw data matrix D is equal to the product M x V x S. Thus, the factors can be thought of as <u>dimensions</u> which underlie the data set.)

The factors found by PARAFAC are unique and non-rotatable.

It is important to understand that the factors that PARAFAC finds are not necessarily orthogonal (i.e., uncorrelated). In fact, there is no reason to expect that they will be. The underlying dimensions found by the analysis are uniquely the ones that account for the maximum amount of variance in the data.

With regard to the goals of the present study, PARAFAC offers two major advantages over direct analysis of the raw data. First, it makes it possible to find underlying, unique parameters of lip position in the vowels of different languages. Since the factors are unique, and given that the measurements I have taken are the appropriate variables to study, one can make the stronger claim that the factors that PARAFAC finds represent the linguistically significant parameters of lip position in vowels. The results of PARAFAC thus provide a statement of which measure or measures of lip position are the linguistically relevant ones for describing the vowels of the languages under investigation.

Second, the assumption of "system-variation" inherent to PARAFAC means that the individual variation that we find to be a problem in analyzing the raw data directly will be effectively dealt with by PARAFAC. The essence of the system-variation assumption is that individuals vary in the lip gestures they use along the same dimensions as the measures and vowels themselves vary. Thus, the variation inherent in all three modes is seen as a property of the system as a whole, rather than as a property of one of the set of objects under study.

While there is no simple way to evaluate whether or not the system-variation assumption holds for a given data set, there are indicators that can help one to detect whether or not the data appear to conform to it. For example, one can look at the matrix of speaker loadings to see if they lie within a similar range. A mixture of negative and positive loadings would, for example, indicate that the individuals do not vary along the same dimensions as the measures and vowels. Another indication that the data set does not conform to the system-variation assumption would be if the speaker loadings did not vary at all. Since we know that individuals do, in fact, vary in their lip positions, this result would indicate that the variation we know to be present is not being accounted for by the PARAFAC model. I shall return to this point subsequently, when discussing the PARAFAC solutions for the individual data sets.

1, 2, 3 and 4 dimensional PARAFAC solutions have been carried out for each language (with the exception of English, for which no 4 dimensional analysis was run). The remainder of this chapter is devoted to a discussion of the criteria used to determine the correct dimensionality for a given data set, and to examination of the solutions obtained for each language. In Chapter 4, the factors will be interpreted, and we will see how they function in separating the vowels of the systems under investigation.

Criteria for Choosing the Solutions

The criteria used here for choosing among different PARAFAC solutions are as follows:

(1) Uniqueness. A solution is considered unique if the same solution is obtained when the analysis is carried out from several different random starting configurations. Two or more solutions with the same factors are referred to as "matching solutions".

(2) Convergence. A solution is considered converged if, starting from one random starting configuration after a certain number of iterations no further change occurs in the solution. The convergence criterion used for the present analyses was 0.1% for each mode.

(3) Relative values of R^2. If, in going from one dimensionality to the next higher dimensionality the value of R^2 (that is, the amount of variance in the data accounted for by PARAFAC) is substantially increased, then (all other things being equal) one would assume that the extra dimension is important in accounting for the variance in the data set, and therefore the solution of higher dimensionality is to be preferred over the ones of lower dimensionality.

(4) Probable adherence to the system-variation assumption. If, for a particular factor the speaker loadings either (a) show virtually no variation or (b)

vary greatly (particularly if several speaker loadings have high negative values), then it is likely that the assumption of system-variation is not being adhered to along the dimension in question. In such a case another solution will hence be considered preferable.

(5) Correlation of factors. If the loadings for some of the factors of a single solution are highly correlated in all three modes, then these factors probably represent the same dimension and therefore a solution of different dimensionality is likely to be the correct one.

(6) Interpretability of factors. Given that each of the above five criteria is satisfied, one naturally wants to make sure that the factors are interpretable in a way that makes sense physiologically. In addition, one wants to be able to show that the factors in questions have an effect on separating the vowels of a given system.

The first five criteria will now be considered separately for the PARAFAC solutions obtained for each language. The sixth criterion will be examined in the next chapter.

ENGLISH

1-factor solutions: Three 1-factor solutions were obtained and were found to match. All three converged after 4 iterations. The value of R^2 was 0.924. As Table 5 shows, there is no indication that the speaker loadings vary in a way contrary to the system-variation assumption.

2-factor solutions: Three 2-factor solutions converged after between 225 and 400 iterations. The solutions matched. R^2 was 0.948. Examination of Table 5 reveals a good deal more variation among speaker loadings along the second factor than along the first. The negative loading for speaker 5 is particularly worthy of mention. Apparently this speaker makes use of factor 2 in a way opposite to the other speakers. Speaker 3 also has a fairly low weighting along this dimension, albeit in the same direction as speakers 1, 2, 4, 6, 7, and 8. The following are the correlations found for the three sets of loadings along the two factors:

Measures	-0.028
Vowels	0.854
Speakers	-0.823

3-factor solutions: Six 3-factor analyses were run and converged after between 302 and 774 iterations. Three of these runs gave one solution and three of them gave a different one. R^2 for the one solution was 0.961 and 0.958 for the other. Inspection of Table 5 shows that the speaker loadings for the first 3-factor solution lie within a reasonable range for all three factors; however, speaker 5 shows deviant behavior along both factors 2 and 3 for the second 3-factor solution. This is especially noticeable with regard to the large negative loading along factor 3. In addition, there is in general much more variation in the speaker loadings along factor 3 than there is along factor 1.

Table 5: Speaker loadings for English PARAFAC solutions of differing dimensionality.

	Factor 1	Factor 2	Factor 3
<u>1-factor solution</u>			
Speaker 1	1359.	---	---
2	1138.	---	---
3	1264.	---	---
4	1221.	---	---
5	1400.	---	---
6	1140.	---	---
7	1118.	---	---
8	1205.	---	---
<u>2-factor solution</u>			
Speaker 1	1068.	431.9	---
2	970.2	254.2	---
3	1211.	96.12	---
4	1031.	287.1	---
5	1447.	-40.64	---
6	946.6	289.8	---
7	959.6	241.0	---
8	947.3	383.7	---
<u>3-factor solution</u> (solution 1; R^2=0.961)			
Speaker 1	1235.	1254.	1280.
2	1055.	972.1	972.6
3	1049.	1139.	882.2
4	1097.	1102.	1068.
5	1311.	969.9	772.6
6	1030.	1023.	1003.
7	1029.	957.6	940.3
8	1151.	1049.	1149.
<u>3-factor solution</u> (solution 2; R^2=0.958)			
Speaker 1	1277.	480.1	567.7
2	1256.	456.3	270.7
3	1400.	288.5	101.9
4	1400.	563.4	286.1
5	1524.	29.57	-110.6
6	1145.	389.6	365.1
7	1167.	379.5	296.9
8	1227.	520.3	459.0

Because no unique solution was obtainable for English at three dimensions, we can conclude that either the 1- or the 2-factor solution is the appropriate representation of the English data set. Further, the erratic speaker loadings along the second factor of the 2-factor solution lead us to suspect that the 1-factor solution may be the correct one, in addition to the fact that this single factor by itself accounts for such a large percentage of the variance. On the other hand, in the 2-factor solution six out of the eight speaker loadings along factor 2 lie within a reasonable range, so it may be that it is only these speakers that do not fit the assumptions of the model along this dimension. Although the choice between the 1- and 2-factor solutions is not a completely clear one, it seems safest to select the 1-dimensional solution, for which the data do not appear to deviate in any way from the assumptions of the model.

CANTONESE

<u>1-factor solutions</u>: Four 1-factor solutions converged after 4 iterations, and were found to match. $R^2 = 0.904$. As shown in Table 6, the speaker loadings all lie within a reasonable range.

<u>2-factor solutions</u>: Six matching 2-factor solutions converged after between 70 and 160 iterations. $R^2 = 0.945$. As Table 6 shows, the speaker loadings along both factors lie within a reasonable range (although the loading for speaker 7 is somewhat lower than the others). The correlations of the factor loadings for each mode are as follows:

Measures	0.798
Vowels	-0.607
Speakers	-0.200

Thus, the two factors are clearly distinct.

<u>3-factor solutions</u>: Seven 3-factor solutions were obtained. Six of these are matching, while one is different from the others. The latter is therefore taken to represent a local maximum and can be ignored. R^2 for the unique solution is 0.964. Examination of Table 6 reveals that while the speaker loadings along factors 1 and 2 lie within a reasonable range, speaker loadings 1 and 4 along factor 3 are negative. In addition, the loading for speaker 3 is comparatively high. Hence the data may not conform to the system-variation assumption along this dimension.

The correlations of the factor loadings for the 3-factor solution are as follows:

	Factor 1-Factor 2	Factor 1-Factor 3	Factor 2-Factor 3
Measures	0.829	0.061	0.145
Vowels	-0.715	-0.253	0.642
Speakers	-0.421	-0.615	0.315

Table 6: Speaker loadings for Cantonese PARAFAC solutions of differing dimensionality.

	Factor 1	Factor 2	Factor 3
1-factor solution			
Speaker 1	1049.	---	---
2	1098.	---	---
3	1350.	---	---
4	1117.	---	---
5	1300.	---	---
6	1167.	---	---
7	1049.	---	---
8	1254.	---	---
2-factor solution			
Speaker 1	861.1	322.4	---
2	883.2	365.1	---
3	930.6	639.6	---
4	888.0	373.3	---
5	946.9	548.5	---
6	862.9	479.3	---
7	981.5	163.9	---
8	873.7	584.4	---
3-factor solution			
Speaker 1	933.5	332.3	-66.64
2	849.4	302.0	174.4
3	853.1	498.3	369.1
4	946.1	360.1	-13.20
5	932.2	459.9	199.3
6	871.5	432.9	111.2
7	942.4	113.4	140.2
8	887.6	526.4	131.2

Since none of the pairs of factors are highly correlated in all three modes, it can be assumed that the factors represent different dimensions.

<u>4-factor solutions</u>: Two 4-factor solutions were run, but did not converge at up to 560 iterations. They did not appear to be approaching the same solution. The final R^2 for the first solution was 0.997, and 0.988 for the second solution. Because they did not meet the convergence or uniqueness criteria, the 4-factor solutions were not considered further.

In summary, since there is a substantial increase in the amount of variance accounted for in going from 1 to 2 factors, the 2-dimensional solution is preferable to the 1-dimensional one for Cantonese. This leaves us to choose between the 2- and 3-factor solutions. The erratic speaker loadings along the third factor of the 3-factor solution lead us to prefer the 2-dimensional solution; however, there are really only two (perhaps three) speakers whose behavior is deviant along this dimension. Thus, as was found to be the case for English, while the higher dimensional solution is not an obviously incorrect one, it seems safer to choose the solution with fewer dimensions.

FINNISH

<u>1-factor solutions</u>: Four 1-factor solutions converged after 4 iterations. They matched one another. R^2 was 0.894. The speaker loadings, shown in Table 7, appear to lie in a reasonable range.

<u>2-factor solutions</u>: Three 2-factor analyses were run. It was difficult to achieve convergence; between 480 and 760 iterations were necessary. The solutions matched. R^2 was 0.945. The 2-factor solution appears to conform to the system-variation assumption, at least with respect to the pattern of speaker loadings shown in Table 7.

The correlations of the factor loadings are as follows:

Measures	0.863
Vowels	0.517
Speakers	-0.371

The factors are thus not highly correlated in all three modes.

<u>3-factor solutions</u>: Four 3-factor solutions converged after between 202 and 480 iterations, and met the uniqueness criterion. R^2 was 0.963. Table 7 shows that the speaker loadings lie within a reasonable range along all three dimensions.

The correlations of the factor loadings are as follows:

	Factor 1-Factor 2	Factor 1-Factor 3	Factor 2-Factor 3
Measures	-0.249	0.733	0.089
Vowels	0.152	0.509	0.239
Speakers	-0.831	-0.367	0.152

Table 7: Speaker loadings for Finnish PARAFAC solutions of differing dimensionality.

	Factor 1	Factor 2	Factor 3
1-factor solution			
Speaker 1	1094.	---	---
2	1086.	---	---
3	1098.	---	---
4	1009.	---	---
5	1124.	---	---
6	1042.	---	---
7	1210.	---	---
8	1054.	---	---
2-factor solution			
Speaker 1	1225.	489.8	---
2	1222.	482.4	---
3	1218.	351.2	---
4	1143.	593.8	---
5	1256.	450.3	---
6	1169.	513.8	---
7	1350.	488.8	---
8	1193.	517.7	---
3-factor solution			
Speaker 1	632.4	516.3	237.8
2	514.3	545.1	363.5
3	821.3	374.8	157.1
4	409.4	673.8	221.1
5	608.9	485.5	358.2
6	562.1	558.1	199.2
7	675.4	583.0	275.7
8	534.5	527.2	306.7

The factors therefore appear to represent different dimensions.

4-factor solutions: Two 4-factor analyses were run for up to 800 iterations without ever achieving full convergence. The two analyses did not appear to be approaching a unique solution. The final R^2 for both 4-factor solutions was 0.971. The speaker loadings along factor 2 (not shown) for the second solution were erratic. Due to the fact that the convergence and uniqueness criteria were not met, the 4-factor solutions were not investigated any further.

Thus, for Finnish it seems fairly clear that the 3-dimensional solution is the correct one, at least with respect to the five criteria we are considering in this chapter. A substantial amount of additional variance is accounted for by the third factor, the system-variation assumption appears to be adhered to, and the uniqueness and convergence criteria are met.

FRENCH

1-factor solutions: Four 1-factor solutions converged after 5 iterations, and uniqueness was achieved. R^2 was 0.817. The speaker loadings, shown in Table 8, all lie within a normal range.

2-factor solutions: Four 2-factor solutions achieved convergence after between 34 and 160 iterations. The uniqueness criterion was met. R^2 was 0.891. As shown in Table 8, the speaker loadings vary within a reasonable range along both factors.

The correlations of the factor loadings are given below:

Measures	-0.528
Vowels	0.318
Speakers	0.611

The two factors thus appear to represent different underlying dimensions.

3-factor solutions: Five 3-factor solutions converged after between 150 and 279 iterations. All five solutions were the same. R^2 was 0.952. As Table 8 shows, there are no extreme values of speaker loadings along any of the three dimensions, although these weightings do vary more along the third factor than they do along the first two factors. The loading for speaker 2 is particularly high.

The correlations of the factor loadings are as follows:

	Factor 1-Factor 2	Factor 1-Factor 3	Factor 2-Factor 3
Measures	0.871	-0.465	-0.470
Vowels	-0.126	0.056	0.657
Speakers	0.397	0.656	0.310

The factors are thus seen to represent different dimensions.

Table 8: Speaker loadings for French PARAFAC solutions of differing dimensionality.

	Factor 1	Factor 2	Factor 3
<u>1-factor solution</u>			
Speaker 1	1014.	---	---
2	1382.	---	---
3	1094.	---	---
4	1119.	---	---
5	1066.	---	---
6	1042.	---	---
7	1114.	---	---
8	1136.	---	---
<u>2-factor solution</u>			
Speaker 1	980.3	160.9	---
2	1221.	665.3	---
3	1100.	31.19	---
4	1124.	63.99	---
5	1035.	172.1	---
6	1029.	84.54	---
7	1075.	182.1	---
8	1123.	102.0	---
<u>3-factor solution</u>			
Speaker 1	984.6	140.8	125.1
2	1129.	419.2	664.3
3	1039.	316.3	18.40
4	1026.	461.3	33.32
5	953.7	370.1	172.5
6	1015.	149.4	73.93
7	1033.	278.9	162.7
8	1056.	347.8	90.61

4-factor solutions: Two 4-factor solutions did not converge after 420 iterations. The two did not appear to be approaching the same solution, and so the uniqueness criterion was not met. R^2 for both 4-factor solutions was 0.962. The speaker loadings (not shown in Table 8) along two out of the four factors in both solutions were extremely erratic, and thus the system-variation assumption appears to be violated along these dimensions. Therefore, the 4-factor solutions for French can be eliminated from further consideration.

Given the five criteria under discussion, French, like Finnish, seems to have three underlying dimensions of lip shape. This is particularly clear for French, for which an even greater additional proportion of the variance is accounted for in going from two to three dimensions.

SWEDISH

1-factor solutions: Four 1-factor solutions achieved convergence after 5 iterations. The solutions matched each other. R^2 was 0.834. The speaker loadings, given in Table 9, seem to lie within a reasonable range.

2-factor solutions: Four 2-factor solutions converged after between 63 and 150 iterations. The same solution was reached from the four starting configurations. R^2 was 0.889. The speaker loadings do not vary erratically, as shown in Table 9.

The correlations of the factor loadings are given below, and indicate that the two factors represent different dimensions:

Measures	0.039
Vowels	0.646
Speakers	0.871

3-factor solutions: Five matching 3-factor solutions converged after between 55 and 200 iterations. R^2 was 0.938. The speaker loadings, as shown in Table 9, vary a fair amount but do not clearly indicate a departure from the assumption of system-variation.

The correlations of the factor loadings, indicating that the factors are not the same across all three modes, are as follows:

	Factor 1-Factor 2	Factor 1-Factor 3	Factor 2-Factor 3
Measures	0.750	-0.112	0.116
Vowels	0.838	-0.500	-0.213
Speakers	-0.369	-0.725	0.421

4-factor solutions: Two 4-factor PARAFAC analyses were run. One of these converged after 320 iterations, with an R^2 of 0.951. The other did not quite achieve convergence after 320 iterations. (R^2 was 0.951), and was approaching a different solution. Since not very much additional variance was accounted for by the fourth factor, and since it appeared that a unique solution would not be obtained, it was decided to discard the 4-factor solution from further consideration.

Table 9: Speaker loadings for Swedish PARAFAC solutions of differing dimensionality.

	Factor 1	Factor 2	Factor 3
1-factor solution			
Speaker 1	1093.	---	---
2	977.0	---	---
3	1209.	---	---
4	965.3	---	---
5	1017.	---	---
6	1121.	---	---
7	1174.	---	---
8	1081.	---	---
2-factor solution			
Speaker 1	1069.	297.8	---
2	969.8	138.3	---
3	1213.	46.51	---
4	954.3	248.1	---
5	1009.	169.1	---
6	1102.	242.5	---
7	1160.	131.8	---
8	1084.	56.27	---
3-factor solution			
Speaker 1	862.3	306.8	352.6
2	922.4	135.9	89.85
3	1125.	320.3	7.792
4	758.1	351.7	273.4
5	854.1	351.2	154.5
6	910.0	310.2	305.1
7	1075.	211.3	122.9
8	1001.	238.4	62.39

It should be noted that Swedish is the only language for which one of the 4-factor solutions achieved convergence; in addition, there was no indication from the speaker loadings that the system-variation assumption was being violated. Carrying out further runs might reveal that a 4-factor solution would be feasible for Swedish; it nonetheless seems that the 3-dimensional solution would be the preferred one, and this is the one that has been pursued in this study. Because there is such a large increase in the percentage of the variance accounted for in going from two dimensions to three dimensions, it seems clear that the 3-factor solution is preferable to the 2-factor solution for Swedish, all other things being equal.

It might be useful at this point to summarize what we have found out so far about the number of underlying dimensions of lip shape in the five languages under investigation. Using five of the six criteria discussed earlier for choosing PARAFAC solutions, we have seen that:

(1) English has either one or two underlying factors. (There is no unique 3-factor solution). Although it is not totally clear how to choose between these solutions, it is a very interesting result that English cannot have its lip positions represented in a 3-dimensional space, given what we have seen for the other four languages, in that English is the only language that lacks front rounded vowels. Also, the small percentage of additional variance accounted for in going from one to two dimensions, in conjunction with the deviant loadings for two of the speakers along the second factor, makes the 1-factor solution preferable to the 2-factor solution.

(2) Cantonese has either two or three underlying factors of lip position. As with English (although to an even greater extent), erratic speaker loadings in the solution of higher dimensionality make the solution of lower dimensionality the preferred one.

(3) Finnish, French and Swedish clearly have three underlying factors, given the criteria discussed up to this point.

Table 10 summarizes the results for all of the languages regarding the criteria of uniqueness, convergence and R^2 values.

The differences among the languages for one of the five criteria - relative amount of variance accounted for - is shown explicitly in Figure 3. Here the R^2 values are plotted as a function of dimensionality for each language. By examination of this figure alone, certain striking differences emerge among the five languages. First, it is clear that the 1-factor solution for English accounts for a much higher percentage of the variance in the data than the 1-factor solutions for any of the other languages. Second, the languages look as though they are divided into three groups: (1) English, (2) Cantonese and Finnish, and (3) French and Swedish. These groupings are in fact reflected by the other criteria we have discussed so far, except that (unlike Cantonese), there is no difficulty in considering Finnish to have three underlying dimensions of lip shape. Finally, the 2-factor solutions for English, Cantonese, and Finnish, and the 3-factor solutions for French and Swedish all account for similar percentages of variance.

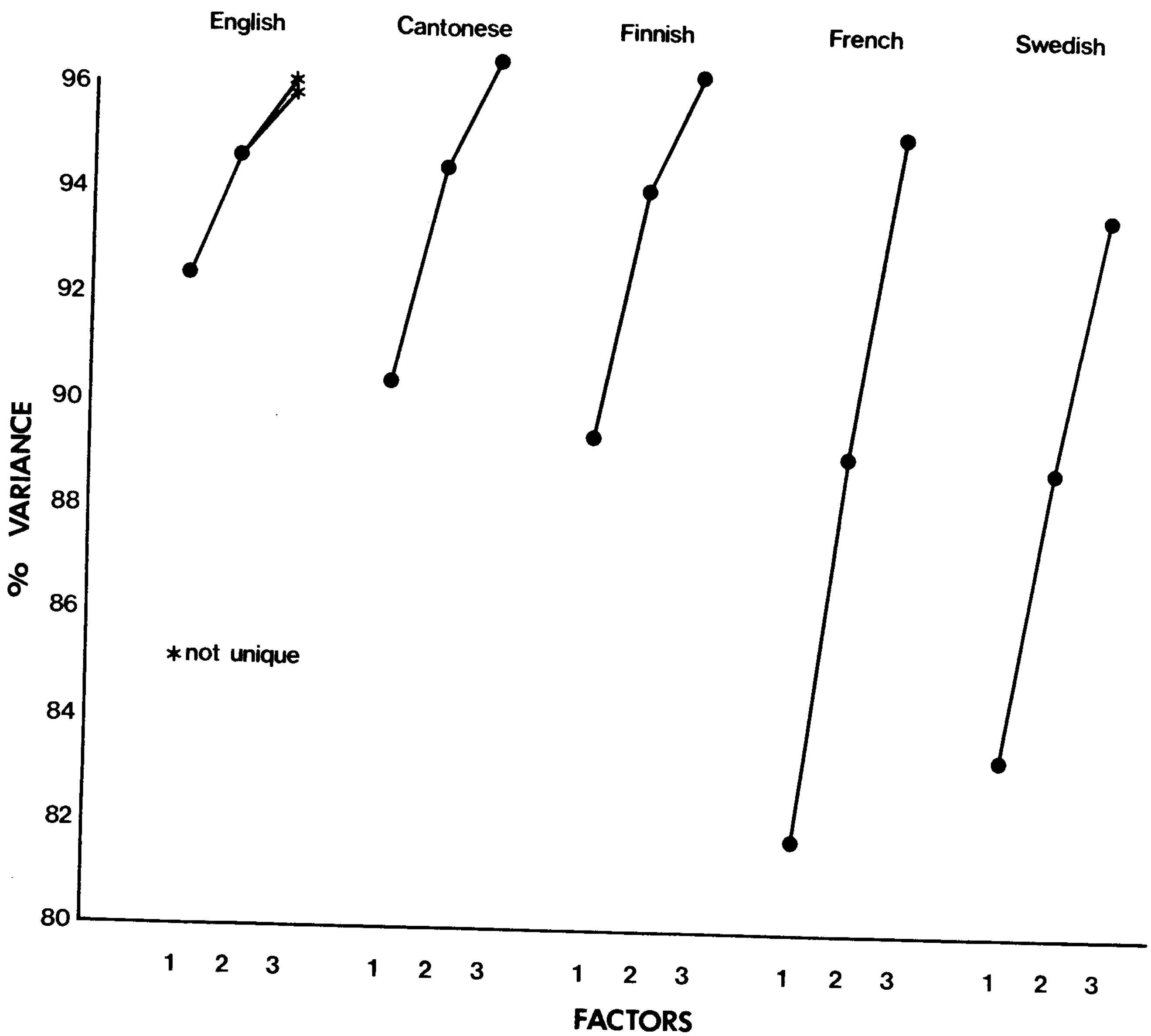
Table 10: R^2 values for converged and unique PARAFAC solutions.

	ENGLISH	CANTONESE	FINNISH	FRENCH	SWEDISH
1-factor	0.924	0.904	0.894	0.817	0.834
2-factor	0.948	0.945	0.942	0.891	0.889
3-factor	* +	0.964	0.963	0.952	0.938
4-factor	---	* +	* +	* +	* +

* = solution did not converge

\+ = no unique solution found

Figure 3: Percent variance for solutions from PARAFAC (ordinate) plotted againtst the number of factors extracted (abcissa). The values are plotted separately for each language.



In the next chapter, the criterion of interpretability of factors will be considered. We will see how the underlying factors for each language can be interpreted in terms of the lip measurements they represent, and how the vowels of each system cluster along the different dimensions.

Chapter 4: Factor Analysis of Lip Shapes: Results

Factor Interpretation

We are now in a position to interpret the factors extracted by PARAFAC, in terms of the underlying parameters of lip shape they represent. We can get a good idea of what these parameters are by examining the ordering of the loadings in the lip measurement space (M), since those measures that have high positive or high negative loadings are the ones that contribute the most to a given dimension. Measures with values lying closer to zero on the scale contribute the least. (It will probably be helpful to the reader to refer to Figures 1 and 2 throughout this discussion). We will now look at the measurement spaces of each language in turn, for the solutions that have been shown to meet the criteria discussed in Chapter 3. While we will ultimately want to focus on the solutions that we have decided are the optimal ones, it will be interesting at this point to look briefly at the solutions of lower dimensionality as well, in order to see what these factors have in common with those of the optimal solutions.

ENGLISH

Figure 4 shows the ordering of the lip measurement loadings along the single factor found to underlie the English data. We find measure 23, horizontal opening, to be located at the extreme upper part of the scale, while we find the other measures grouped toward the bottom of the scale. Because measure 23 has such a high positive loading relative to the other measures, we can conclude that the factor underlying the English data is primarily one of horizontal opening.

CANTONESE

1-factor solution: Figure 5 shows the ordering of the measurement loadings for the 1-factor solution for Cantonese. As with English, this factor is seen to be directly proportional to horizontal opening (measure 23); in addition, measure 24 (the area enclosed by the lips in the front view) has a relatively high positive loading along this factor. There is an interesting difference between the 1-factor solution for Cantonese and the 1-factor solution for English regarding the location of measures 20, 21 and 22 (vertical opening); for English, these measures are located at the opposite end of the scale from measure 23 (horizontal opening), while for Cantonese they have loadings around 0.8.

2-factor solution: Factor 1 of the 2-factor solution looks very much like the 1-factor solution, with regard to the measurement space shown in Figure 6. Factor 1 and factor 2 are directly proportional to measure 23, horizontal opening, and to a lesser degree to measure 24, the area in the front view. Factor 2 is also proportional to vertical opening (measures 21, 20, 22). While both factors 1 and 2 are to a large extent affected by horizontal opening and front view area, one interesting difference between the factors lies in the placement of measures 1 and 3 (upper and lower lip protrusion, respectively, as measured with reference to the upper front teeth). While measures 1 and 3 have loadings above 0.8 along factor 1, they have much lower loadings along factor 2; measure 1 has, in fact, a loading close to zero along the second factor.

Figure 4: Lip measure loadings for the English 1-factor solution

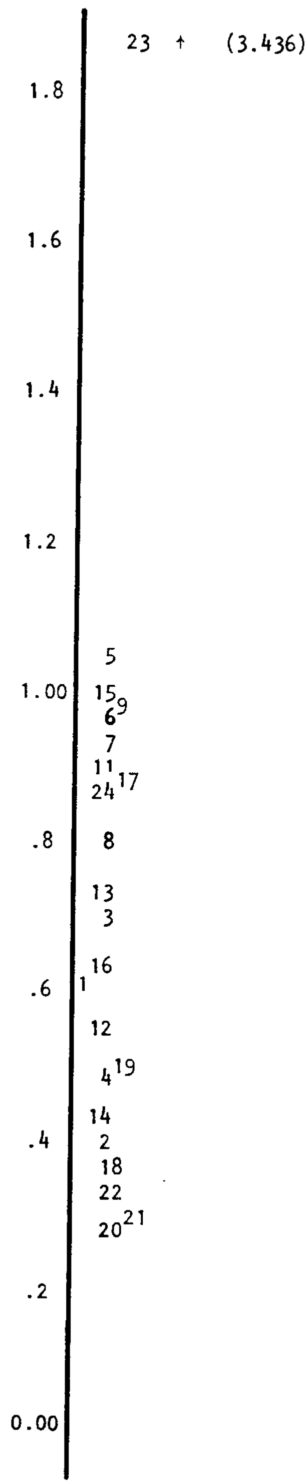


Figure 5: Lip measure loadings for the Cantonese 1-factor solution

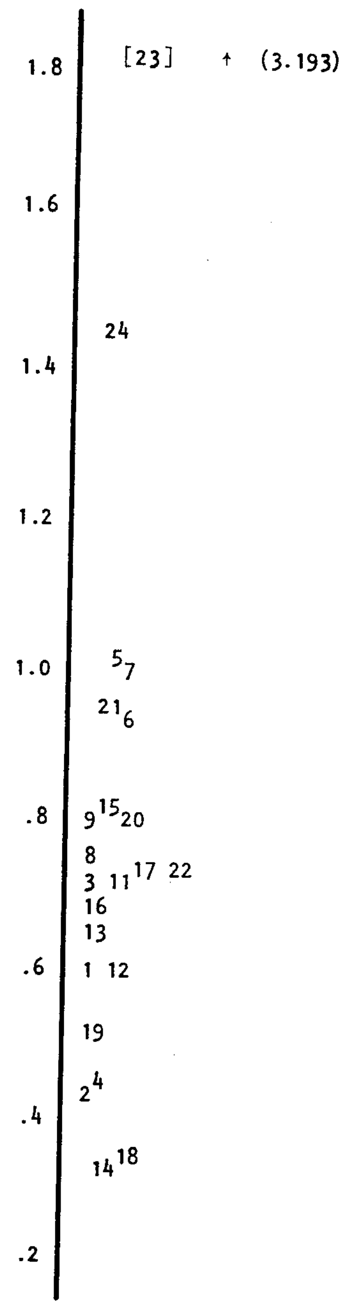
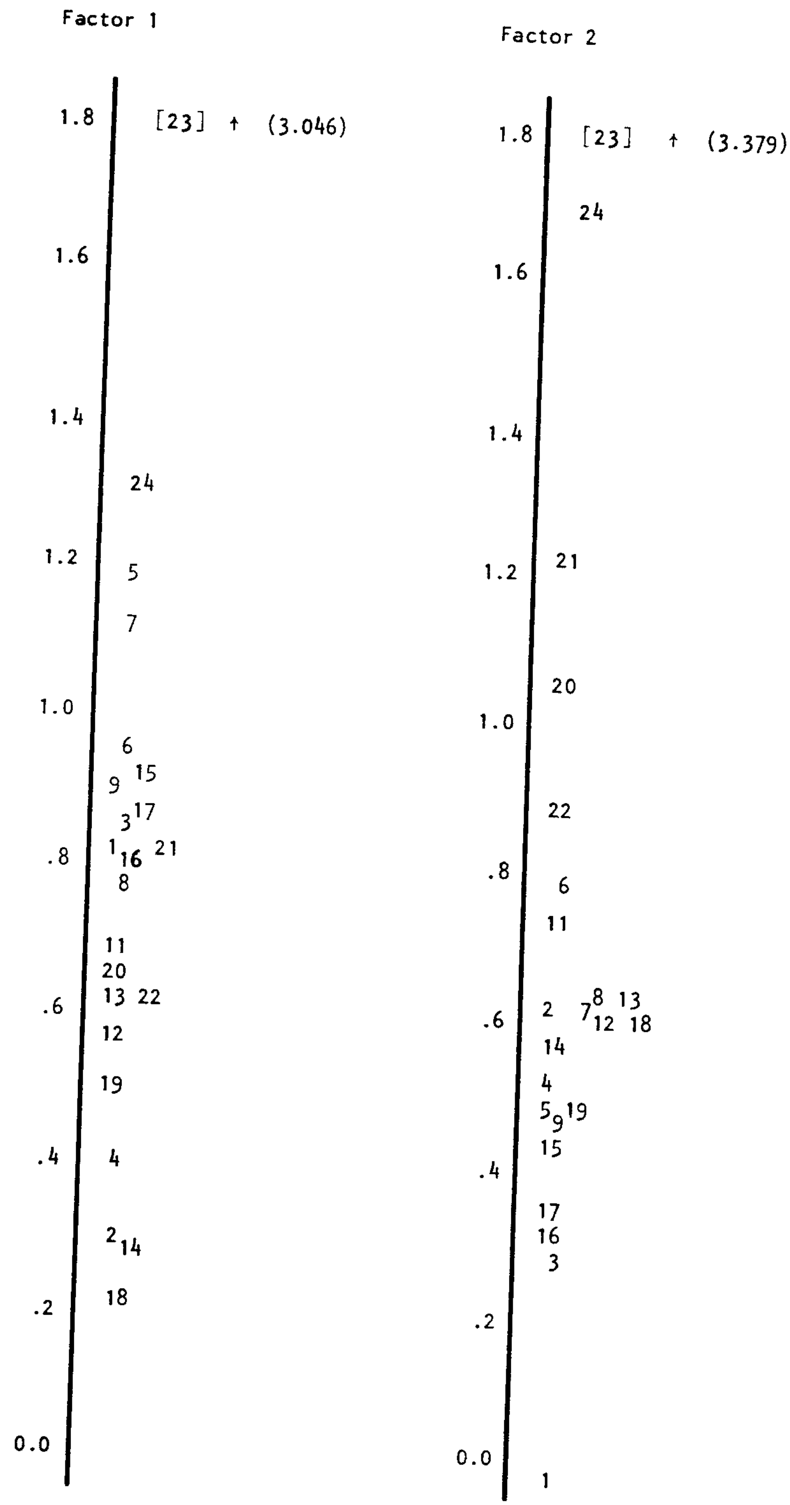


Figure 6: Lip measure loadings for the Cantonese 2-factor solution



We can get an idea of how similar the factors are across solutions by looking at the correlations of the measurement, vowel and speaker loadings. Two comparisons are of interest here. First, the correlations of the measure loadings will tell us how close the factors from different solutions are physiologically. This is true because the underlying dimensions found by PARAFAC naturally must reflect the 23 measurements of lip position being analyzed. Second, high correlations in all three modes will tell us that the different factors are basically the same, in that the measures, vowels and speakers all pattern in similar fashion along them. The correlations were obtained using a program called CMPARE (Scientific Software Associates, 1981).

The correlations of the factor loadings in all three modes for the 1-factor solution with the two factors of the 2-factor solution are shown in Table 11 below.

		1-FACTOR	2-FACTOR	
		1	1	2
1-FACTOR				
1	measures	---	0.979	0.904
	vowels	---	-0.550	0.998
	speakers	---	0.171	0.931

Table 11: Correlations of factor loadings for different Cantonese PARAFAC solutions.

It can be seen from this table that the measurement loadings along both factors of the 2-factor solution are highly correlated with the measure loadings along the factor of the 1-factor solution; with respect to the measures, the correlation is especially high for factor 1 of the 2-factor solution. This result is not surprising, given our interpretation of these dimensions; horizontal opening is the greatest contributor to all three factors. Also, since the correlations are high in all three modes between the factor of the 1-factor solution and factor 2 of the 2-factor solution, it appears that this second factor is the one most closely related to the one-dimensional solution.

FINNISH

<u>1-factor solution</u>: The ordering of measurement loadings for the 1-factor solution for Finnish, shown in Figure 7, is similar to the 1-factor Cantonese solution. This factor is directly proportional to horizontal opening (measure 23), and to a lesser degree to the area enclosed by the lips in the front view (measure 24).

<u>2-factor solution</u>: Figure 8 shows the ordering of measurement loadings for the 2-factor solution for Finnish. Factor 1 is primarily related to horizontal opening and front view area, although the measures of vertical opening also have relatively high positive loadings. Factor 2 is directly proportional to upper and lower lip protrusion (measures 1 and 3). Measures 5 and 15 also have relatively high positive loadings. Measure 5 is the distance from point C (the corner of the mouth) to the outermost point on the upper lip surface (point F), and measure 15 is the distance from point C to a vertical line drawn through point F. These last two parameters are therefore both measures of protrusion, and we can conclude

Figure 7: Lip measure loadings for the Finnish 1-factor solution

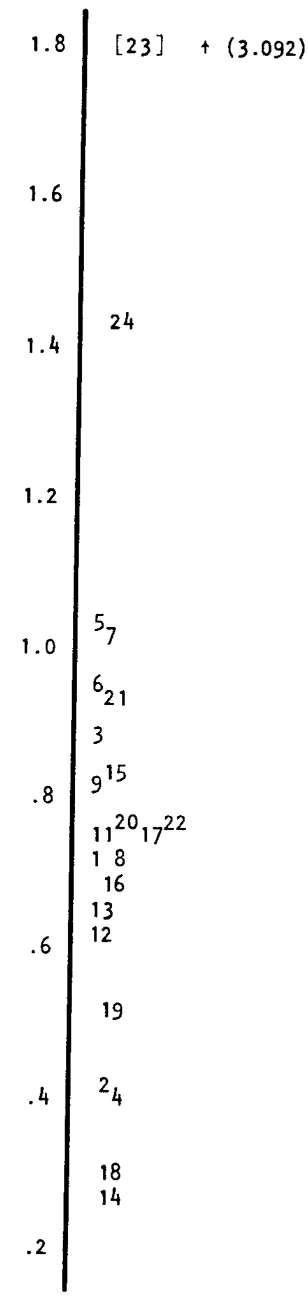


Figure 8: Lip measure loadings for the Finnish 2-factor solution

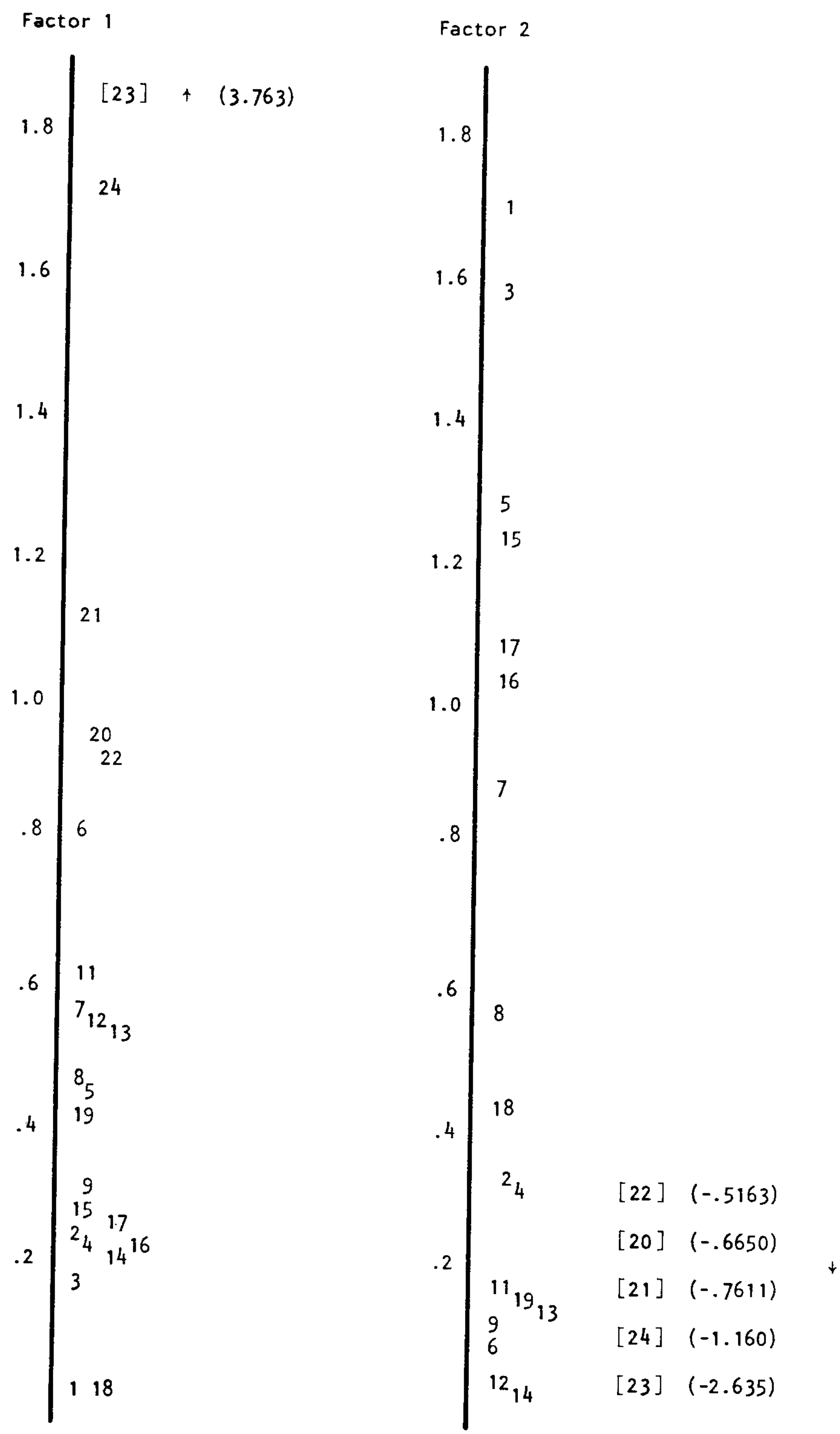
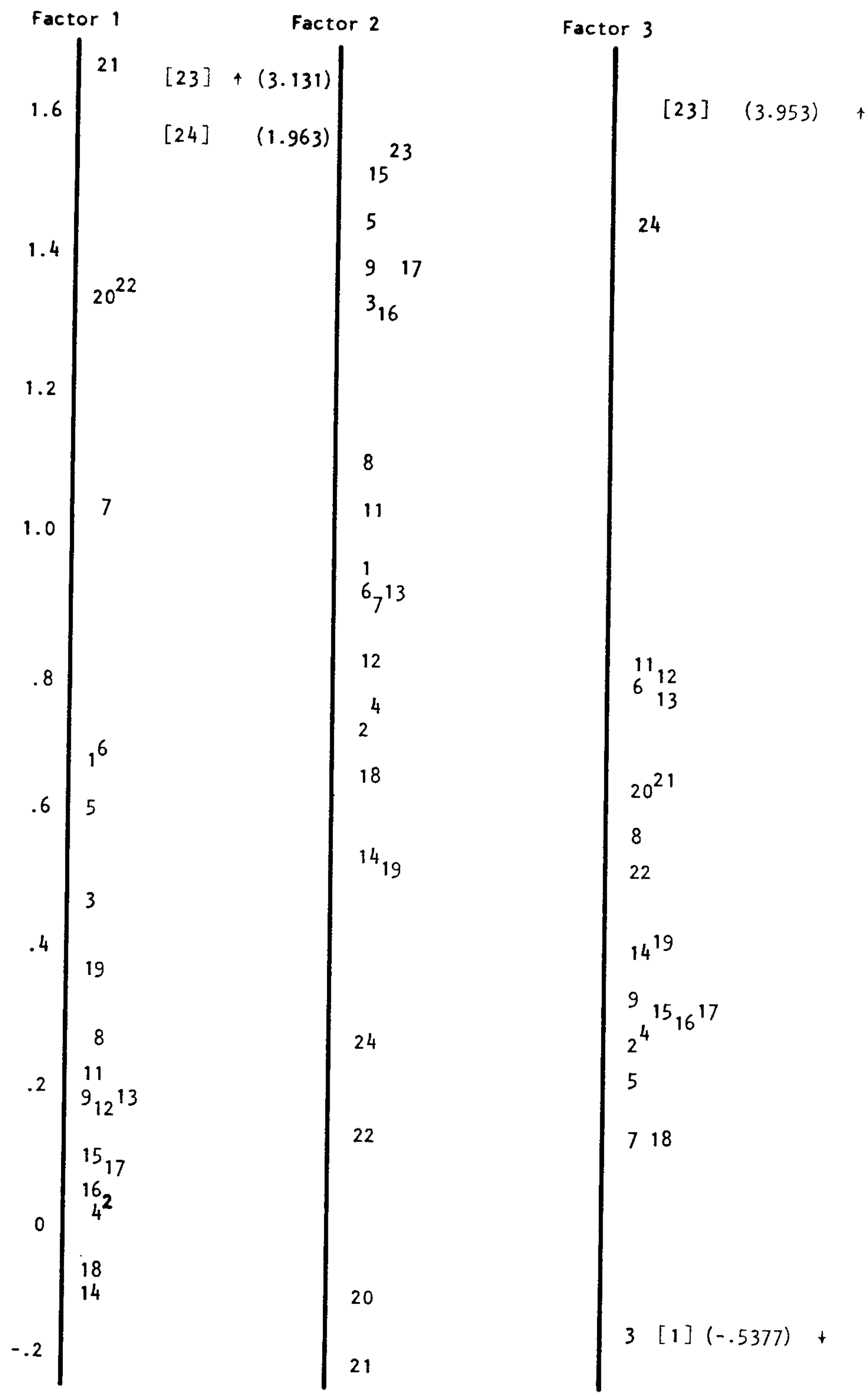


Figure 9: Lip measure loadings for the Finnish 3-factor solution



that factor 2 is largely a protrusion factor. In addition, we see that measures 23 and 24 (horizontal opening and front view area) have high negative loadings along factor 2. We can conclude from these facts that factor 2 is directly proportional to measures of protrusion, and inversely proportional to horizontal opening and front view area.

<u>3-factor solution</u>: As shown in Figure 9, Factor 1 is primarily related to horizontal opening (measure 23), and to front view area (measure 24). Measures 21, 20 and 22 also have relatively high loadings along this factor. Looking at the loadings along factor 2, we see that measure 23 (horizontal opening) has a fairly large positive weighting. In addition, we expect measures 3, 5, 9, 15, 16, and 17 to contribute to this dimension; measures 5 and 15 are measures of upper lip protrusion (from the corner of the mouth), while measures 3, 9, 16, and 17 are all measures of lower lip protrusion (see Figure 1). Therefore, factor 2 seems to represent a dimension of horizontal opening and protrusion.

Factor 3 is primarily related to horizontal opening and front view area. An important difference between this factor and the first factor lies in the placement of measures 1 and 3 (upper and lower lip protrusion); while both of these measures have loadings above 0.4 along factor 1, they have negative loadings along factor 3.

The correlations among the loadings for the different solutions for Finnish are given below in Table 12.

		1-FACTOR	2-FACTOR		3-FACTOR		
		1	1	2	1	2	3
1-FACTOR							
1	measures	---	0.924	0.603	0.849	0.277	0.860
	vowels	---	1.000	0.521	0.742	0.298	0.952
	speakers	---	0.995	-0.451	0.599	-0.260	0.261
2-FACTOR							
1	measures	---	---	---	0.899	-0.033	0.956
	vowels	---	---	---	0.744	0.301	0.952
	speakers	---	---	---	0.524	-0.185	0.325
2	measures	---	---	---	0.751	-0.434	0.855
	vowels	---	---	---	0.142	-0.511	0.661
	speakers	---	---	---	-0.905	0.949	0.155

Table 12: Correlations of factor loadings for different Finnish PARAFAC solutions.

It can be concluded from Table 12 that the measure loadings of the 1-factor solution are highly correlated with the measure loadings along the first factor of the 2-factor solution. These loadings are less highly correlated with the measure loadings along any of the factors of the 3-factor solution. The measure loadings along factor 1 of the 2-factor solution are most highly correlated with the measure loadings along factor 3 of the 3-factor solution, and reasonably highly correlated with the loadings in this mode along factor 1. The measure loadings along factor 2 of the 2-factor solution are fairly highly correlated (0.855) with the measure loadings along factor 3 of the 3-factor solution.

Looking at the loadings across all modes, we can see that the factor of the 1-factor solution is extremely similar to factor 1 of the 2-factor solution. Also, their is a reasonably high correlation in two modes (measures and vowels) between factor 1 of the 1-factor solution and factor 3 of the 3-factor solution. Otherwise, all of the factors behave differently from one another either with regard to variance among vowels or with regard to variance among speakers.

FRENCH

1-factor solution: Figure 10 shows the pattern of lip measurement loadings for the 1-factor solution for French. As with the other languages, this factor is primarily related to horizontal opening (measure 23), and to a lesser extent to front view area (measure 24).

2-factor solution: (see Figure 11). The ordering of the measure loadings along factor 1 of the 2-factor solution is very similar to the 1-factor solution. This factor is directly proportional to horizontal opening, as well as to front view area. The ordering of the loadings along factor 2 is quite different. This dimension is directly proportional to vertical opening (measures 7, 20, 21, 22), and to lower lip protrusion (measure 3). It is inversely proportional to horizontal opening between the lips.

3-factor solution: (see Figure 12). Factor 1 is directly related to horizontal opening, as well as to front view area. To a more minor extent it is related to measure 5 (the distance from the corner of the mouth, point C, to the outermost point on the upper lip surface, point F), and to measure 7 (vertical opening). Factor 2 is also directly proportional to horizontal opening and to front view area; however, unlike for factor 1, two parameters of protrusion from the teeth (measures 1 and 3) are seen to have negative loadings. Factor 3, like factor 2 of the 2-factor solution, is directly proportional to vertical opening between the lips, and to a lesser extent to lower lip protrusion. It is inversely proportional to horizontal opening.

The correlations among the factor loadings for the different PARAFAC solutions for French are given in Table 13 below.

Figure 10: Lip measure loadings for the French 1-factor solution

Factor 1

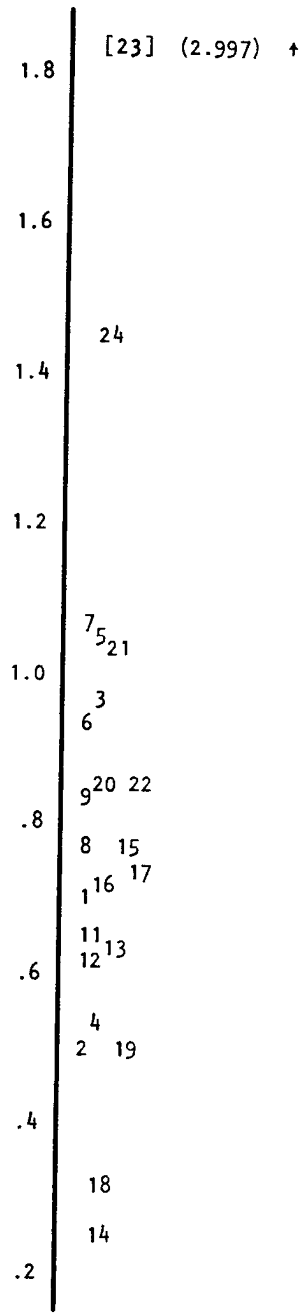


Figure 11: Lip measure loadings for the French 2-factor solution

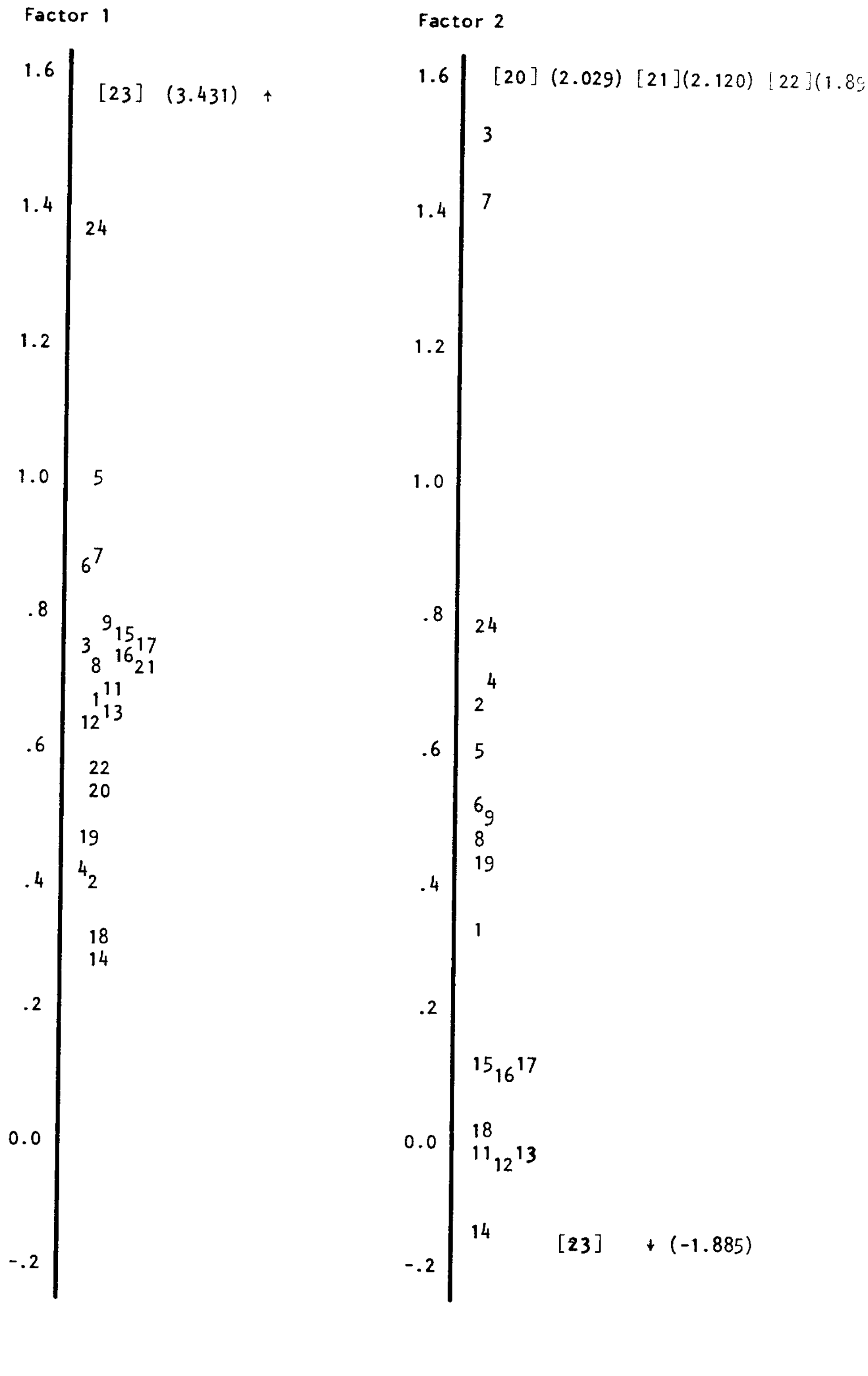
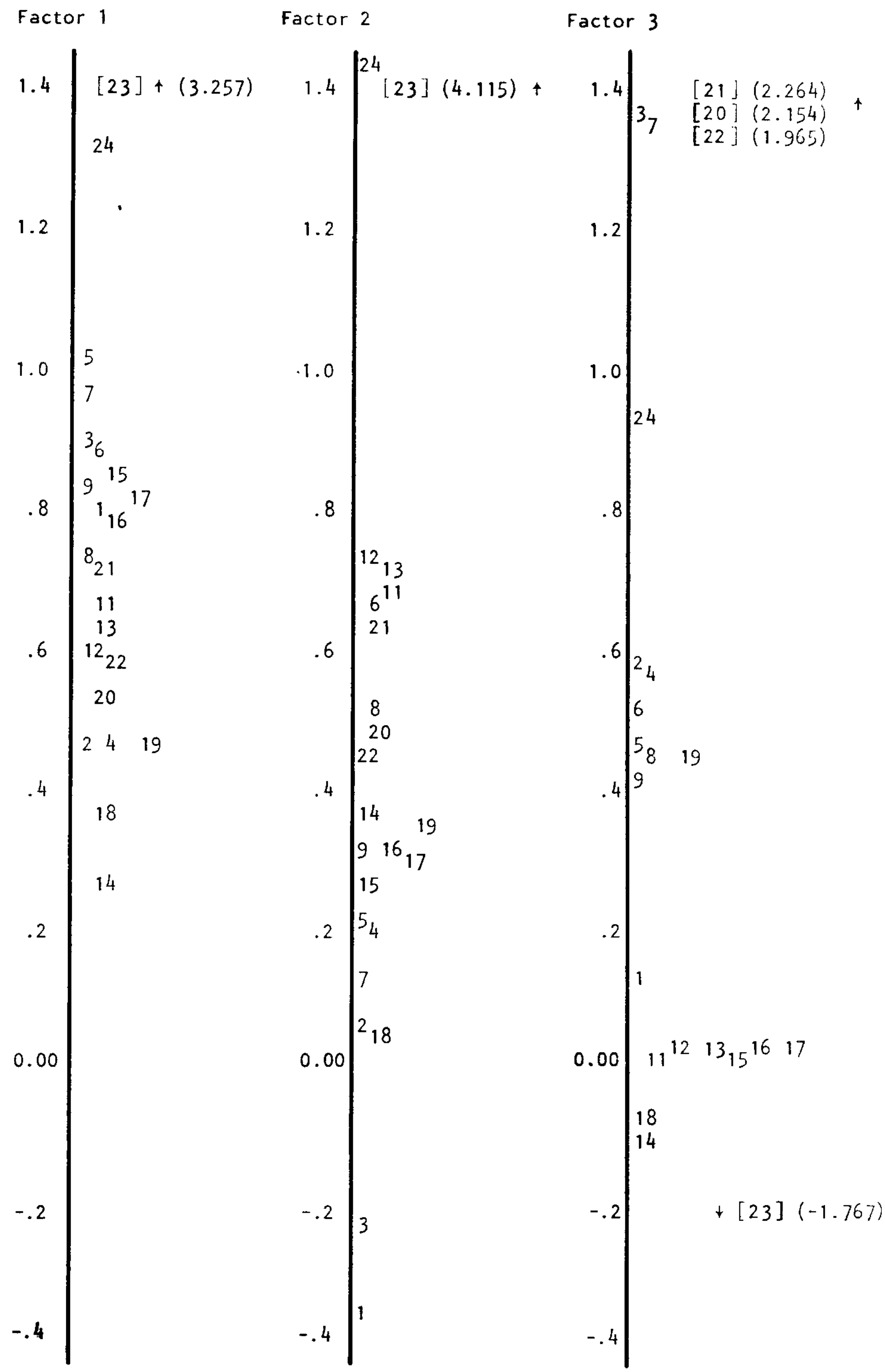


Figure 12: Lip measure loadings for the French 3-factor solution



		1-FACTOR	2-FACTOR		3-FACTOR		
		1	1	2	1	2	3
1-FACTOR							
1	measures	---	0.975	-0.324	0.976	0.871	-0.272
	vowels	---	0.997	0.388	-0.021	0.992	0.724
	speakers	---	0.920	0.871	0.884	0.608	0.875
2-FACTOR							
1	measures	---	---	---	0.996	0.912	-0.479
	vowels	---	---	---	-0.034	0.996	0.670
	speakers	---	---	---	0.889	0.765	0.617
2	measures	---	---	---	-0.506	-0.550	0.994
	vowels	---	---	---	0.146	0.300	0.916
	speakers	---	---	---	0.656	0.300	0.998

Table 13: Correlations of factor loadings for different French PARAFAC solutions

We see from this table that the measurement space of the 1-factor solution is highly correlated with the measurement spaces of (a) factor 1 of the 2-factor solution and (b) factor 1 of the 3-factor solution. The ordering of measurements along the first factor of the 2-factor solution is virtually identical to that along the first factor of the 3-factor solution, and also very similar to the second factor of the 3-factor solution. The measure loadings along factor 2 of the 2-factor solution are very highly correlated with the measure loadings along factor 3 of the 3-factor solution, as we saw qualitatively when interpreting these factors.

Looking at all three modes together, we see that the factor of the 1-factor solution and factor 1 of the 2-factor solution are very highly correlated, as are the second factor of the 2-factor solution and the third factor of the 3-factor solution.

SWEDISH

<u>1-factor solution</u>: (see Figure 13). As with all the other languages, the factor of the 1-factor solution is directly related to horizontal opening, and to a lesser degree to front view area.

<u>2-factor solution</u>: (see Figure 14). Factor 1 is very similar to the 1-factor solution; it is directly proportional to horizontal opening, and to a lesser degree to front view area. Measure 5 (the distance between the corner of the mouth and the outermost point on the upper lip surface) also has a relatively high positive loading. Factor 2 is directly proportional to both vertical opening (measures 7, 20, 21, 22) and upper and lower lip protrusion (measures 1 and 3). It is inversely proportional primarily to horizontal opening.

<u>3-factor solution</u>: (see Figure 15). Factor 1 of the 3-factor solution is directly related primarily to horizontal opening. To a lesser extent it is also related to front view area (measure 24), and to the distance between points C and F (measure 5). Factor 2 is directly proportional to horizontal opening (and to a lesser

Figure 13: Lip measure loadings for the Swedish 1-factor solution

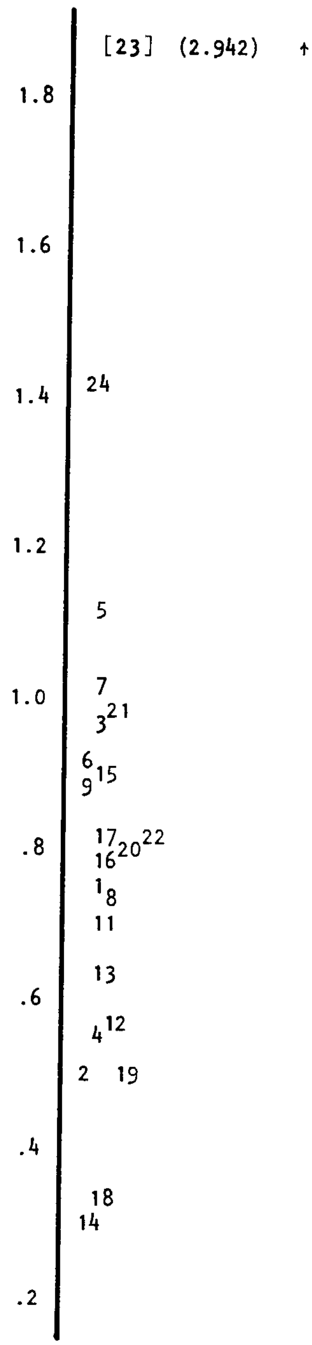


Figure 14: Lip measure loadings for the Swedish 2-factor solution

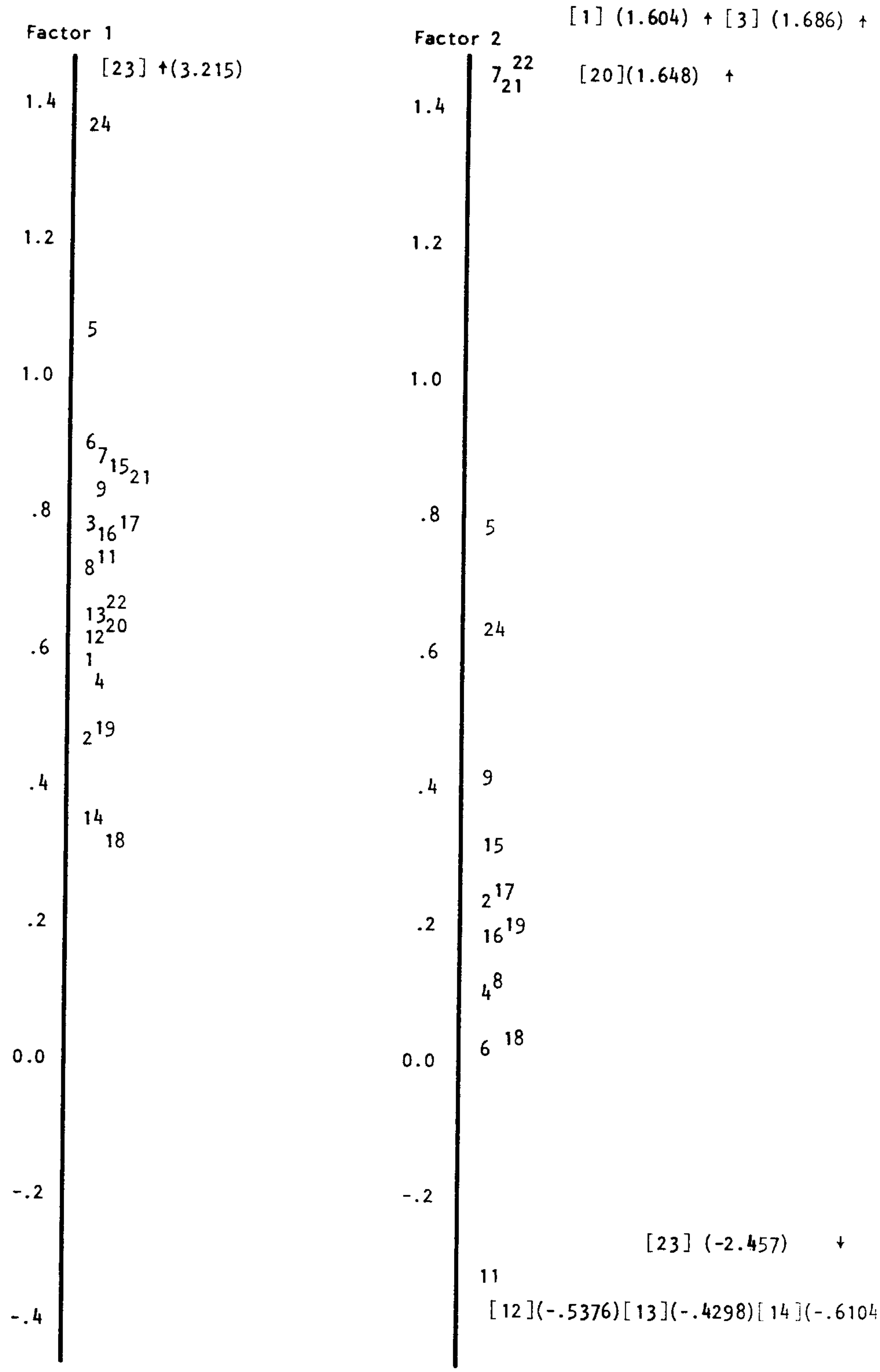
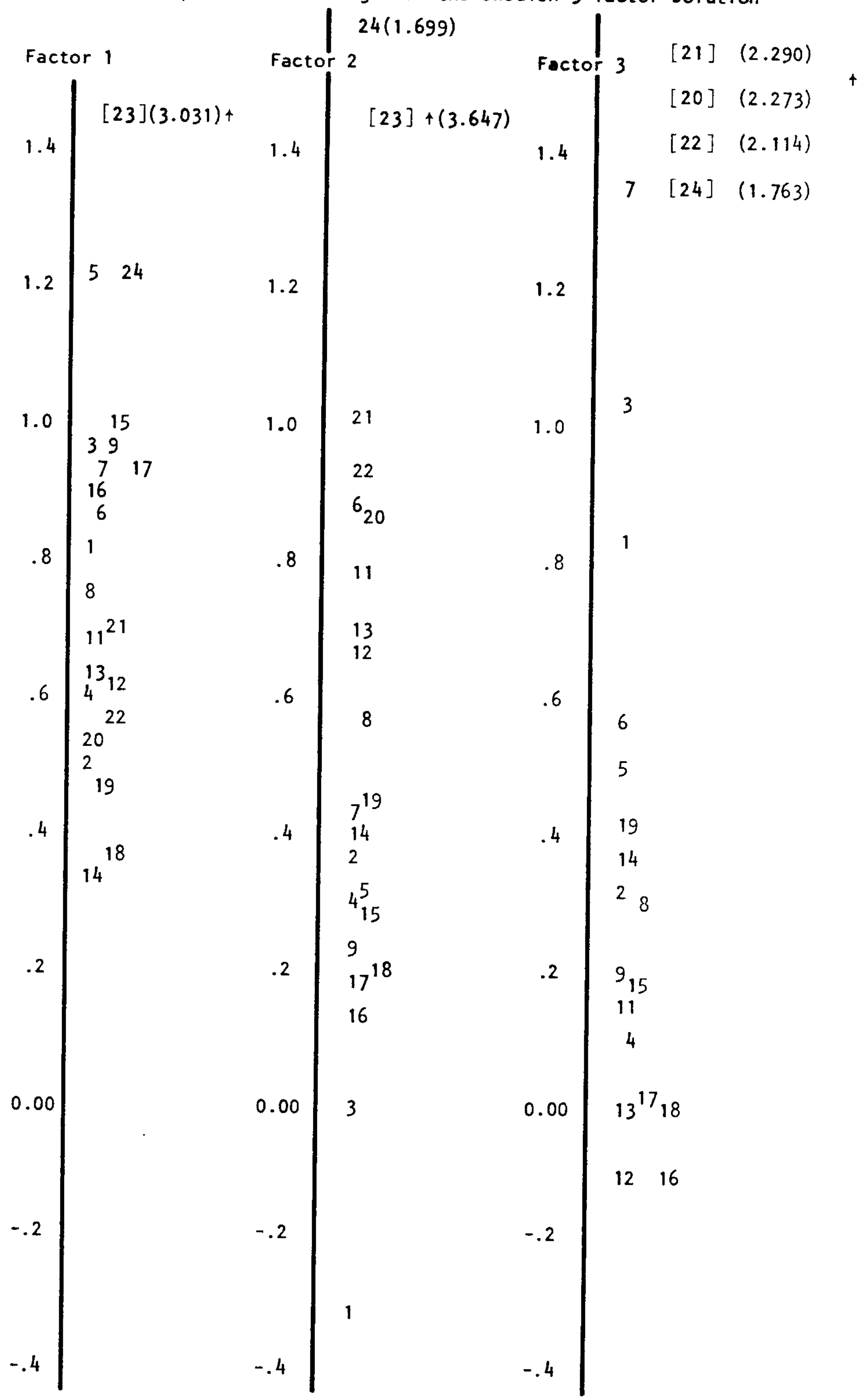


Figure 15: Lip measure loadings for the Swedish 3-factor solution



degree to front view area). The measures of vertical opening (21, 22, 20) also have relatively high positive loadings. In addition, we note that measures 1 and 3 (upper and lower lip protrusion with reference to the teeth) have negative loadings along this factor. Factor 3 is directly proportional to vertical opening and front view area. Also, measures 1 and 3 have relatively high positive weightings.

We can see how these factors correspond to each other quantitatively by examining the correlations among them, which are given in Table 14.

		1-FACTOR	2-FACTOR		3-FACTOR		
		1	1	2	1	2	3
1-FACTOR							
1	measures	---	0.987	-0.356	0.972	0.835	0.102
	vowels	---	0.999	-0.463	0.821	0.986	-0.077
	speakers	---	0.994	-0.365	0.826	0.051	-0.260
2-FACTOR							
1	measures	---	---	---	0.980	0.867	-0.032
	vowels	---	---	---	0.839	0.992	-0.121
	speakers	---	---	---	-0.780	0.371	0.977
2	measures	---	---	---	-0.465	0.545	0.751
	vowels	---	---	---	-0.758	-0.582	0.918
	speakers	---	---	---	-0.780	0.371	0.977

Table 14: Correlations of factor loadings for different Swedish PARAFAC solutions.

The measurement space of the 1-factor solution is highly correlated with the measurement spaces of (a) factor 1 of the 2-factor solution and (b) factor 1 of the 3-factor solution. Also, the measure loadings along factor 1 of the 2-factor solution are highly correlated with the measure loadings along factor 1 of the 3-factor solution. None of the other measurement spaces correlate especially highly with one another. Looking at all modes together, we see that the factor of the 1-factor solution is virtually identical to factor 1 of the 2-factor solution. It is also fairly highly correlated with factor 1 of the 3-factor solution.

We have seen that all of the factors extracted by PARAFAC are interpretable in terms of types of lip movements, and that the lip measurement spaces of the solutions of higher dimensionality have at least one factor in common with solutions of lower dimensionality. At this point it seems worthwhile to point out some of the similarities and differences we have seen regarding the underlying factors for these languages with the parameters found to be relevant in other studies. First, we see (perhaps surprisingly) that the dimension of horizontal opening seems to account for a major portion of the variance in the data for every language. Second, we find, as Fromkin found for English, that measures of horizontal opening, vertical opening and lower lip protrusion tend to contribute a great deal to the underlying dimensions in four out of the five languages, where more than one factor was extracted. We note, however, for English that with the extraction of one factor, accounting for 92% of the variance in the data, a dimension corresponding primarily to the single parameter of horizontal opening is all that is necessary. We note further that upper lip protrusion appears as a component of the factors underlying the Cantonese, Finnish, French and Swedish data sets (it will be recalled that it was this parameter that was found in Chapter 2 not to differ significantly across languages for the vowels [i], [y] and [u], and that Fromkin found to vary the least from speaker to speaker across all the vowels investigated). This component is reflected by the relatively high loadings of measure 1 (upper lip protrusion measured from the teeth) in some cases, but we have also seen that measures 5 and 15 (upper lip protrusion measured from the corner of the mouth) appear more often as important contributors to the interpretation of the underlying dimensions. These are parameters that were not included in Fromkin's study, nor in the analyses of variance described in Chapter 2. We may also mention in this connection that for Finnish, measures 9, 16 and 17, all distances from the corner of the mouth to the outermost point on the lower lip surface turn out to be important measures of lower lip protrusion, in addition to measure 3 (lower lip protrusion from the teeth). Finally, it is interesting to note that a factor that is directly proportional to vertical opening and inversely proportional to horizontal opening was found to underlie the French data. This finding is in agreement with Abry, et al (1979), who concluded that the ratio of the lip axes (i.e., the ratio of the horizontal opening between the lips to the vertical opening between the lips) was important for distinguishing the vowels of French.

Now that we have seen what the dimensions of the different PARAFAC solutions represent and have in common with each other, we may now focus our attention on those solutions that we found to be the appropriate ones in Chapter 3 (one factor for English, two factors for Cantonese, and three factors for Finnish, French and Swedish). There is perhaps an easier way to see the effect of the factors than by just looking at the ordering of the loadings in the measurement space. This is illustrated in Figure 16 for the English 1-factor solution. In the side view, the solid and dashed lines represent deviations from a neutral lip shape (not drawn). The neutral shape is based on the raw data measurements taken for the Cantonese vowel [ɛ], as produced by one speaker. (The same vowel is used as a neutral shape for all languages, in order to isolate the effect of the factors from differences in vowel quality across languages). The dashed lines represent positive values of the factor, calculated by adding lip measure loadings 1, 2, 3 and 4 to the neutral shape. (The loadings were first multiplied by a constant). Similarly, the solid lines represent negative values of the factor, calculated by subtracting lip measure loadings 1, 2, 3 and 4 (multiplied by a constant) from the neutral shape. By adding and subtracting these factor loadings, we see the effect of increases and decreases in the factor itself. The same procedure was used to see the effect of the factor looking at the front view of the lips, using measure loadings 21 and 23 (multiplied by a constant). Note that the deviations drawn do not represent actual reconstructed lip shapes, and these diagrams are to be taken only as illustrations of the relative <u>effects</u> of the underlying factor. We see for English that the main effect of the factor is on horizontal opening; an increase in this dimension leads to an increase in horizontal opening, and a decrease leads to a decrease in horizontal opening.

Figures 17 and 18 show the effects of factors 1 and 2 for the 2-factor solution for Cantonese. We see that an increase in factor 1 implies an increase mainly in horizontal opening and a smaller increase in upper and lower lip protrusion, as we saw earlier when examining the ordering of the measurement loadings. Similarly, a decrease in factor 1 implies a decrease in these parameters. Looking at Figure 18, we can conclude that an increase in factor 2 results in virtually no change in lip protrusion, but does result in an increase in horizontal and vertical opening (although the contribution of the former measure is smaller). The area of the mouth opening is also clearly increased.

Figures 19, 20 and 21 illustrate the effects of the factors underlying the 3-dimensional solution for Finnish. We see that an increase in factor 1 results in an increase in horizontal and vertical opening, as well as an increase in the area enclosed by the lips in the front view. There is also an accompanying increase in upper and lower lip protrusion. Looking at Figure 20, we observe that an increase in factor 2 leads to an increase in horizontal opening and upper and lower lip protrusion. There is virtually no change in vertical opening, and what change exists amounts to a decrease in this parameter. Finally, the effect of an increase in factor 3 (see Figure 21) is primarily to increase the horizontal opening between the lips. Since there is also a slight increase in vertical opening, we can expect that the area enclosed by the lips will also increase (and this was shown to be the case by examining the ordering of the measure loadings). We see in addition a small decrease in protrusion (especially of the upper lip), for increases in this factor.

The effects of the factors underlying the 3-dimensional solution for French are shown in Figures 22, 23 and 24. Looking first at Figure 22, we see that an increase in factor 1 leads to a very slight increase in upper and lower lip protrusion, and to a relatively large increase in horizontal opening. Since there is a small increase in vertical opening between the lips, we see that an increase in factor 1 also leads to an increase in front view area.

Figure 23 shows that, as for factor 1, an increase in factor 2 results primarily in an increase in horizontal opening. However, for factor 2 there is also a small accompanying decrease in both upper and lower lip protrusion. Finally, we see from Figure 24 that an increase in factor 3 effects primarily an increase in vertical opening, as well as a smaller decrease in horizontal opening. There is also a relatively large increase in lower lip protrusion.

Figures 25, 26 and 27 show the effects of the factors underlying the 3-factor solution for Swedish. An increase in factor 1 leads to an increase in horizontal opening, as well as to a smaller, but fairly substantial increase in upper and lower lip protrusion. There is also a very slight increase in vertical opening. The effect of an increase in factor 2 is also to increase horizontal opening, but there is a somewhat greater increase in vertical opening as well (in comparison with factor 1), resulting in an overall increase in front view area. There is a concomitant decrease in upper and lower lip protrusion, but this effect is very small. Looking at Figure 27, we see that an increase in factor 3 results primarily in an increase in vertical opening and in upper and lower lip protrusion.

These findings are summarized in Table 15.

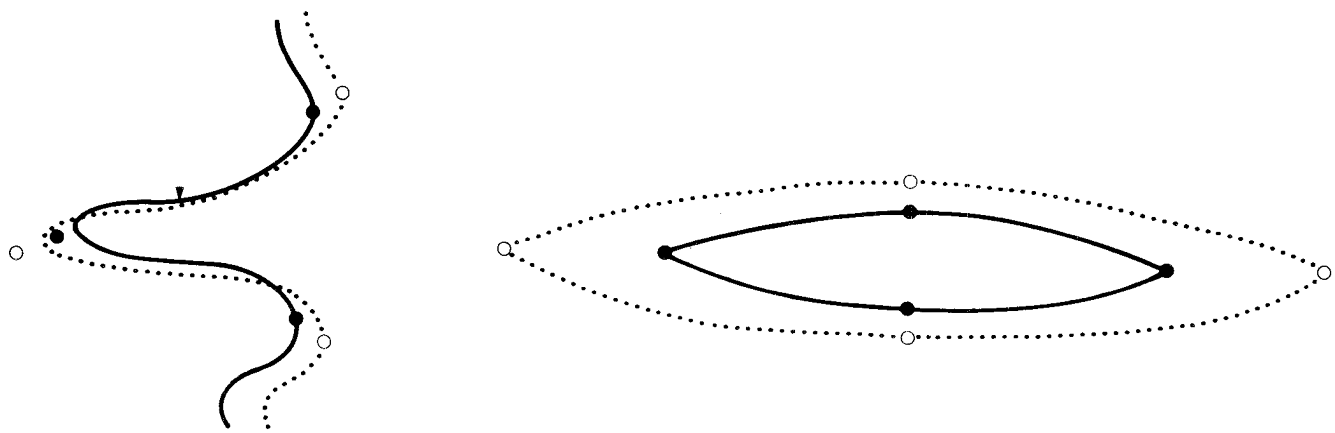


Figure 16: Effects of the factor underlying the English data. The dashed lines represent positive values of the factor, and the solid lines represent negative values of the factor, relative to a neutral lip shape (see text). The side view (left) is 3.08 times life size, and the front view (right) is 1.93 times life size. Figures 17-27 and Figures 37 and 38 (Chapter 5) are constructed in identical fashion, with the same scale.

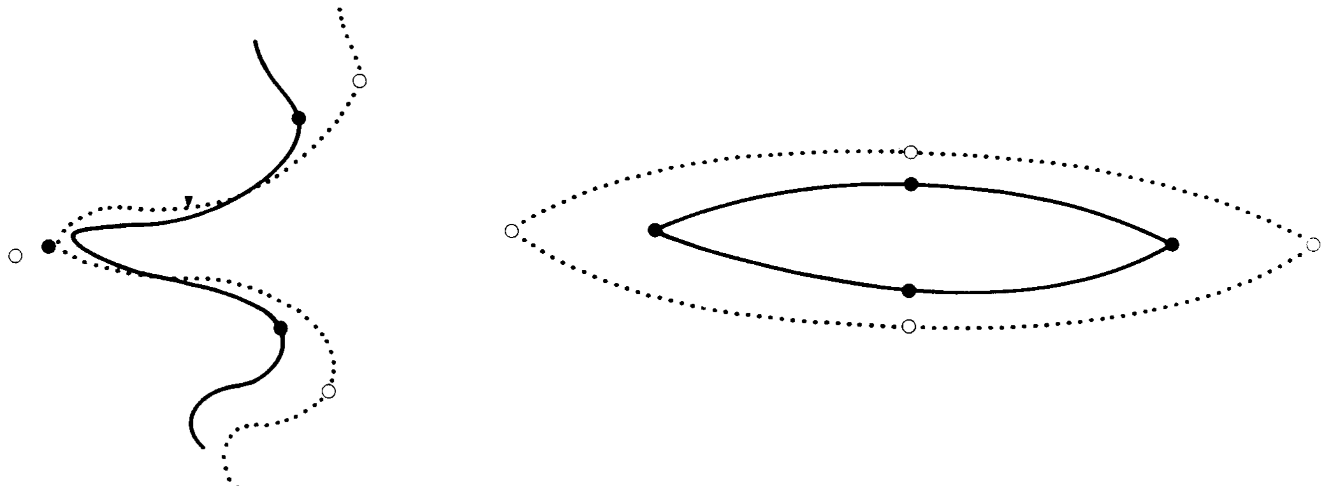


Figure 17: Effects of Cantonese factor 1 (2-factor solution).

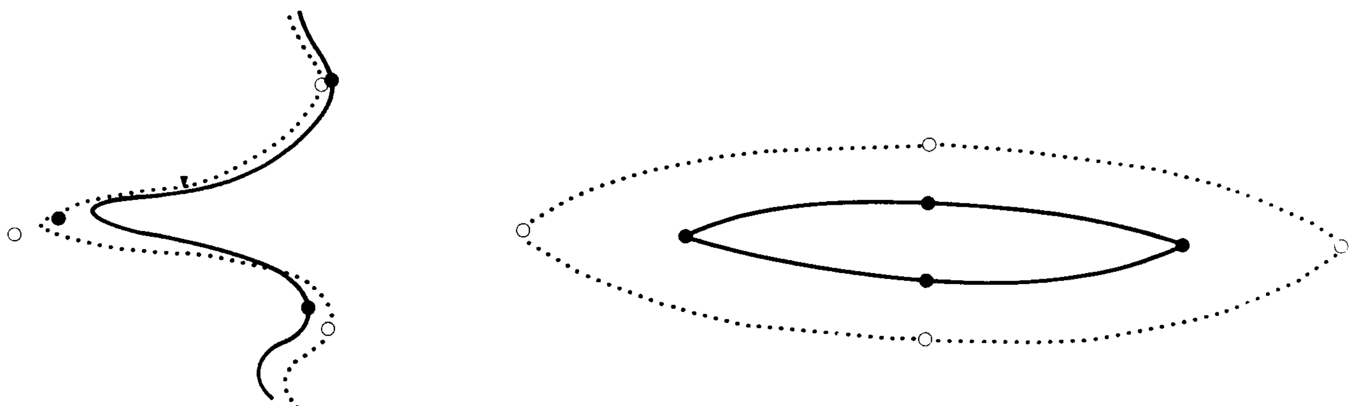


Figure 18: Effects of Cantonese factor 2 (2-factor solution).

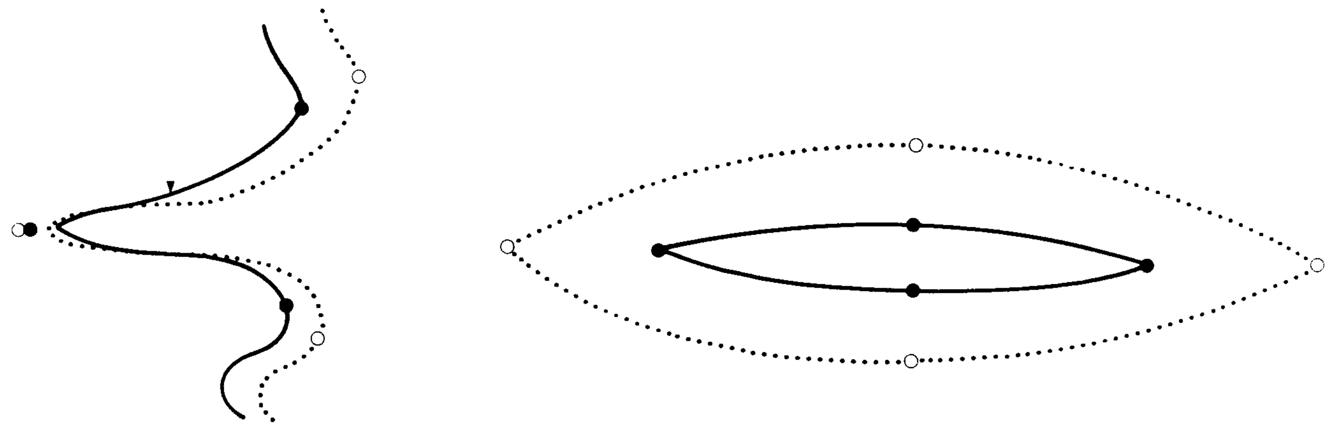


Figure 19: Effects of Finnish factor 1 (3-factor solution).

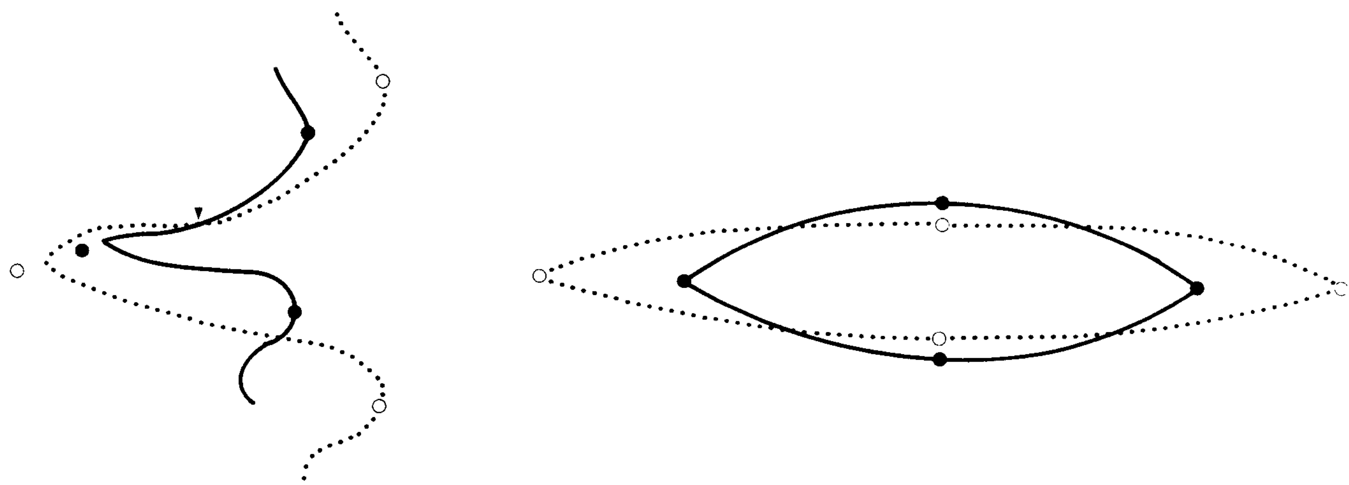


Figure 20: Effects of Finnish factor 2 (3-factor solution).

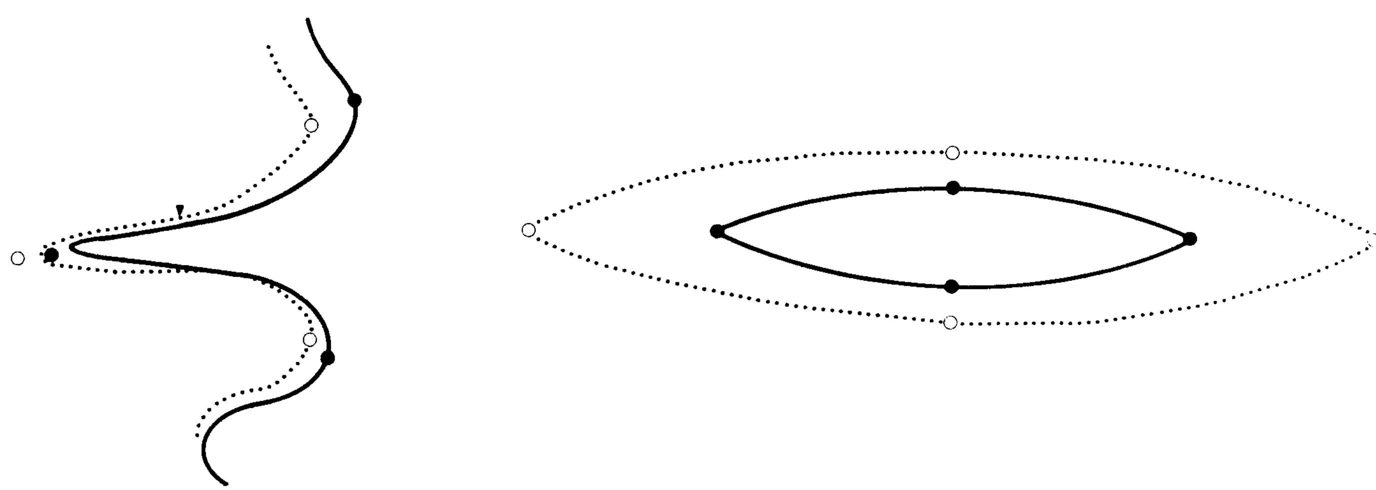


Figure 21: Effects of Finnish factor 3 (3-factor solution).

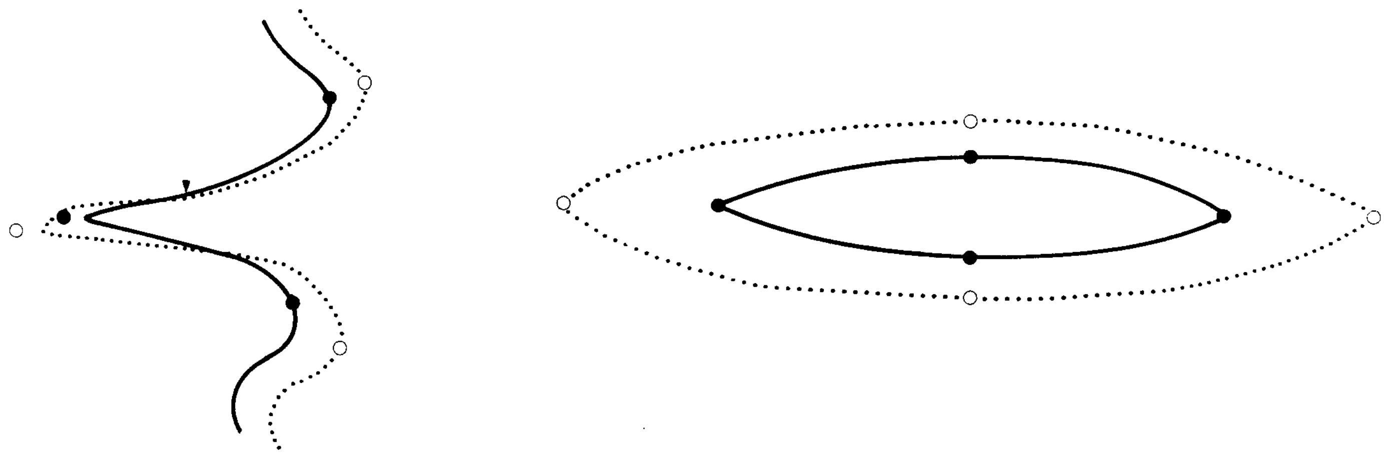


Figure 22: Effects of French factor 1 (3-factor solution).

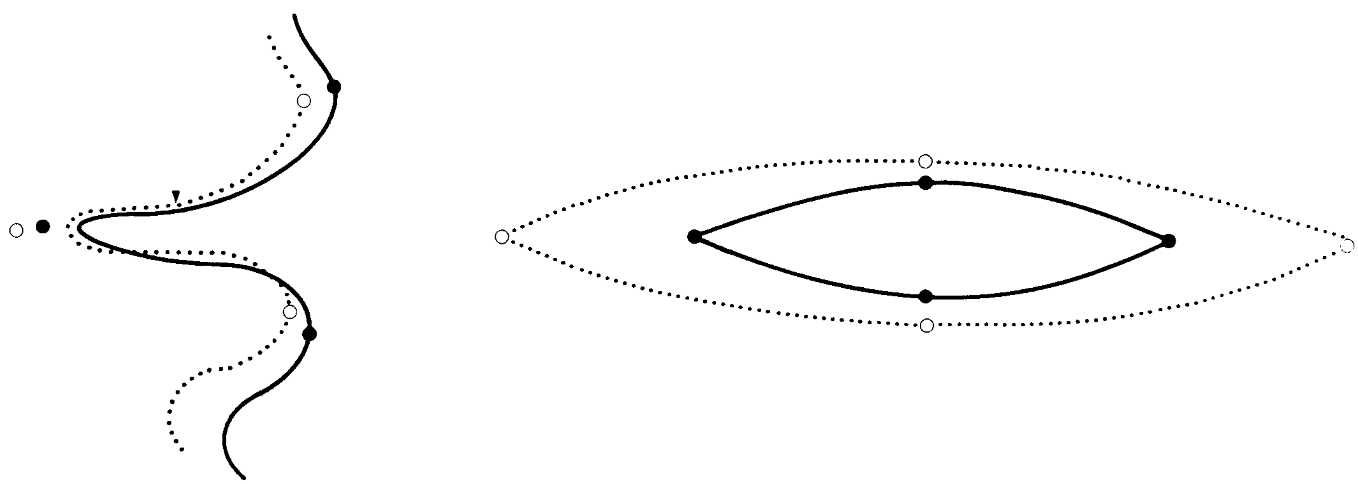


Figure 23: Effects of French factor 2 (3-factor solution).

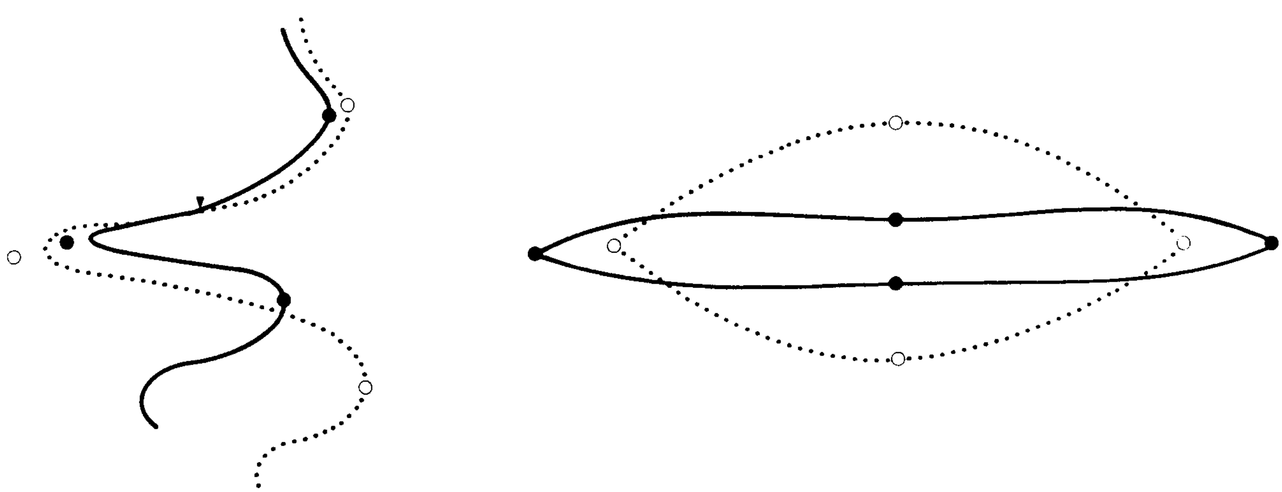


Figure 24: Effects of French factor 3 (3-factor solution).

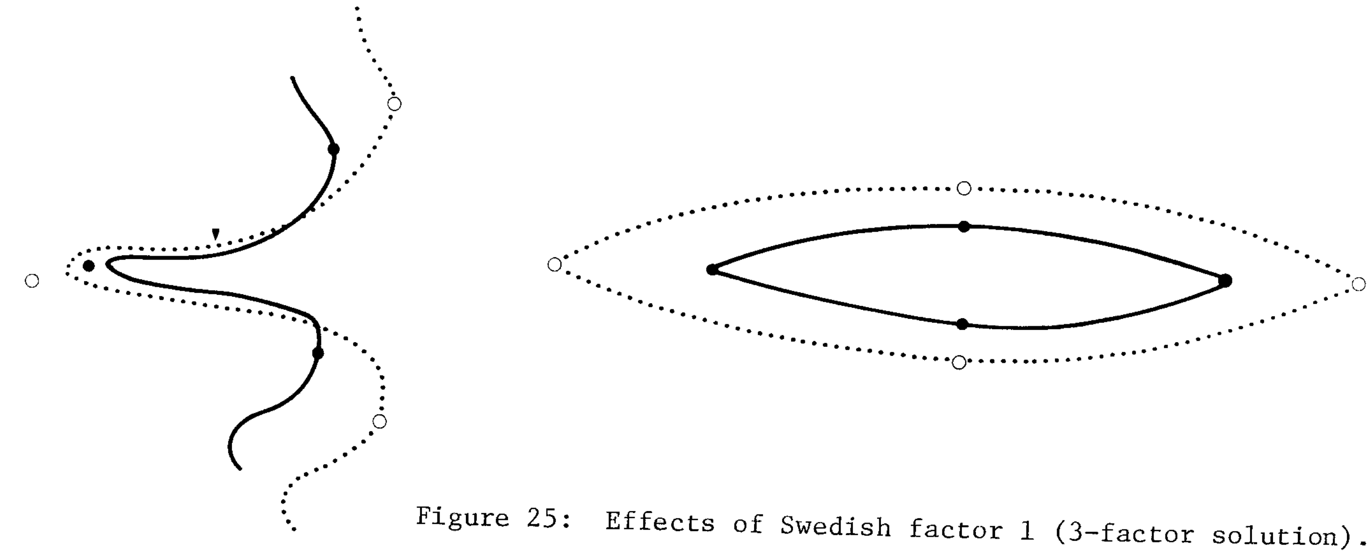


Figure 25: Effects of Swedish factor 1 (3-factor solution).

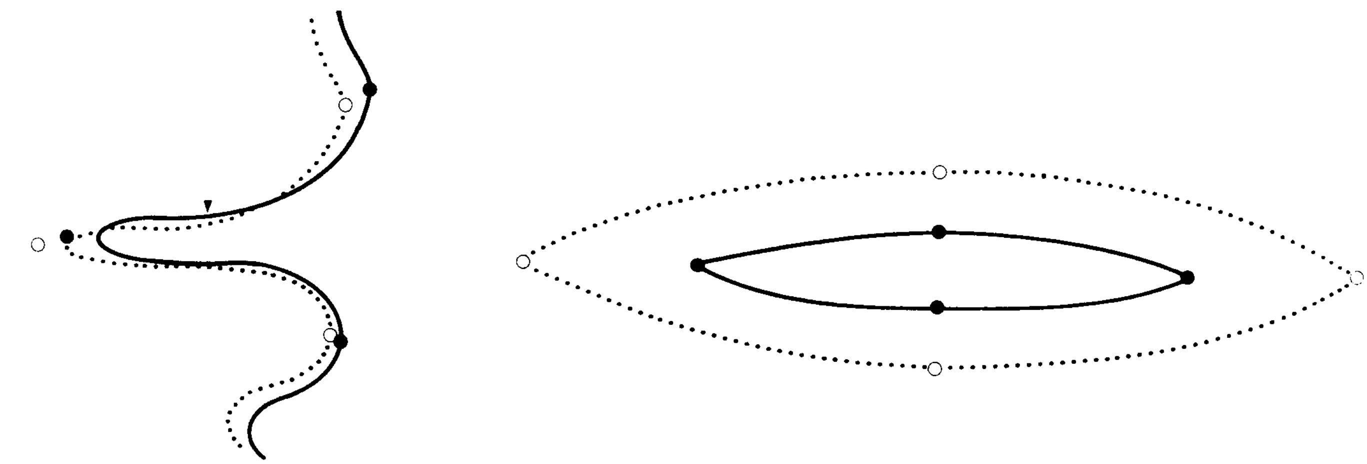


Figure 26: Effects of Swedish factor 2 (3-factor solution).

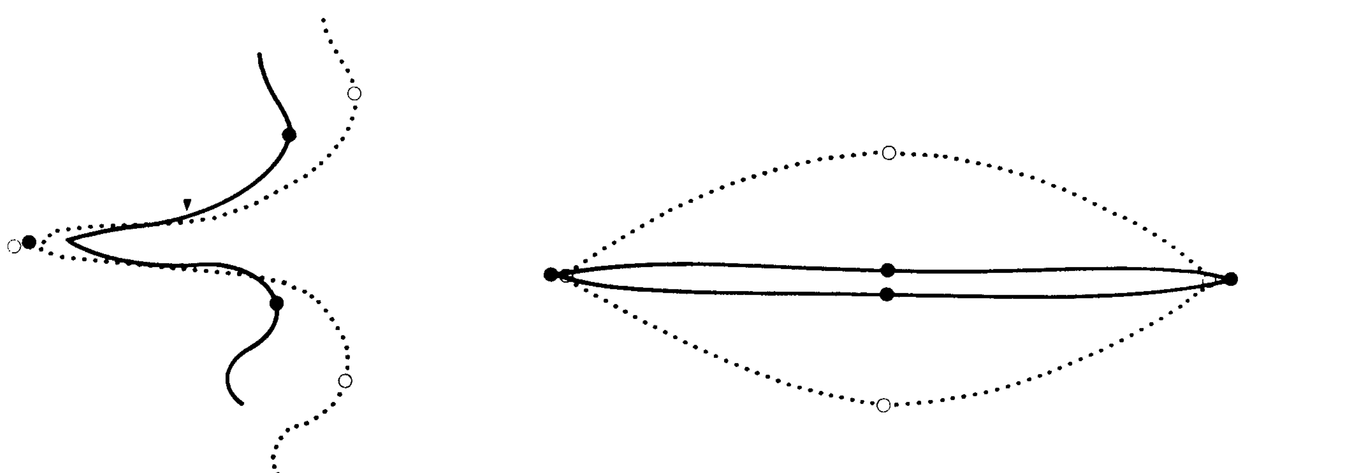


Figure 27: Effects of Swedish factor 3 (3-factor solution).

Table 15: Interpretation of factors of the optimal PARAFAC solutions for each language. Less important components are in parentheses.

	FACTOR 1	FACTOR 2	FACTOR 3
ENGLISH	Directly proportional to horizontal opening.	---	---
CANTONESE	Directly proportional to horizontal opening (and protrusion).	Directly proportional to horizontal opening, front view area (and vertical opening).	---
FINNISH	Directly proportional to horizontal opening, front view area, vertical opening (and protrusion).	Directly proportional to horizontal opening and protrusion.	Directly proportional to horizontal opening and front view area. (Inversely proportional to protrusion).
FRENCH	Directly proportional to horizontal opening, front view area (and vertical opening and protrusion).	Directly proportional to horizontal opening and front view area. (Inversely proportional to protrusion).	Directly proportional to vertical opening and lower lip protrusion. Inversely proportional to horizontal opening.
SWEDISH	Directly proportional to horizontal opening, front view area, and protrusion.	Directly proportional to horizontal opening, front view area (and vertical opening). (Inversely proportional to protrusion).	Directly proportional to vertical opening, front view area, and protrusion.

Vowel Patterning Along the Factors

In the previous section we were able to ascertain which parameters of lip position the factors underlying each language represent. Since these factors have been shown to reflect particular measures and combinations of measures of lip shape, we can now use them to look at how the vowel systems of the languages under investigation make use of their underlying parameters of lip position. That is, we can look at how the vowels in these languages pattern along the dimensions extracted by PARAFAC.

Recall that one of the sets of loadings in the PARAFAC equation consists of weightings for each of the individual vowels along the factors. In this section we will look at the pattern of these loadings (multiplied by the mean speaker loading) for each language, along the dimensions of the optimal solutions.

ENGLISH (1-factor solution)

We found previously that the factor underlying the English data is primarily one of horizontal opening. Increases in this factor result in increases in horizontal opening, and decreases result in decreases in horizontal opening. Figure 28 illustrates how this parameter is reflected in the patterning of the vowels. We see first that the vowels are separated into two basic groups, rounded and unrounded, with the unrounded ones naturally exhibiting a higher degree of horizontal opening than the rounded ones. Among the unrounded vowels, the ordering is interesting; low and mid unrounded vowels are found higher on the scale than the high vowels [i] and [ɩ]. This pattern is also true of the unrounded vowels; the high vowel [u] shows the smallest degree of horizontal opening.

CANTONESE (2-factor solution)

Figure 29 shows the pattern of vowel loadings along factors 1 and 2 for Cantonese. Recall that factor 1 was found to be primarily one of horizontal opening, with a smaller component of protrusion. The most striking aspect of this diagram is how poorly factor 1 separates the vowels of Cantonese, as compared with factor 2. Apparently the data fit the PARAFAC model best when most of the variance in the vowel space is accounted for by the second factor. Hence, while the 2-factor solution for Cantonese was found to be the correct one in terms of the six criteria discussed in Chapter 3, for linguistic purposes only one of these factors appears to be necessary. It is nevertheless interesting to note the ordering of the vowels along factor 1; vowels that we expect to have components of both horizontal opening and protrusion ([ɔ], [œ]) are found to have the highest loadings, vowels that we expect to have only the protrusion component ([u], [y]) follow, while vowels with only the component of horizontal opening come last. Thus, protrusion does appear to play a role in the ordering of these vowels, despite the fact that they are so poorly separated.

Factor 2, which we found to be related to horizontal opening, front view area (and to some extent vertical opening), produces a much clearer pattern of separation. Looking at this factor, we find that the vowels are first divided into rounded and unrounded types. Within the group of unrounded vowels, we see that the low and mid vowels are grouped together at the high end of the scale, while the high vowel [i] lies lower down. Similarly, for the rounded vowels, the

Figure 28: Vowel x mean speaker loadings for the English 1-factor solution

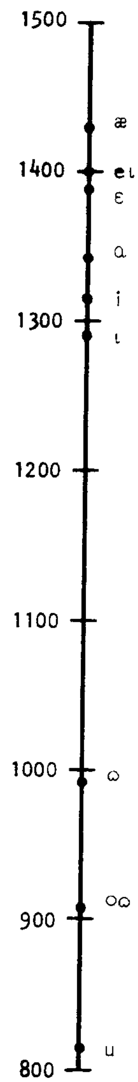
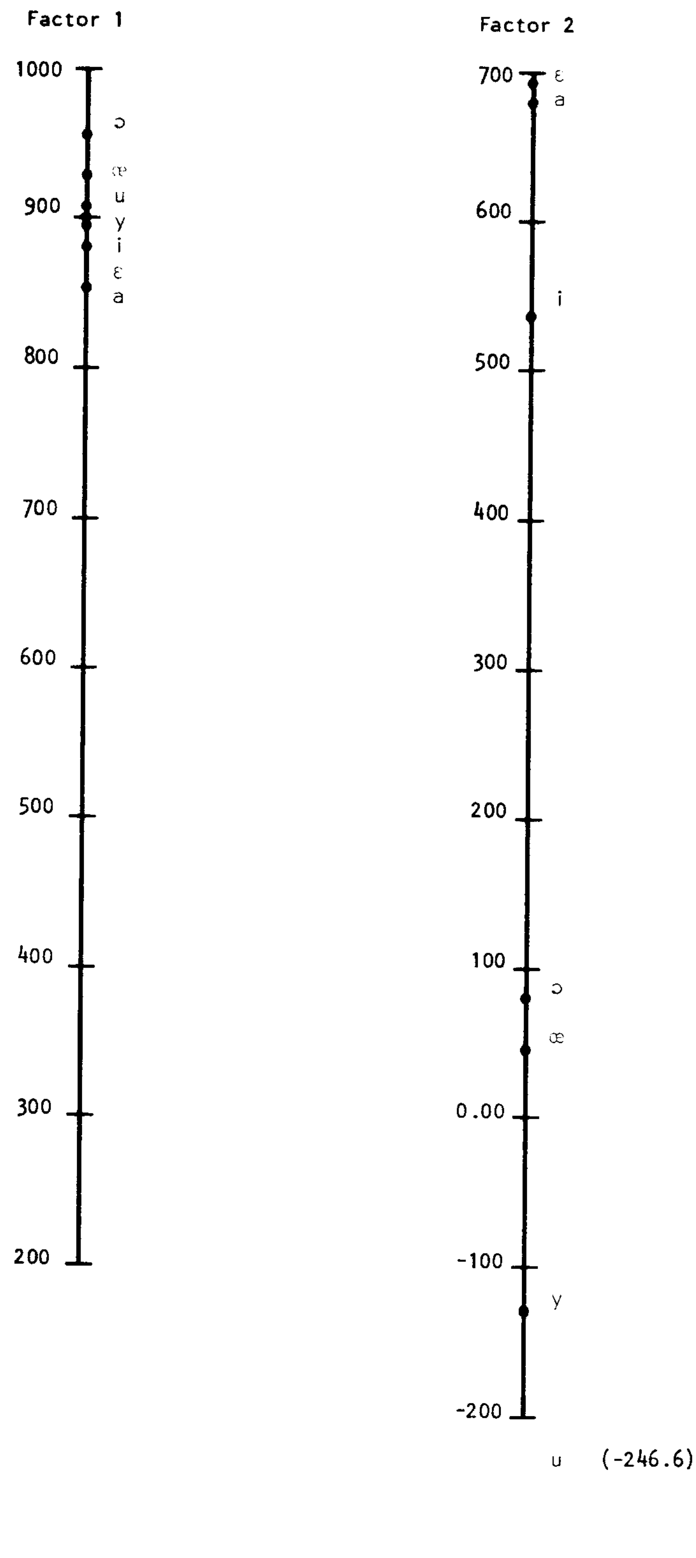


Figure 29: Vowel x mean speaker loadings for the Cantonese 2-factor solution



mid vowels [ɔ] and [œ] cluster together near zero, while the high vowels [y] and [u] have the lowest amounts of horizontal opening and front view area.

FINNISH (3-factor solution)

Figure 30 shows the pattern of vowel loadings along the three factors found to underlie the Finnish data. Factor 1 separates the vowels primarily in terms of the parameters horizontal opening, front view area, and vertical opening. The vowel [æ] is seen to have the largest amounts of these parameters, while the vowels [u] and [y] have the lowest. The mid vowels [ø], [e] and [o] are all grouped very close together at the upper end of the scale, indicating that they use comparatively similar amounts of horizontal opening, vertical opening and front view area in their production.

Factor 2, which we found to be related to horizontal opening and to upper and lower lip protrusion, is seen to have virtually no effect in separating the Finnish vowels from one another. While in order to account for the variance in the data set as a whole we found the 3-factor solution to be the optimal one, for linguistic purposes only two factors appear necessary for Finnish. The third factor, which we saw to be directly proportional to horizontal opening and front view area, and to some extent also inversely proportional to upper and lower lip protrusion, separates the vowels much more effectively. At one end of the scale we find vowels that we expect to have high values of horizontal opening and area, and no component of protrusion, while at the other end of the scale we find rounded vowels, which we expect to have relatively lower values for horizontal opening and area, and high values for upper and lower lip protrusion.

FRENCH (3-factor solution)

Figure 31 shows the pattern of vowel loadings along the three factors extracted for French. As was the case for Finnish, only two of these factors appear to be necessary for linguistic purposes, in that the first factor has virtually no effect on separating the vowels. The other two factors separate the vowels quite effectively. We found that factor 2 represented primarily a dimension of horizontal opening and front view area, and was to a smaller extent inversely proportional to upper and lower lip protrusion. Thus, we see the vowels [i], [e], [ɛ] and [a], which we expect to have the greatest amounts of horizontal opening and area, and simultaneously the lowest amounts of protrusion, to be located in a group at the high end of the scale. The next group, with loadings lying close to zero, consists of the vowels [ɔ] and [œ], which we expect to have some non-negligible amount of horizontal opening and area, but in addition a component of protrusion. At the low end of the scale we find the close rounded vowels, that we expect to have substantial components of protrusion and minimal components of horizontal opening and area.

Factor 3, which we found to be related primarily to vertical opening and lower lip protrusion, and to a smaller extent inversely proportional to horizontal opening, separates the vowels in a way quite different from the second factor. Vowels that we expect to have relatively high values of either vertical opening or lower lip protrusion or both are located at the high end of the scale. Vowels with the least amount of vertical opening (even ones that would be expected to have high amounts of lower lip protrusion) are located toward the bottom of the scale, indicating that this factor is primarily affected by the vertical opening parameter.

Figure 30: Vowel x mean speaker loadings for the Finnish 3-factor solution

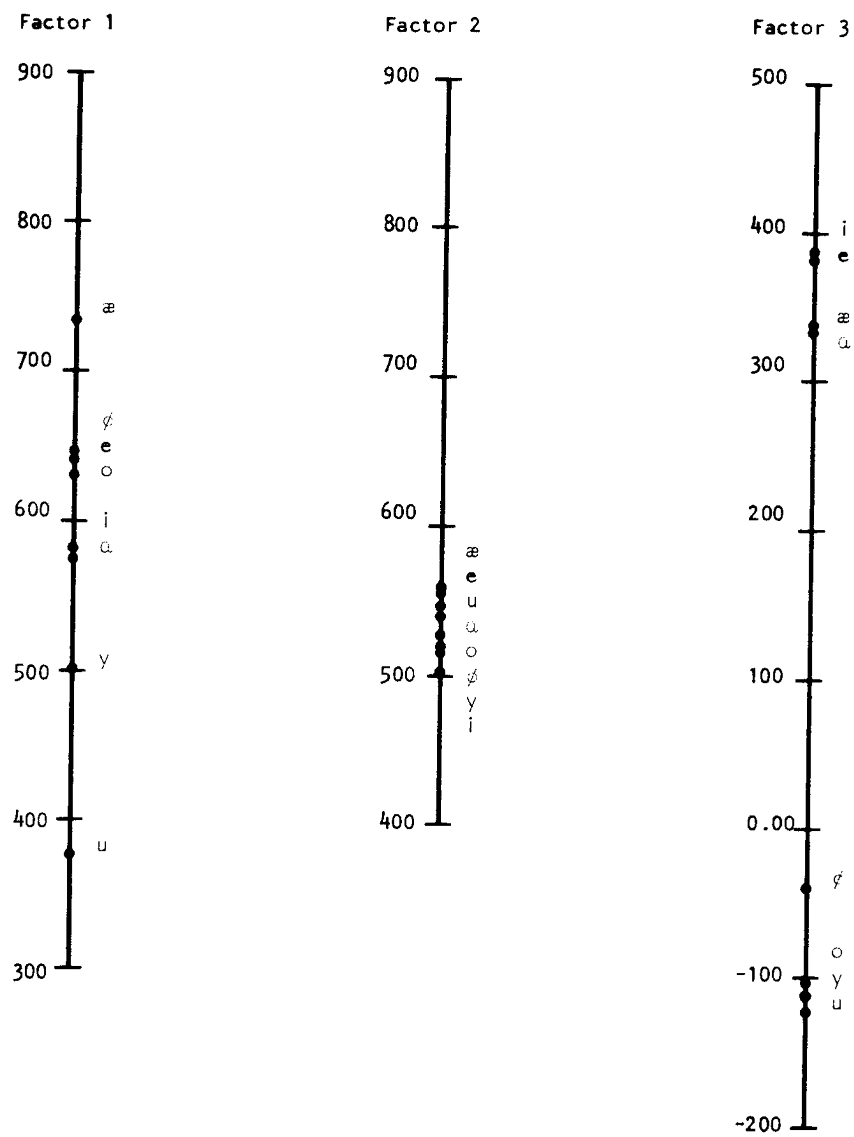
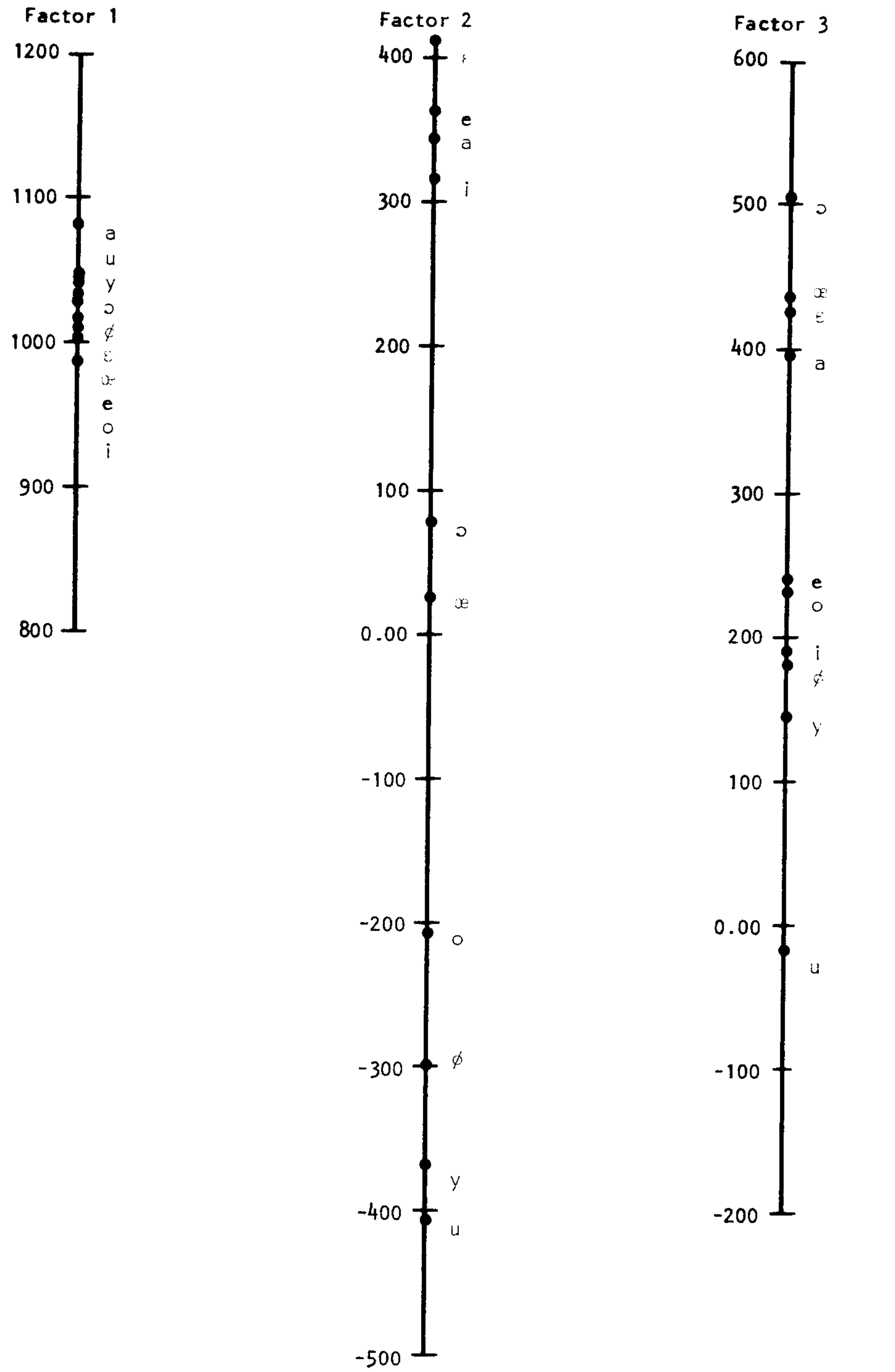


Figure 31: Vowel x mean speaker loadings for the French 3-factor solution



SWEDISH (3-factor solution)

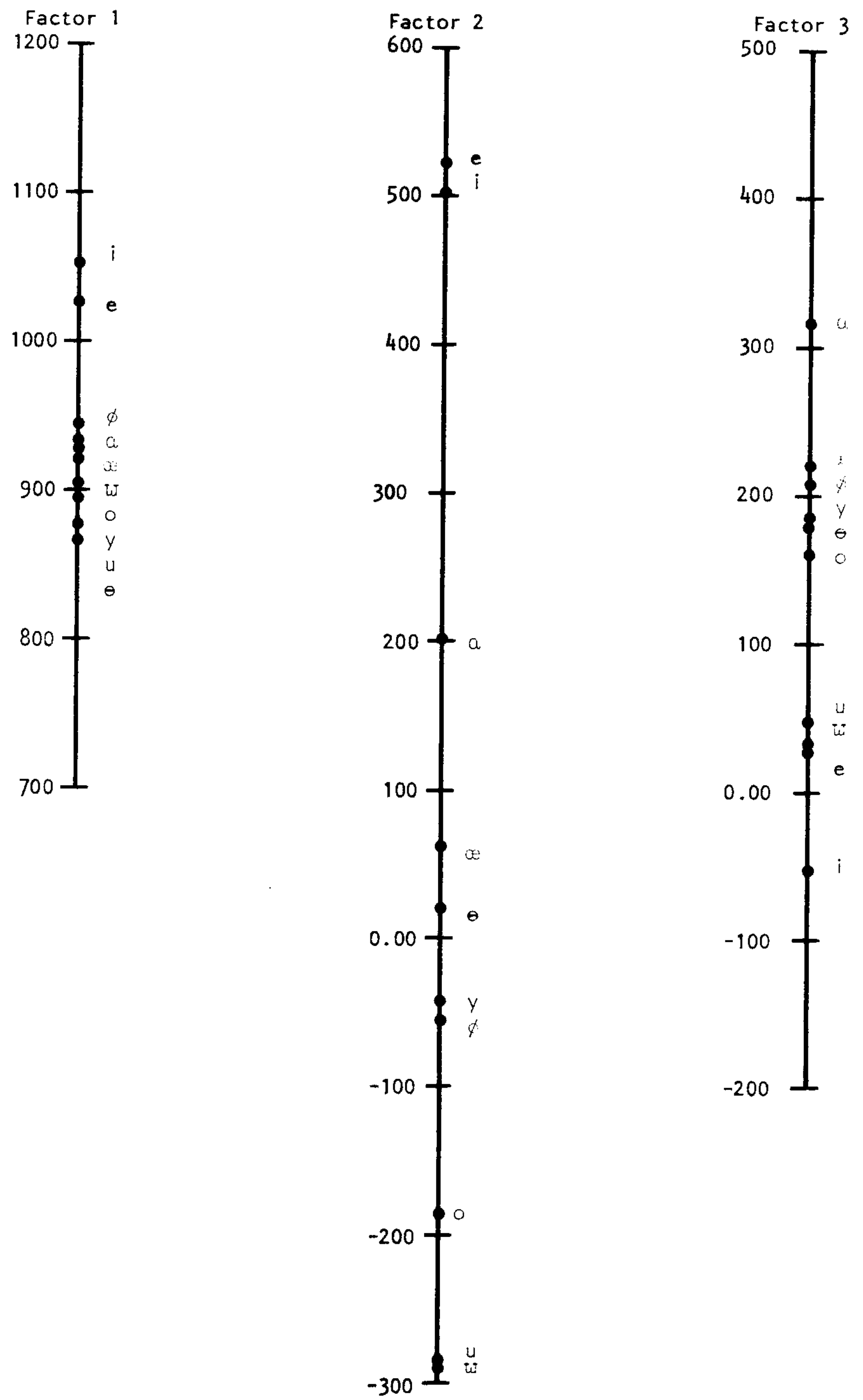
The loadings for the vowels for the 3-factor solution for Swedish are shown in Figure 32. Unlike the 3-factor solutions for Finnish and French, all three factors have an effect on separating the Swedish vowels (although the first factor produces a poorer pattern of separation than the other two factors). This finding seems to go along with the result discussed in Chapter 3, in that Swedish was the only language for which a 4-factor solution might conceivably have been feasible. Factor 1 was found to be primarily one of horizontal opening and front view area (with some component of protrusion). From the figure we see that the major effect of this factor is to separate those vowels that we expect to have the largest horizontal opening ([i] and [e]) from the other vowels.

Factor 2 was seen to be directly related primarily to horizontal opening and front view area, and to a smaller extent inversely related to upper and lower lip protrusion. Thus, we find the vowels with the greatest amount of horizontal opening ([i] and [e]) to be located at the upper end of the scale, while we find the vowels that we expect to have virtually no component of either horizontal opening or area at the lowest end of the scale ([u] and [ʉ]). Vowels that have components of both horizontal opening and area, <u>and</u> protrusion are found in the middle ([œ], [ɵ], [y] and [ø]). The vowel [o] appears to lie in between these two extremes. It is interesting to note in this connection that factor 2 separates these vowels according to the traditional descriptions of inrounding and outrounding (see Chapter 1); the inrounded vowels [u] and [ʉ] are located together at one end of the scale, while the outrounded vowels [y] and [ø] are located very close to each other, just around zero. The vowel [o] appears to be intermediate in its behavior with regard to this division. These findings will be taken up again later, in the cross-linguistic comparison.

Factor 3, which we found to be related to vertical opening, front view area and protrusion, separates the Swedish vowels in quite a different manner. The vowel [ɑ], which we expect to have the largest component of vertical opening among the Swedish vowels, is located at the high end of the scale. It is actually not surprising that it should have such a high positive loading along a dimension that is also directly proportional to protrusion, in that the Swedish [ɑ] is often somewhat rounded, and would therefore be expected to exhibit some component of protrusion as well. The next group of vowels along the scale, [œ], [ø], [y], [ɵ] and [o], also would be expected to have reasonable components of vertical opening relative to the other vowels, as well as a substantial amount of protrusion. The vowels located near zero ([u], [ʉ], [e] and [i]) are vowels that have the smallest amounts of vertical opening; in addition, [u] and [ʉ] would be expected (according to the traditional definition of inrounding) to have relatively small components of protrusion in comparison with the other rounded vowels.

In summary, we have seen that the vowels of the five languages pattern in predictable ways along the underlying dimensions of lip shape extracted by PARAFAC. We have also seen that while the higher dimensional solutions appeared to be the optimal ones for Cantonese, Finnish, and French according to the criteria discussed in Chapter 3, one factor in each of these solutions appears to be unnecessary in distinguishing among the vowels of these languages. In the next chapter, we will compare the vowel spaces along those dimensions for which the measurement spaces are highly correlated, and in this way we will be able to discover differences and similarities in how the vowels pattern along comparable dimensions in the five languages.

Figure 32: Vowel x mean speaker loadings for the Swedish 3-factor solution



Chapter 5: Cross-linguistic Comparisons

In the preceding two chapters we saw that it was possible to use a type of 3-mode factor analysis, PARAFAC, to find underlying dimensions of lip position in the five languages under study. We were able to interpret these dimensions in terms of the measurements of lip shape they represent, and we then used these dimensions to examine the patterning of the vowels along them for each language. In the present chapter we will compare the underlying factors of the optimal solutions extracted for each language (one factor for English, two factors for Cantonese, and three factors for Finnish, French, and Swedish). We will do this, first by examining the correlations of the lip measurement loading matrices across languages, and then by comparing the vowel spaces for those factors for which the lip measurement loading matrices are highly correlated. Finally, a method of finding a common factor space, for the four languages that have front rounded vowels, will be described. This common space will be used to compare the similarly transcribed vowels across the four languages.

Comparison of Factors Across Languages

In order to find the correlations of the lip measure loadings along the factors for the optimal solutions for each language, a program called CMPARE was used, as in Chapter 4. The correlations of the measure loadings across languages are given in Table 16. The asterisk marks those correlations that are higher than 0.900. Summarizing the information in this table, we see that the highly correlated measurement spaces divide themselves into two sets: (1) the measurement loadings along factor 1 for English, Cantonese, French, and Swedish all correlate highly with one another ($r > 0.930$) and (2) the measurement loadings along factor 2 for Cantonese, French and Swedish, and along factor 3 for Finnish all have correlations with each other in excess of 0.950.

Because the measurement loadings along these factors are so highly correlated with one another, we may compare the patterning of the vowels along the dimensions belonging to the above two sets. That is, we will now be able to observe how the vowel systems of the different languages make use of those underlying parameters of lip shape that they have in common. Of course, since the lip measurement matrices are not perfectly correlated with one another, the comparison can only be approximate. However, the high correlations of the lip measure loadings indicate that the underlying parameters are similar enough to make comparison of the vowel systems worthwhile.

Before looking at the vowel spaces, it will be useful to repeat here the interpretations we found in Chapter 4, for the factors in question. Table 17 provides this information. For set 1, we see that the primary component common to these factors is the horizontal opening between the lips. Front view area also contributes to the interpretation of factor 1 for French and Swedish, and protrusion is a relevant parameter for Cantonese, French and Swedish. For set 2, horizontal opening is again the primary component, in addition to front view area; for Finnish, French and Swedish, the factors are also inversely proportional to upper and lower lip protrusion.

Figure 33 shows the patterning of the vowels along factor 1 for English, factor 1 for Cantonese, factor 1 for French and factor 1 for Swedish. We note

Table 16: Correlations of lip measurement loadings for the optimal PARAFAC solutions across languages. Eng = English, Can = Cantonese, Fin = Finnish, Fr = French, Sw = Swedish. The numbers refer to particular factors, and an asterisk marks any correlation above 0*.900.

	Can 1	Can 2	Fin 1	Fin 2	Fin 3	Fr 1	Fr 2	Fr 3	Sw 1	Sw 2	Sw 3
Eng 1	*.937	.751	.595	.553	.824	*.955	.852	-.642	*.960	.748	-.291
Can 1	---	---	.790	.384	.808	*.988	.846	-.393	*.984	.792	.015
Can 2	---	---	.860	-.089	*.956	.823	*.953	-.257	.766	*.988	.132
Fin 1	---	---	---	---	---	.767	.757	.097	.704	.848	.532
Fin 2	---	---	---	---	---	.401	.118	-.688	.489	-.090	-.688
Fin 3	---	---	---	---	---	.837	*.995	-.450	.794	*.972	-.097
Fr 1	---	---	---	---	---	---	---	---	*.991	.809	-.058
Fr 2	---	---	---	---	---	---	---	---	.831	*.968	-.096
Fr 3	---	---	---	---	---	---	---	---	-.493	-.266	.870

Table 17: Interpretation of the factors for which the lip measurement loading matrices are highly correlated across languages. Less important components are in parentheses.

<u>Set 1</u>

English (factor 1)	Directly proportional to horizontal opening.
Cantonese (factor 1)	Directly proportional to horizontal opening (and protrusion).
French (factor 1)	Directly proportional to horizontal opening, front view area (and vertical opening and protrusion).
Swedish (factor 1)	Directly proportional to horizontal opening, front view area, and protrusion.

<u>Set 2</u>

Cantonese (factor 2)	Directly proportional to horizontal opening, front view area (and vertical opening).
Finnish (factor 3)	Directly proportional to horizontal opening and front view area. (Inversely proportional to protrusion).
French (factor 2)	Directly proportional to horizontal opening and front view area. (Inversely proportional to protrusion).
Swedish (factor 2)	Directly proportional to horizontal opening, front view area (and vertical opening). (Inversely proportional to protrusion).

Figure 33: Vowel x mean speaker loadings along the factors of set 1 (see Table 17)

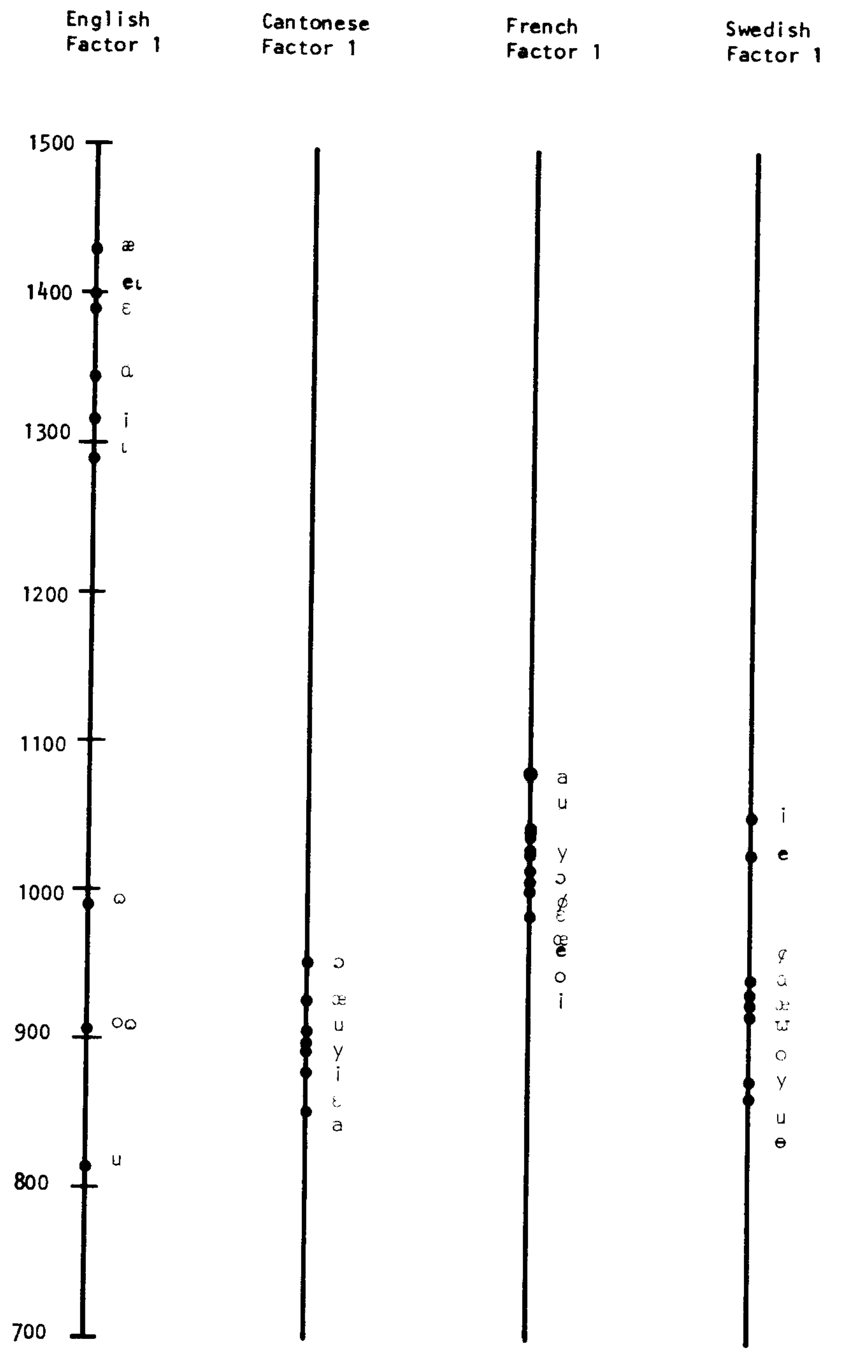
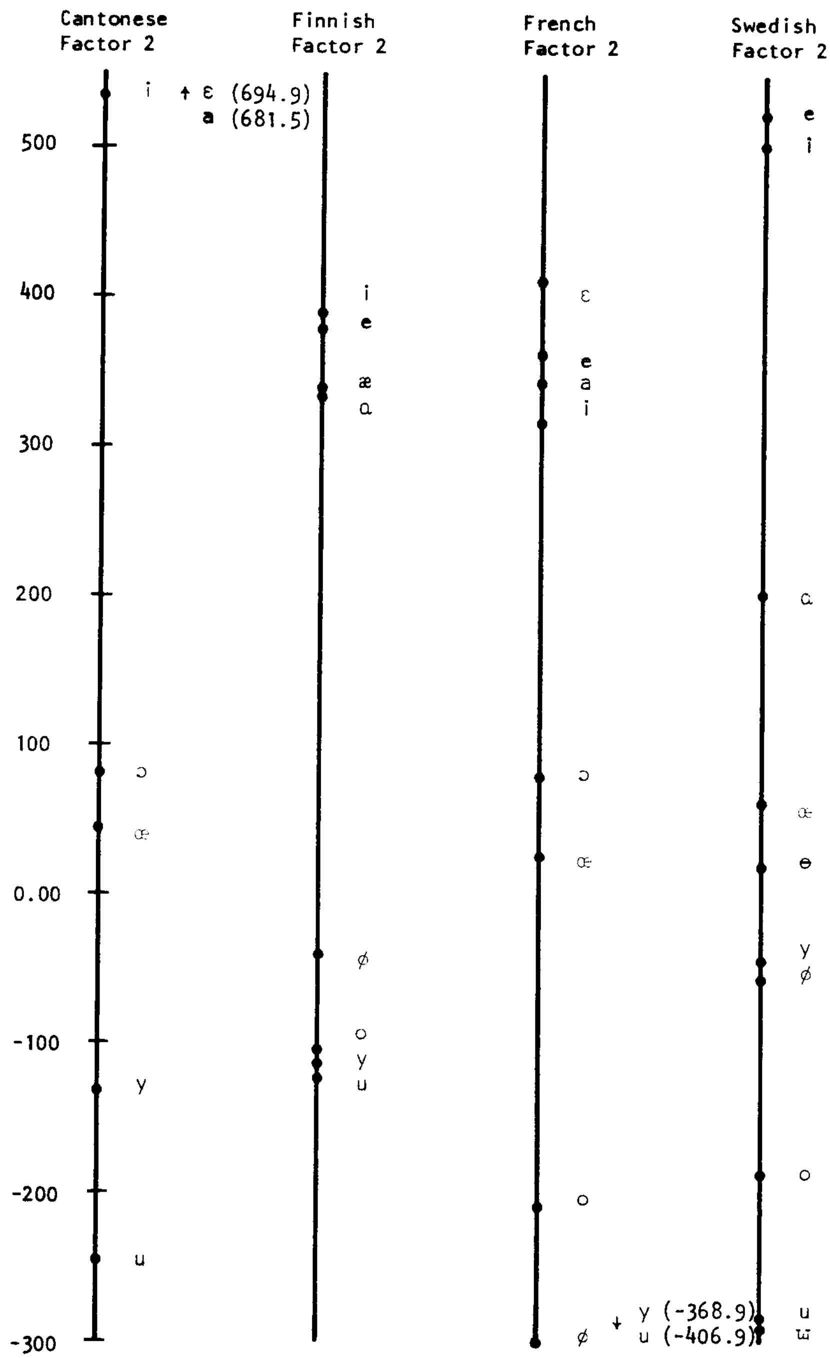


Figure 34: Vowel x mean speaker loadings along the factors of set 2 (see Table 17)



first that while the English vowels are well separated by their underlying dimension, the Cantonese and French vowels are poorly separated. The Swedish vowels [i] and [e] form a group separate from the other vowels. It is important to note here that this result should not be interpreted to mean that a dimension related to horizontal opening is not capable of distinguishing the vowels of Cantonese and French; rather, it means that given a 2-dimensional solution for Cantonese and a 3-dimensional solution for French, the optimal way to account for the variance among the vowels is to put the burden of separation on the other factors. While this fact in itself is interesting, i.e., that French and Cantonese differ from Swedish, and especially from English, in how much variance in the vowel space is effectively accounted for by highly correlated optimal dimensions of lip shape, we are unfortunately unable to draw very many conclusions regarding the patterning of the Cantonese and French vowels along these factors. The best we can say is that for English and Swedish, a factor related to horizontal opening effectively separates rounded from unrounded vowels, given the optimal PARAFAC solutions for these languages. Also, we see clearly for English that the parameter of horizontal opening alone is enough to distinguish degrees of rounding among the vowels [ɑ], [ɔɑ] and [u]; as one would expect from Sweet's comments regarding "normal" and "abnormal" rounding, the high vowel [u] appears at the far end of the scale.

Figure 34 shows the patterning of the vowels along factor 2 for Cantonese, factor 3 for Finnish, factor 2 for French and factor 2 for Swedish. These factors, which for all languages are directly proportional to horizontal opening and front view area, differ primarily from the factors of set 1 in that three out of the four dimensions are inversely proportional to upper and lower lip protrusion. Another way to express this is to say that these factors (with the exception of factor 2 of Cantonese, which is not significantly affected by protrusion) are proportional to the ratio of horizontal opening and front view area to protrusion. We see from Figure 34 that the vowels of all four languages are separated quite effectively by these factors. The results shown in the figure can be summarized as follows:

(1) For all languages, the factors separate traditionally labeled "rounded" from "unrounded" vowels. The Swedish [ɑ] lies in a intermediate position between the rounded and unrounded vowels, and in fact is closer to the rounded group.

(2) For the languages with the so-called lax rounded vowels [ɔ] and [œ] these vowels are clearly separated from the so-called tense rounded vowels ([y], [ø], [u] and [o]). This is true also for the tense/lax pairs found in French and Swedish. For French, the lax vowels [ɔ] and [œ] form one group, while their tense counterparts [o] and [ø] form another. For Swedish, [œ] and [ɵ] form one group, separate from [ø]. [ʉ], the phonologically tense counterpart of [ɵ], is located at the lowest end of the scale. Thus in all these vowels tenseness is associated with a smaller area of lip opening and greater lip protrusion.

(3) For the vowels [y] and [u]:

(a) The ordering of these vowels is the same for all languages, with [u] lying further down the scale than [y].

(b) There are differences among the languages regarding how close these vowels cluster together. For Finnish, [u] and [y] lie very close together, for Cantonese they lie further apart, and for Swedish they lie extremely far apart.

These results (a) and (b) indicate that [u] is, in some general sense, more rounded than [y] in all four languages, but that the languages differ as to how much more rounded [u] is than [y].

(4) For the vowels [ø] and [o]:

(a) There are differences among the languages as to how these vowels are ordered relative to each other and relative to [y] and [u]. For Finnish and Swedish, [ø] has a higher value for the ratio of horizontal opening and front view area to protrusion, while [o] has a lower value; the opposite is the case for French. Hence, [o] is in some sense more "rounded" in Finnish and Swedish than is [ø], while in French [ø] is more rounded than [o], along this factor. Also, the Finnish and French [ø] and [o] lie further up along this dimension than [y] and [u], but for Swedish [ø] and [o] lie between [y] and [u]. The importance of this difference between Swedish and the other languages will be discussed below, in relation to the classical inrounding/outrounding distinction.

(b) For Finnish, the vowels [y], [u], [ø] and [o] all lie close together on the scale of the ratio of horizontal opening and front view area to protrusion, while for French and Swedish there is a good deal more separation among these four vowels. In other words, Finnish speakers make less of a rounding distinction along this dimension than do French and Swedish speakers.

With regard to points (3) and (4) above, some interesting observations can be made about the results presented here and the predictions made by Armstrong (1967) in her description of the phonetics of French. Armstrong, working in the tradition of Jones, treats each member of the pairs of vowels [u]/[y], [o]/[ø] and [ɔ]/[œ] as having the same lip position as the other member of the pair. Lip position is seen as being correlated with tongue height, so that [u]/[y] have the most rounding, [o]/[ø] less rounding, and [ɔ]/[œ] less rounding still. While the results of this study suggest that French and Cantonese conform to this expectation, Finnish and Swedish do not. For Finnish, while [y] and [u] are almost equally rounded (at least along the dimension under discussion), [o] is also virtually identical in rounding to [y] and [u] (i.e., <u>not</u> less rounded), and [ø] stands apart from the other three rounded vowels. Swedish contradicts the expected result in the opposite way. Although [u] is more rounded than [o], both these vowels are more rounded than [y] and [ø]. [y] and [ø] show no difference in rounding along this factor, in that they lie extremely close together on the scale. This last fact about Swedish is elaborated under (5) below.

(5) As mentioned in Chapter 4, the factor underlying the Swedish data reflects the inrounding/outrounding distinction. The inrounded vowels [u] and [ʉ] lie at the lowest end of the scale (i.e., they have relatively low values of horizontal opening and front view area, and relatively high values of protrusion), while the outrounded vowels [y] and [ø] are grouped together close to zero, indicating that they have non-negligible components of horizontal opening and area, as well as protrusion. The vowel [o] lies between the extremes of inrounding and outrounding. This intermediate position of [o] is worth noting, in that a similar result has been described by McAllister, et al (1974), who measured the electromyographic activity of the orbicularis oris muscle in the articulation of the Swedish vowels [u], [ʉ], [y], [ø], [o] and [œ]. The purpose of their study was to see if the rounded vowels of Swedish were heterogeneous in terms of their EMG activity,

and if any observed heterogeneity was correlated with the classical inrounding/outrounding division. They found, in fact, that the shapes of the integrated electromyographic curves indicated that the vowels could be divided into two groups, the first consisting of the vowels [y], [ø] and [œ], and the second consisting of [u], [ɯ] and [o]. These groups thus reflect the traditional outrounding (group 1) vs. inrounding (group 2) distinction. They note, however, that [o] is difficult to classify, in that it occasionally also manifested group 1 characteristics. This difficulty appears in the present study as well, in terms of our scale of the ratio of horizontal opening and front view area to protrusion.

Note that the inrounding/outrounding distinction does not account for the patterning of the rounded vowels in all four languages. This is particularly true for Finnish, where the rounded vowels are grouped very close together on the scale. While it is arguable that the patterning of the French and Cantonese vowels does reflect an inrounding/outrounding distinction, in no other language is this distinction as clear as it is in Swedish. We can conclude, therefore, that the inrounding/outrounding division (to the extent to which it is reflected by the factor proportional to the ratio of horizontal opening and front view area to protrusion) is a language-specific fact. This division is important in Swedish and absent in Finnish, along this dimension. I have been told, in fact, by Swedish speakers learning Finnish that in order to approximate the Finnish [y], they are instructed to produce a vowel that is close to [ɯ] in their own language. In other words, the Swedish [y] is "too outrounded" to sound like a Finnish [y].

We have seen in this section that it is possible to compare the patterning of the vowels across languages along those factors for which the lip measurement spaces are highly correlated. First, this comparison has shown that the vowels of English, none of which are front rounded, are well separated by a single factor of horizontal opening, and this solution is in addition the optimal one. Second, while there exist many similarities in the ordering of the vowels of the different languages along dimensions that are in general proportional to the ratio of horizontal opening and front view area to protrusion, there are differences relating primarily to how closely particular vowels cluster together. We have also found certain problems with this approach to comparing the vowel spaces across languages. First, of the two sets of factors for which the measurement spaces correlate highly, only one set separates the vowels effectively enough to allow for any conclusions to be drawn regarding the patterning of the similarly transcribed vowels. Second, while the measurement spaces are highly correlated with one another, these spaces are more highly correlated for certain pairs of languages than others, and in no case are they perfectly correlated. Consequently, the results of this comparison can only be considered approximate. In the next section, an alternative approach to comparing the patterning of vowels along the underlying parameters will be proposed, in an attempt to solve these problems.

Cross-linguistic Comparisons Within a Common Factor Space

Up to this point, the primary role that PARAFAC has played in this study has been to help us to discover the underlying parameters of lip position in five languages. Using the six criteria discussed in Chapter 3, we arrived at the conclusion that the optimal solutions for each language consisted of one factor for English, two factors for Cantonese, and three factors for Finnish, French and Swedish. We found in general that for the optimal solutions of the languages with more than one factor, given a solution of n dimensions actually only n-1 factors were needed to account for the variance in the vowel space. This use of PARAFAC has been extremely helpful, in that (a) we have been able to find, in a non-arbitrary way, the parameters of lip position that underlie the data sets for each language and (b) we have been able to observe differences and similarities in the patterning of the vowels in each language along particular factors. However, we saw in the previous section that problems arose when we tried to compare the factors across languages, because (1) the solutions found are not perfectly correlated and therefore represent different coordinate systems and (2) only one set of the two sets of comparable factors separated the vowels effectively enough to allow us to conclude anything about the vowels of the languages other than English and Swedish. We would therefore like to be able to choose PARAFAC solutions that not only adequately represent the data (i.e., have high R^2 values, as well as fulfilling the additional five criteria), but that in addition can be made comparable to one another. Deciding on which solutions these may be involves once again considering the solutions that are not necessarily the optimal ones. However, since such a large amount of additional variance is accounted for in going from one dimension to two dimensions for each language, we may confine the decision to choosing between the 2- and 3-factor solutions, for the languages other than English.

Because English has turned out to be quite different from the other languages (i.e., 92% of the variance in the data is accounted for by a single factor, that separates the English vowels effectively), only the languages with front rounded vowels are included in the present comparison. With regard to these four languages, after PARAFAC has been carried out, there are four separate factor spaces, each of which correlates very highly with its corresponding raw data matrix. However, as mentioned before, these solutions cannot be directly compared, because they represent different coordinate systems. In order to solve this problem of comparability, a generalized type of canonical correlation (Carroll, 1965) was used, in the form of a computer program called CANON, implemented by Louis Goldstein at UCLA. CANON takes as input N data sets (matrices) and produces a single matrix, which represents a least squares approximation to the input data matrices. The new matrix is arrived at one vector at a time, by finding a linear composite of each of the N matrices that correlates most highly with the first canonical vector (Z). This Z vector is chosen so as to maximize the sum of the squared correlations (r_i^2) between itself and each linear composite of each data set; that is, the quantity

$\sum_{i=1}^{N} r_i^2$ (referred to by Carroll as R^2) is maximized, and R^2 is thus an index of how good the fit is between the original data sets and the matrix produced by CANON. It is convenient to divide R^2 by N, the number of data sets, so that it ranges between 0.00 and 1.00. There will thus be n Z-vectors, n R^2 values and n linear composites per data set, given that there are n dimensions in the data set of lowest dimensionality.

CANON can be applied to the present problem of comparing lip measurements across languages in the following way. If we take the four sets of lip measure loading matrices (M) as input to CANON, we will get out a new matrix (henceforth referred to as the "Canonical M" matrix) that represents a least squares approximation to the four input lip measure loading matrices. The output is therefore still a matrix of lip measurement loadings. If this new matrix shows a good fit to the original four matrices, then we will have succeeded in finding a single coordinate system within which to describe lip position across the four languages. That is, we will be in a position to compare how the vowels in these different languages make use of a single set of underlying factors. It should be noted that using CANON in this way is tantamount to rotating the PARAFAC solutions, which should lower the fit of the data to the PARAFAC model; however, a high R^2/N will indicate that the original factor spaces do not need to be altered drastically to conform to the Canonical M space.

Returning to the question of choosing between the two and three dimensional PARAFAC solutions, it is now clear that the decision will also be affected by the value of Carroll's R^2/N. Thus, not only should the PARAFAC solutions fulfill the criteria raised earlier, but the solutions chosen must be sufficiently compatible for R^2/N to be high.

This leaves us with three main alternatives: (1) 2-factor solutions for all languages, (2) 3-factor solutions for all languages, and (3) a 2-factor solution for Cantonese and 3-factor solutions for the other languages.

Alternative (2) is not advisable, given the problems that we found earlier for the Cantonese 3-factor solution. Alternative (1) is feasible in terms of the criteria of uniqueness, convergence, etc., and a CANON analysis of this form was carried out. As a result, it was found that R^2/N for the first canonical variate (Z vector) was 0.995, but for the second canonical variate it was only 0.547. Accordingly, this alternative was not pursued further. Alternative (3) fulfills all the criteria: the solutions are unique, they converge, the PARAFAC R^2 is very high in all cases, and Carroll's R^2/N for both canonical variates was found to be very high (0.998 and 0.956, respectively). Thus it was decided to continue the analysis using the results obtained from a Canonical M matrix of two dimensions, derived from one two dimensional space (for Cantonese) and three three dimensional spaces (for Finnish, French and Swedish).

How PARAFAC and CANON were applied to the data sets of each language is diagrammed explicitly at the top of Figure 35. The remaining portion of the figure will be explained later, and the reader may refer to it when necessary.

In order to interpret the canonical factors, we may make use of the methods described in Chapter 4. We can get a detailed view of what these factors represent by examining the ordering of the measure loadings in the Canonical M space (see Figure 36). With regard to factor 1, at one end of the scale we find measures from point B (the fixed point on the upper teeth) to points C and D (the corner of the mouth and the most forward point of contact between the lips, respectively). At the other end of the scale we find measure 24 (the area of the mouth opening in the front view), and extremely far down at this end we find measure 23 (the horizontal opening in the front view). Looking at the loadings along canonical factor 2 we find at one end measures 1, 3, and 5 (protrusion from the teeth), while at the other end of the scale are measures 20, 21, and 22 (all of which represent vertical opening in the front view), as well as measure 24 (the front view area). Measure 23, the horizontal opening, appears in the middle of the scale, so we expect its contribution to canonical factor 2 to be small.

To summarize, canonical factor 1 can be said to be related mainly to horizontal opening (with some component of lip protrusion as well), while canonical factor 2 appears to be directly proportional to lip protrusion as measured from the teeth, and inversely proportional to vertical opening between the lips.

Figure 35: Outline of the Analysis

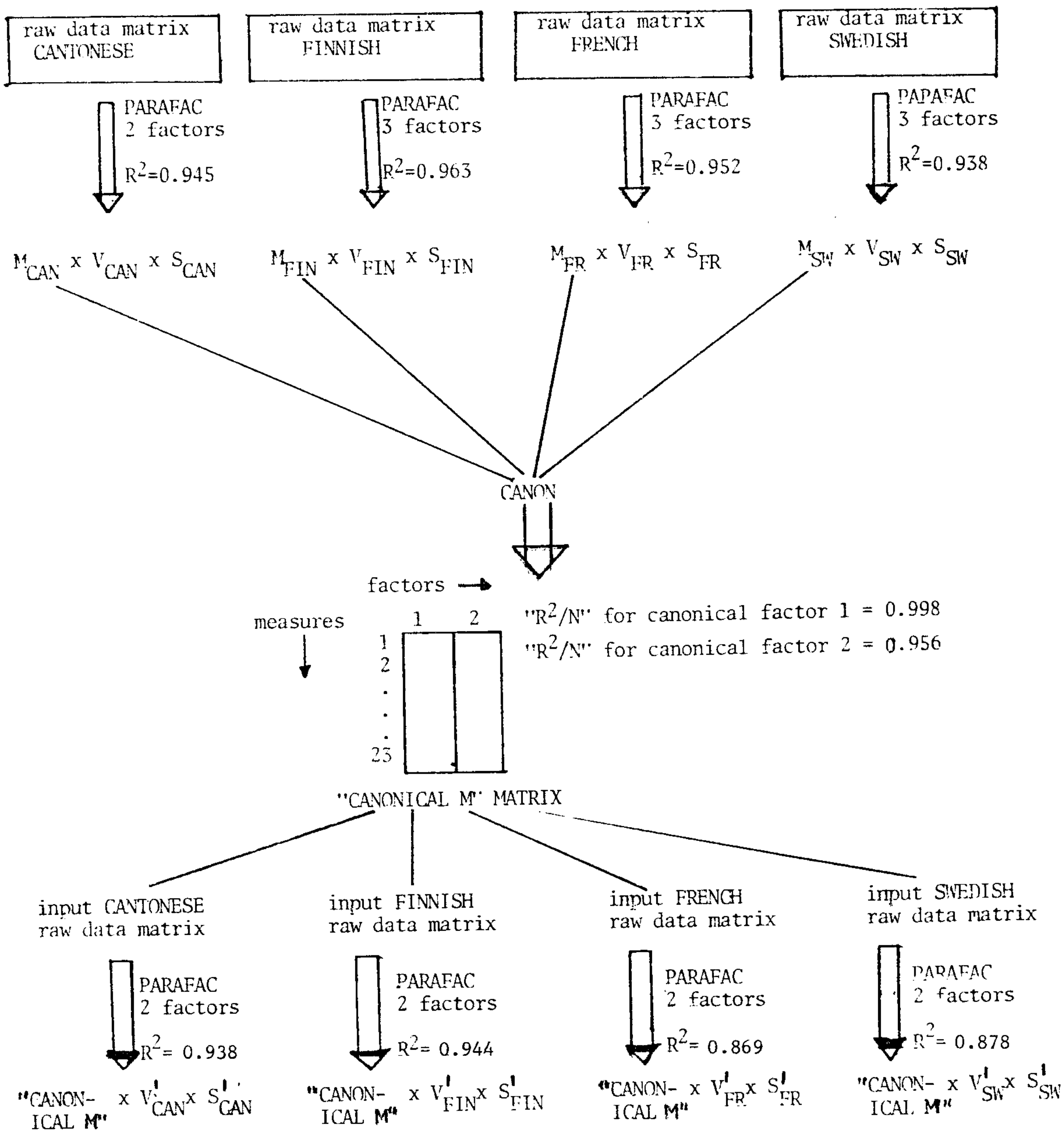
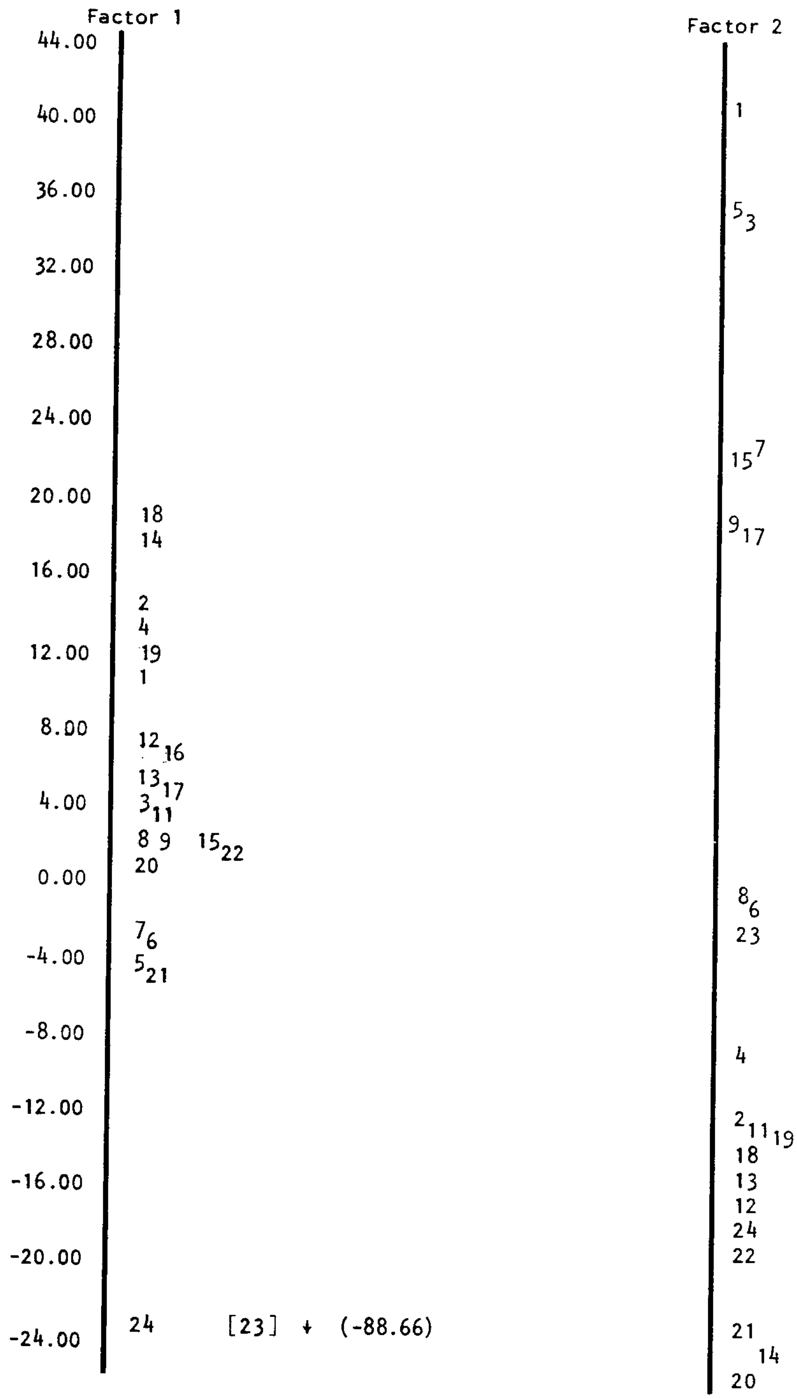


Figure 36: Canonical M space
(Lip measure loadings from CANON along canonical factors 1 and 2; true loadings x 10^2)



The effects of the canonical factors can be represented as illustrated in Figures 37 and 38. These figures were constructed in the same way as was done in Chapter 4, except in this case it was necessary to first normalize the canonical lip measure loadings (using PARAFAC), to give a mean squared loading of 1. Note that as before the deviations drawn do not represent actual reconstructed lip shapes, and so the diagrams are to be taken only as illustrations of the relative effects of canonical factors 1 and 2. We can see, for example, for canonical factor 1 (Figure 37) that a positive value of this factor represents a very slight increase in protrusion, combined with a large decrease in horizontal opening, as we saw by examining the Canonical M space itself. Similarly, a large positive value of canonical factor 2 (Figure 38) represents a large increase in the amount of protrusion (from point B to points E and F), combined with a substantial decrease in vertical opening.

We may now turn to the question raised at the beginning of this section; that is, we can ask whether or not the vowels in these four languages differ with respect to their use of canonical factors 1 and 2. In order to answer this question, PARAFAC was run a second time on each of the four sets of measurement data, but this time the M matrix was constrained to be the Canonical M matrix for all languages, as illustrated at the bottom of Figure 35. Note that because of this constraint the original PARAFAC measure loading matrices have been altered, and therefore the product V x S (vowel loadings x speaker loadings) is now also altered to conform to the new common factor space. However, because the data set for each language is different, V x S is still language specific.

The loadings in the vowel space along canonical factor 1 (horizontal opening) were multiplied by the mean speaker loading for each language. The value of the product vowel loading x mean speaker loading can be thought of as an average loading for a given vowel along canonical factor 1, and these loadings can now be compared across languages. They are plotted for each language in Figure 39. Here we observe the following:

(1) In all languages, this factor separates traditionally labeled "rounded" from "unrounded" vowels; as would be expected, rounded vowels show a low degree of horizontal opening while unrounded vowels show a high degree. However, the factor of horizontal opening does not create very much separation among the unrounded vowels, which might have been expected (cf. Jones′ division of lip position into "spread", "neutral" and "round").

(2) In Cantonese and French we find the subgroupings (a) high, rounded (b) mid, rounded and (c) unrounded. French is similar, but the mid front [ø] patterns with the high vowels. In Swedish we find the high rounded front vowel [y] grouped with the mid rounded vowels, indicating a greater degree of horizontal opening for this vowel. The Swedish [ɑ] is also near the mid rounded vowels. As mentioned before, this vowel is, in fact, somewhat rounded, and so its location on the scale is not surprising.

(3) So-called lax rounded vowels in French and Swedish show greater horizontal opening than their tense counterparts. Also, in general low mid rounded vowels form subgroups of their own (in e.g. Cantonese, where there is no phonological basis for a tense/lax distinction, for the vowels considered here).

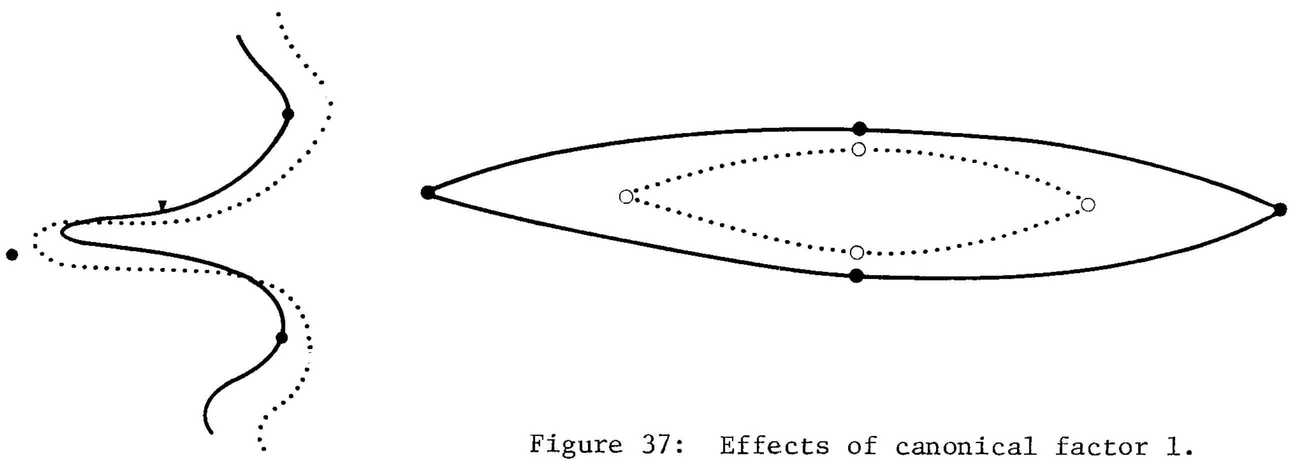


Figure 37: Effects of canonical factor 1.

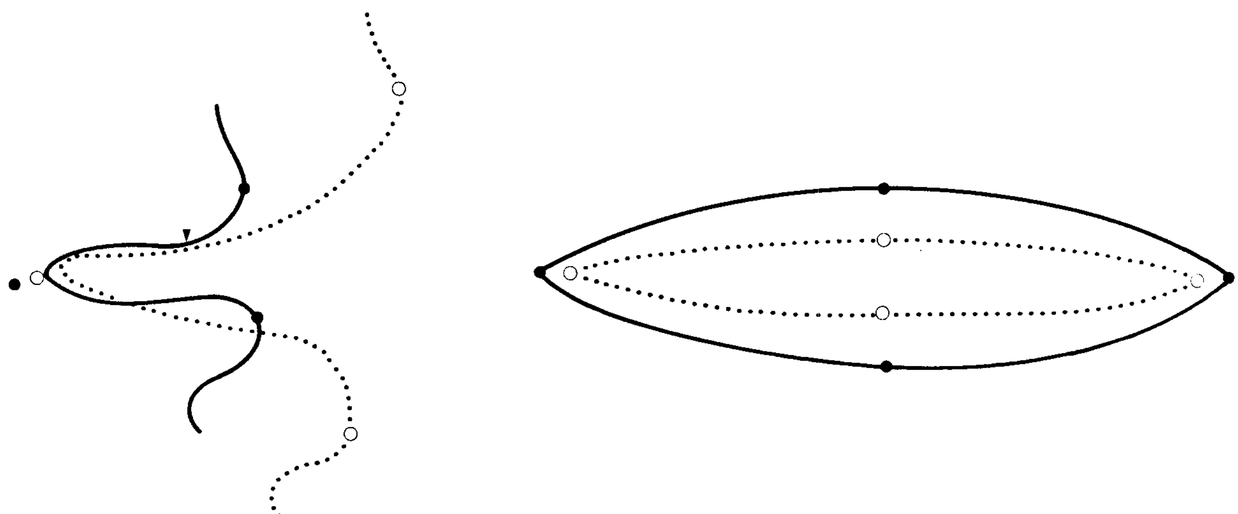


Figure 38 Effects of canonical factor 2.

Figure 39: Vowel x mean speaker loadings along canonical factor 1 (horizontal opening)

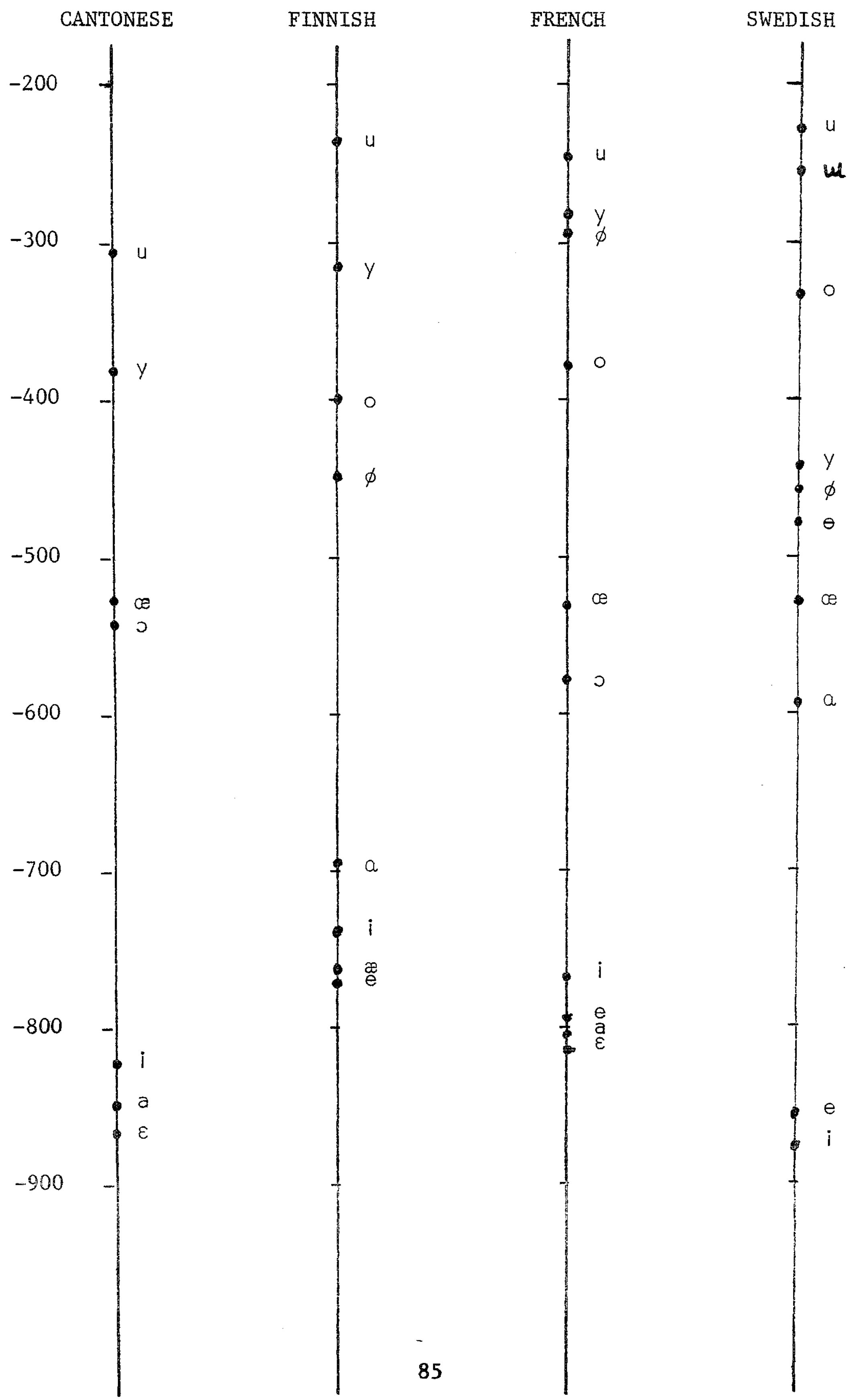
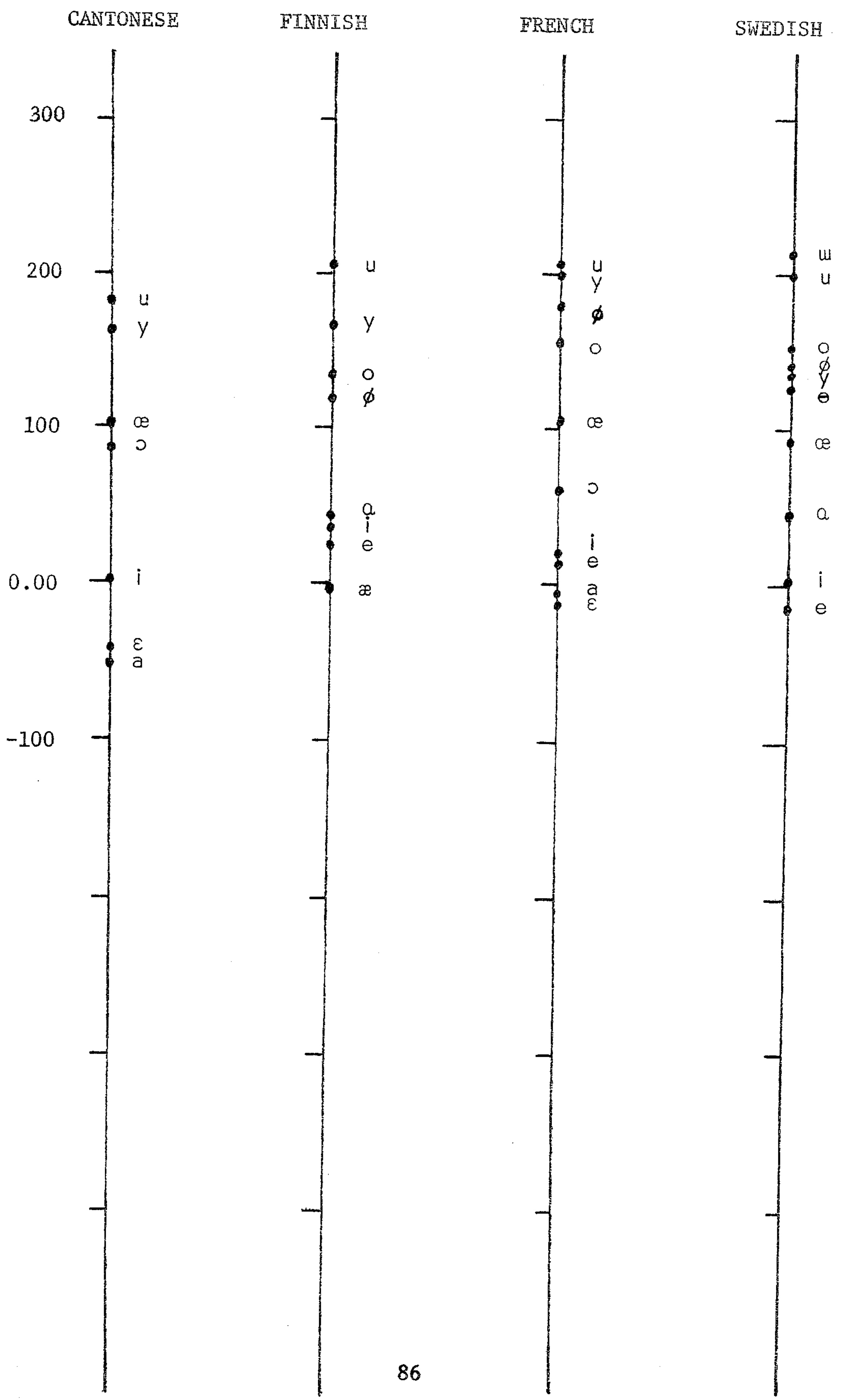


Figure 40: Vowel x mean speaker loadings along canonical factor 2 (protrusion/vertical opening)



(4) While the overall ordering of vowels is similar from language to language along canonical factor 1, in some languages vowels within particular subgroups (e.g., high, round) are more closely tied to one another than in other languages. For example, in Finnish, there is a good deal of separation between [u], [y] and [ø], while in French these vowels lie close together on a scale of horizontal opening.

Figure 40 shows the vowel x mean speaker loadings along canonical factor 2 (protrusion/vertical opening), and we find a pattern similar to the factor 1 vowel space. As with factor 1, rounded and unrounded vowels are separated by factor 2, and in general there is an ordering, at least among rounded vowels, corresponding to vowel height, with low mid vowels being further down the scale than high mid vowels. Although the scale is compressed relative to the factor 1 vowel space, there are many differences between languages in the relative spacing of vowels within the subgroups "round" and "unround" along the scale of protrusion/vertical opening than we saw with the scale of horizontal opening. For example, we see that the French [u] and [y] lie extremely close together on this scale. These vowels are less close in Cantonese, more separated in Finnish, and most distant in Swedish, for which [u] and [y] lie quite far apart. The results with regard to Swedish are particularly interesting in this light; note that [u] and [ɯ] are grouped very close together at one end of the scale (indicating a large value for the ratio protrusion/vertical opening), while the high front rounded vowel [y] is located much closer to the mid front rounded vowel [ø]. This grouping of [u] and [ɯ] together is just what we would expect from the traditional description of inrounding and outrounding in Swedish vowels. It should also be noted that this grouping is found along canonical factor 1 (horizontal opening) as well. In addition, more recent work done by McAllister (1980) has shown that while there is lip movement in the posterior-anterior direction in the production of [u] and [ɯ], there is in addition substantial compression of the lips in the superior-inferior (i.e., vertical) direction. Given vertical compression of the lips and hence a very small vertical opening, we would expect to find these two vowels grouped together at an extreme end of the scale; similarly, we would not expect to find the outrounded vowels [y] and [ø] to be located at either extreme, but to be grouped together towards the middle of the scale, which is exactly what we observe.

We may also reiterate in this connection that the inrounding / outrounding distinction between the groups [u], [ɯ] and [y], [ø] has in addition shown up along the dimensions of (a) the ratio of horizontal opening and area to protrusion (factor 2 of the Swedish 3-factor solution) and (b) the simple scale of horizontal opening (canonical factor 1). It is noteworthy that the latter dimension is in fact capable of distinguishing the inrounded from the outrounded vowels by itself in Swedish. In addition, we see that while the Swedish [o] lies in an intermediate position between the inrounded and outrounded categories along canonical factor 1 (horizontal opening), it tends to group more with the <u>outrounded</u> vowels along the scale proportional to the ratio of protrusion to vertical opening. This is in contradiction to the result found by McAllister, et al (1974) mentioned earlier. It seems that all that can be reasonably concluded at this point is that the Swedish [o] does not clearly belong to one or the other category.

Finally, another result discussed by McAllister (1980) is worthy of mention. The purpose of his study was to test the hypothesis that the tense/lax distinction for Swedish rounded vowels was correlated with the degree of displacement of the lips from a neutral position. Upper and lower lip movements in both the anterior-posterior and inferior-superior directions were measured for four tense/lax vowel pairs. Only two of these pairs correspond to vowels included in the present investigation: [ɯ] - [ɵ] and [ø] - [œ]. Examination of the movement data provided strong support for the hypothesis, in that in general the tense vowels exhibited less vertical opening and more protrusion than their lax counterparts. (No such tense/lax division was clearly reflected in the EMG data for these vowels). If we look at the vowel loadings along canonical factor 2 (protrusion/vertical opening), we see that this is in fact the case for the Swedish [ʉ] - [ɵ] and [ø] - [œ] pairs; in each case, the tense vowel lies higher on the scale than its lax counterpart. In addition, we find the same result for the French rounded tense/lax vowel pairs [o] - [ɔ] and [ø] - [œ] along canonical factor 2. Furthermore, we note that identical results were obtained for both Swedish and French along (a) the dimensions proportional to the ratio of horizontal opening and lip area to protrusion and (b) canonical factor 1 (horizontal opening). Hence, the findings in the present study support the hypothesis that the tense/lax distinction in rounded vowels is correlated with particular dimensions of lip shape.

Tables 18 and 19 reorganize the data presented in Figures 39 and 40 in terms of hierarchies along the dimensions of horizontal opening and protrusion/ vertical opening.

In summary, we have seen that the languages under study differ in the lip positions they use, especially in the production of rounded vowels. In other words, the languages differ as to how "rounded" (in some general sense) a given rounded vowel may be. These differences have been observed along the two canonical factors, and also along a dimension related to the ratio of horizontal opening and front view area to protrusion, that was found to underlie the optimal solutions for the four languages with front rounded vowels (set 2). The differences relate primarily to the relative spacing of the rounded vowels along the factors. For English, it was seen that a dimension of horizontal opening (set 1) alone effectively separates rounded from unrounded vowels.

Another important result has been that the categories inrounding/outrounding and tense/lax are reflected in the patterning of the vowels along the factors. While the distinction between inrounding and outrounding is clearcut along all three dimensions for Swedish, this is not true for the other three languages with front rounded vowels, in that the relative spacing among the vowels for Cantonese, Finnish and French differs from factor to factor and from language to language. Thus, the inrounding/outrounding distinction appears to be a language-specific fact, and is most obviously important for Swedish. On the other hand, the tense/lax distinction is reflected along all three of the dimensions investigated for both French and Swedish, the only languages with what could be analyzed as tense/lax rounded vowel pairs.

In addition, it was shown that while the notion of a close correlation between tongue height and lip position can be observed along the factors (in that in general high vowels are more rounded than mid vowels), this correlation is cross-cut (especially for Swedish) by the inrounding/outrounding distinction. Thus, high front rounded vowels are not, in general, equal in rounding along any dimension to high back rounded vowels; similarly, the vowels [o] and [ø] are not, in general, equally rounded. More importantly, the degree to which the amount of rounding is unequal <u>depends upon the language</u>.

Table 18: Hierarchical ordering of languages for similar vowels along canonical factor 1 (horizontal opening). The languages are shown in order of decreasing loadings along this factor.

/i/ :	Swedish >> Cantonese >> French > Finnish
/e/ :	Swedish >> French ≃ Finnish
/ɛ/ :	Cantonese >> French
/a/ :	Cantonese >> French
/ɑ/ :	Finnish >> Swedish
/ɔ/ :	French > Cantonese
/o/ :	Finnish > French > Swedish
/u/ :	Cantonese >> French ≃ Finnish ≃ Swedish
/y/ :	Swedish >> Cantonese >> Finnish > French
/ø/ :	Swedish ≃ Finnish >> French
/œ/ :	Swedish ≃ French ≃ Cantonese

\>> = difference greater than or equal to 50

\> = difference less than 50 and greater than or equal to 25

≃ = difference less than 25

Table 19: Hierarchical ordering of languages for similar vowels along canonical factor 2 (protrusion/vertical opening). The languages are shown in order of decreasing loadings along this factor.

/i/ :	Finnish > French > Swedish ≃ Cantonese
/e/ :	Finnish ≃ French >> Swedish
/ɛ/ :	French >> Cantonese
/a/ :	French >> Cantonese
/ɑ/ :	Swedish ≃ Finnish
/ɔ/ :	Cantonese > French
/o/ :	French ≃ Swedish > Finnish
/u/ :	French ≃ Finnish ≃ Swedish > Cantonese
/y/ :	French >> Finnish ≃ Cantonese >> Swedish
/ø/ :	French >> Swedish > Finnish
/œ/ :	French ≃ Cantonese ≃ Swedish

\>> = difference greater than or equal to 25

\> = difference less than 25 and greater than or equal to 12.5

≃ = difference less than 12.5

It is therefore clear that similarly transcribed vowels in different languages may make use of different lip gestures. We would now like to ask the question: Are the differences observed due to the fact that the vowels in these languages are not acoustically the same vowel? This question will be addressed in the next chapter.

Chapter 6: Acoustic Correlates of Lip Position in Vowels

In the Introduction the question was raised as to the nature of the relationship between lip position and formant frequency in the vowels of different languages. In particular, we would like to know (a) with what degree of accuracy is it possible to predict lip position from formant frequency and (b) given that such a prediction is feasible, do the necessary equations differ from language to language?

Recall that Ladefoged, et al (1978) measured lateral x-rays of five speakers of American English producing ten vowels. In this study they showed that the distance between the upper and lower lips (d) could be predicted using multiple regression from a particular combination of the formant frequencies F1, F2 and F3. The equation they found was the following:

$$d = 0.003F2 - 0.000000343(F2 \times F3) + 4.143(F1/F2) - 2.865$$

The correlation between the observed lip distance and the predicted lip distance was 0.78. In order to see if a higher correlation could be obtained, using a larger number of subjects and other measures of lip position, a pilot study was conducted for the English data. In this study I attempted to predict the raw measures 1, 3, 7, 23 and 24 directly from formant frequency for the data collected from the eight English speakers pronouncing nine vowels. This prediction was done using a stepwise multiple regression program, where the dependent variable represented a particular measure for the nine vowels produced by the eight speakers, and the independent variables consisted of the first three formant frequencies of these vowels, as well as particular products and ratios of the formant frequencies. The results were extremely discouraging; Table 20 below gives the highest correlations obtained for each measure:

Measure	Correlation Coefficient (Multiple R)
1 (distance from tooth to upper lip)	0.331
3 (distance from tooth to lower lip)	0.493
7 (distance between outermost points of upper and lower lips)	0.682
23 (horizontal opening)	0.665
24 (front view area)	0.662

Table 20: Correlation coefficients obtained from multiple regression analysis, predicting raw measures of lip position from formant frequency for American English.

These results lend themselves to two interpretations. First, it could be the case that it is simply not possible to predict lip position from formant frequency accurately. Second, it is possible that individual variation in lip position among subjects might create problems in predicting lip shapes from acoustic data. If the second interpretation is correct, then we can remedy the situation by appealing once again to PARAFAC, which has been shown to deal successfully with speaker variation, and attempt to predict the underlying factor of lip position from formant frequency.

In order to test the second hypothesis, the stepwise multiple regression program was run again, using the individual products of the eight speaker loadings and the nine vowel loadings along the single factor extracted by a PARAFAC analysis. (Because this was a preliminary analysis, only 17 measures of lip position were used; R^2 was 0.923). While this factor extracted for English differs slightly from the factor described in Chapters 3 and 4 for English (using 23 measures of lip position), the patterning of the vowel loadings is quite similar to the pattern we observed before. Figure 41 plots the vowel loadings obtained in this analysis, and it can be seen that these loadings tend to be higher for vowels with a large mouth opening and lower for rounded vowels. The regression equation obtained to predict this underlying factor (as represented by the product of the vowel x speaker loadings) from formant frequency was as follows:

$$\text{Underlying Lip Factor (L)} = 20.44\ \frac{F2}{F3} + 0.005\ \frac{F1xF3}{F2} - 1.610$$

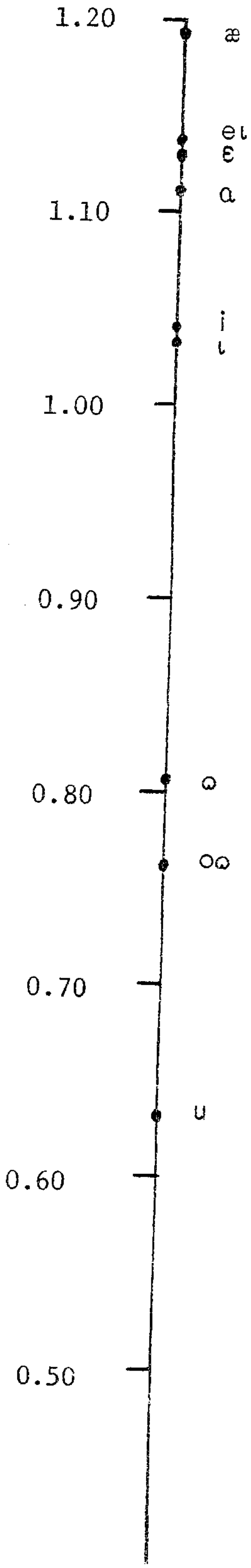
The correlation between the actual lip factor and the predicted lip factor was 0.831. Having predicted the values of the vowel x speaker loadings, it was then possible to take the actual loadings of lip measurements given by PARAFAC, together with the vowel x speaker loadings predicted by the regression, to reconstruct a predicted set of lip measures, that depend on formant frequency. The correlation obtaining between these predicted lip measurements and the raw lip data was 0.945.

Hence, we can conclude that it is possible to predict lip position from formant frequency, at least for English, with a fairly high degree of accuracy, and that the necessary equation requires only two terms.

Given that the factor extracted by PARAFAC can be predicted successfully from formant frequency for English, we may now go on to address the question of whether or not the relationship between lip position and formant frequency differs from language to language. As we saw in the previous chapter, English differs from the other languages in that the optimal solution for it consists of a single factor. Accordingly, we will restrict ourselves to comparing the relationship between lip position and formant frequency in Cantonese, Finnish, French and Swedish.

One possible approach to this question would be to attempt to predict each of the underlying factors of the optimal solutions found for each language from the formant frequencies. While this approach would tell us what the relationship between lip shapes and formants is for each individual language, it is not clear how we could compare the equations obtained, since the underlying factors differ from language to language. On the other hand, in Chapter 5 it was shown that by using CANON it was possible to find a common measurement space (the "Canonical M" space) that correlated highly with the individual factor spaces for each of the

Figure 41: English vowel loadings from PARAFAC along the underlying factor L



four languages. We can therefore make use of this result to predict the two underlying canonical factors (one proportional to horizontal opening, the other to the ratio of protrusion to vertical opening) from the formant frequencies for each individual language.

Once again, a stepwise multiple regression program was used for this purpose. The general form of the equation given by the program is shown below:

$$V' \times S' = b_1X_1 + b_2X_2 + b_3X_3 + b_4P + \text{Constant}$$

where $V' \times S'$ = predicted product of vowel and speaker loadings on a given factor (dependent variable)

X = a set of independent variables consisting of the first three formant frequencies, and their cross-products and ratios, as described in Ladefoged, et al (1978). The step-wise multiple regression procedure determined the terms of the set that produced the best correlation.

P = variable representing variation due to speaker; as P was a dummy variable, it was always equal to 1

b = (beta) weighting of a particular variable

Recall that while the measurement space is constrained to be identical for all languages (and therefore the physiological correlates of each factor are the same across languages), the product of the vowel loadings and the speaker loadings is language-specific.

Two regression equations were obtained for each language, one per factor. The correlation coefficients (multiple R) ranged between 0.842 and 0.911. The actual regression equations for each language are given in Table 21. In order to compare these equations across languages, a set of constant formant frequencies (F1, F2, F3) was introduced into the regression equations, to simulate the vowels [i, e, æ, ɑ, o, u, y, ø] (data taken from Terbeek, 1977). We can now observe the similarities and differences in the patterning of vowels that have been constrained to be acoustically identical across languages, along the factors of (1) horizontal opening and (2) the ratio of protrusion to vertical opening. We are thus really asking the question: If the vowels in these four languages were acoustically identical, would they use the above two underlying dimensions of lip position differently?

The variable P was originally introduced into the regression equations in order to make it possible to later analyze statistically the differences found among the vowel x speaker loadings predicted from formant frequency (i.e., to obtain a scatter plot of predicted vowel x speaker loadings). This is, however, beyond the scope of the present study. Instead, in looking at the results of the regression analyses, the mean beta weight (b) for each variable P was found for each language for each factor, and these constants were used in the equations. It should be noted that while it would have been possible to use equations with fewer terms than those given in Table 21, the point of the present investigation was not to find the simplest equations, but rather to find equations with

Table 21: Regression equations for each language. $\bar{b}$ = the mean beta weight for the variable P that extracted speaker variation, and was added to the equations.

CANTONESE

factor 1: (R=0.911)

$$V \times S = -1.039 \times F3 - \frac{0.524 \times F1 \times F2}{10^3} - \frac{5.118 \times 10^6}{F3} + \frac{1.286 \times 10^8}{F1 \times F2} + 4.337 \times 10^3; \quad \bar{b} = -6.605 \times 10^1$$

factor 2: (R=0.890)

$$V \times S = 0.762 \times F1 - 0.256 \times F3 - \frac{0.212 \times F1 \times F2}{10^3} - \frac{2.349 \times 10^3 \times F1}{F3} + 0.735 \times 10^2; \quad \bar{b} = -4.937 \times 10^1$$

FINNISH

factor 1: (R=0.897)

$$V \times S = \frac{-0.412 \times F1 \times F2}{10^3} + \frac{4.468 \times 10^6}{F3} - \frac{2.442 \times 10^{11}}{F1 \times F2 \times F3} + \frac{6.524 \times 10^4 \times F3}{F1 \times F2} - 2.053 \times 10^3; \quad \bar{b} = -2.027 \times 10^2$$

factor 2: (R=0.883)

$$V \times S = \frac{-0.157 \times F1 \times F2}{10^3} + \frac{4.468 \times 10^6}{F3} - \frac{2.442 \times 10^{11}}{F1 \times F2 \times F3} + \frac{2.757 \times 10^4 \times F3}{F1 \times F2} - 4.221 \times 10^2; \quad \bar{b} = -8.915 \times 10^1$$

FRENCH

factor 1: (R=0.891)

$$V \times S = 2.865 \times F1 - 0.528 \times F3 - \frac{1.809 \times F1 \times F2}{10^3} - \frac{5.054 \times 10^6 \times F1}{F2 \times F3} + 1.173 \times 10^3; \quad \bar{b} = 1.284 \times 10^2$$

factor 2: (R=0.885)

$$V \times S = 1.049 \times F1 - 0.195 \times F3 - \frac{0.664 \times F1 \times F2}{10^3} - \frac{1.969 \times 10^6 \times F1}{F2 \times F3} + 7.740 \times 10^2; \quad \bar{b} = 1.767 \times 10^1$$

SWEDISH

factor 1: (R=0.875)

$$V \times S = \frac{-0.515 \times F2 \times F3}{10^4} + \frac{2.586 \times 10^6}{F1 \times F3} - \frac{1.585 \times 10^2 \times F2 \times F3}{F1 \times F3} - - 3.611 \times 10^2; \quad \bar{b} = 7.873 \times 10^1$$

factor 2: (R=0.842)

$$V \times S = \frac{-8.91 \times 10^2 \times F1}{F3} + \frac{1.058 \times 10^6}{F3} - \frac{4.233 \times F2 \times F3}{10^4 \times F1} - 1.308 \times 10^2; \quad \bar{b} = -5.513$$

comparable and relatively high correlation coefficients, so that the predictions would be as accurate as possible.

Discussion and Results

Figure 42 shows the vowel x speaker loadings predicted from formant frequency plotted along canonical factor 1, for each language. The figure shows that if, for example, a (mean) speaker of Cantonese wanted to produce an [u] with a given set of formant frequencies, he would have considerably less horizontal opening than a speaker of French producing the same vowel. As we have seen, this factor of horizontal opening separates rounded from unrounded vowels. However, the separation is much less distinct in Swedish, where the spacing is relatively even among all vowels within the entire vowel space. There appears to be no common ordering among the unrounded vowels, but all languages except French order rounded vowels identically along the dimension of horizontal opening. The spacing among the rounded vowels themselves, however, differs from language to language.

The location of [ɑ] on canonical factor 1 for Swedish is particularly striking. The formant frequencies for this vowel were measured from a pronunciation that was classified as unrounded (Terbeek, 1977; pg. 64), yet it is placed relatively close to the front rounded vowels [ø] and [y]. In other words, the relationship between the acoustic structure of vowels and the degree of spreading of the lips in Swedish is such that a low back vowel is associated with a somewhat rounded lip position. And, as mentioned earlier, the Swedish phonemic /ɑ / has a somewhat rounded phonetic realization.

Figure 43 shows the predicted vowel x speaker loadings on canonical factor 2 (protrusion/vertical opening). The following observations can be made: (1) all languages show large separation between the unrounded and rounded groups of vowels, (2) no language has the same ordering among the rounded or the unrounded vowels, (3) three languages show relatively even spacing within the rounded group of vowels; the exception is Swedish, where these vowels lie very close together on a dimension of protrusion/vertical opening, and (4) The spacing among the unrounded vowels is relatively even for all languages except Finnish, where these vowels show very little separation at all.

These results indicate that languages differ greatly in the lip gestures they use to make the same acoustic distinctions among vowels. If we look at the ordering of pairs of vowels within the subgroups "rounded" and "unrounded" along both factors 1 and 2, we see that the four languages have only two characteristics in common:

(1) To distinguish between [y] and [ø], all languages use relatively lower values of horizontal opening (i.e., relatively <u>higher</u> values of canonical factor 1) and relatively higher values of protrusion/vertical opening for [y], and relatively higher values of horizontal opening and relatively lower values of protrusion/vertical opening for [ø].

(2) To distinguish between [u] and [o], all languages use relatively lower values of horizontal opening and relatively higher values of protrusion/vertical opening for [u], and relatively higher values of horizontal opening and relatively lower values of protrusion/vertical opening for [o].

Figure 42: Vowel x Speaker loadings predicted from formant frequency along canonical factor 1 (horizontal opening).

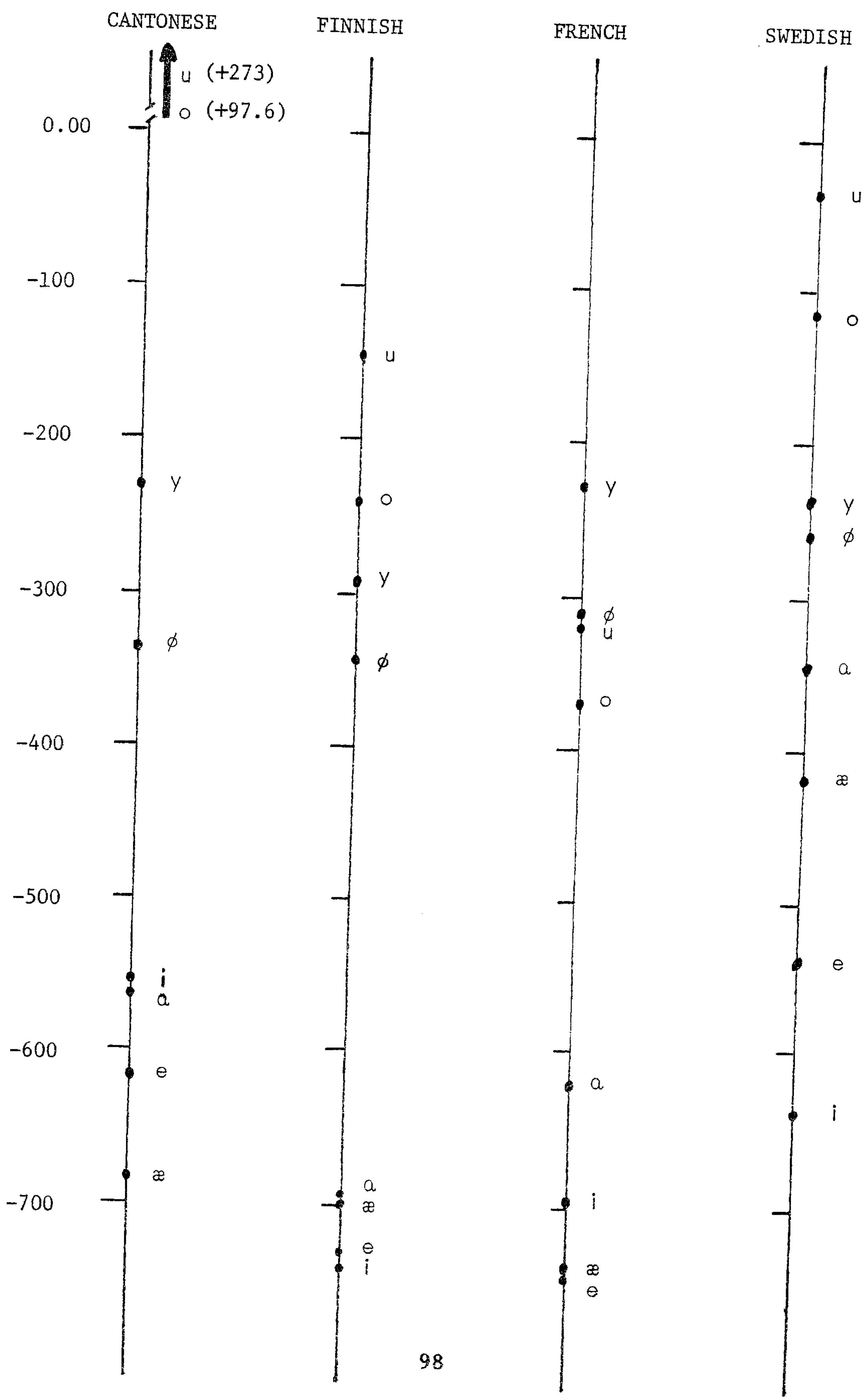


Figure 43: Vowel x Speaker loadings predicted from formant frequency along canonical factor 2 (protrusion/vertical opening).

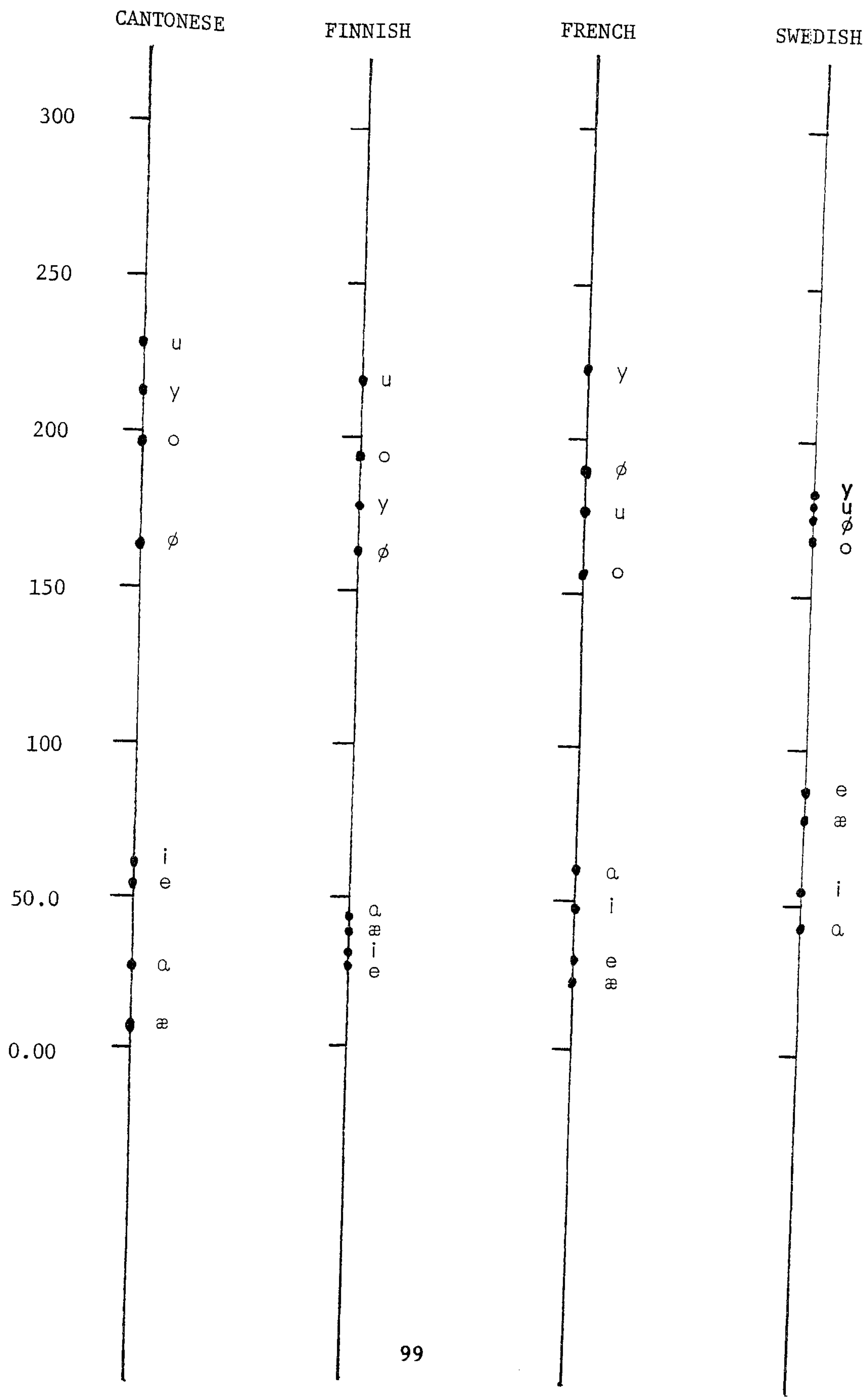


Table 22: Relative weightings of factors 1 and 2 used to distinguish pairs of vowels across languages.

\+ = relatively higher weighting of a given factor

\- = relatively lower weighting of a given factor

		i/e	i/æ	i/ɑ	e/æ	e/ɑ	æ/ɑ	u/y	u/ø	u/o	y/ø	y/o	ø/o
CANTONESE	factor 1	+ -	+ -	+ -	+ -	- +	- +	+ -	+ -	+ -	+ -	- +	- +
	factor 2	+ -	+ -	+ -	+ -	+ -	- +	+ -	+ -	+ -	+ -	+ -	- +
FINNISH	factor 1	- +	- +	- +	- +	- +	- +	+ -	+ -	+ -	+ -	- +	- +
	factor 2	+ -	- +	- +	- +	- +	- +	+ -	+ -	+ -	+ -	- +	- +
FRENCH	factor 1	+ -	+ -	- +	- +	- +	- +	- +	- +	+ -	+ -	+ -	+ -
	factor 2	+ -	+ -	- +	+ -	- +	- +	- +	- +	+ -	+ -	+ -	+ -
SWEDISH	factor 1	- +	- +	- +	- +	- +	- +	+ -	+ -	+ -	+ -	- +	- +
	factor 2	- +	- +	+ -	+ -	+ -	+ -	- +	+ -	+ -	+ -	+ -	+ -

Otherwise, the relative amounts (weightings) of canonical factors 1 and 2 used to distinguish pairs of vowels differ greatly from language to language. A comparison of these weightings for 12 pairs of vowels is given in Table 22.

In summary, the results presented here provide evidence that the relationship between lip position and formant frequency is to a large extent language-specific. Given that the equations differ so greatly from language to language, and given that the articulatory correlates of the acoustically identical vowels are complex, including tongue position and lip position (and, to some degree, larynx position), we might expect that languages can differ in the relative amounts of these articulatory components that they use to produce a particular acoustic result. However, a closer investigation of the relationship between vowel quality and lip position in these languages would be needed before an explanation can be provided for the kinds of differences that have been observed among the acoustically identical vowels.

Conclusion

This study has addressed itself to three questions:

(1) Which measure or measures of lip position are the linguistically relevant ones for describing the vowels of English, Cantonese, Finnish, French and Swedish?

(2) Do similarly transcribed vowels in these five languages make use of different lip gestures?

(3) What is the relationship between lip position and formant frequency in the vowels of the five languages? Is this relationship language-specific?

In order to answer the first question, a type of 3-mode factor analysis (PARAFAC) was used to extract underlying dimensions of lip position in each of the five languages. Using six criteria for choosing PARAFAC solutions, we found that the optimal solutions for each language consisted of one factor for English, two factors for Cantonese and three factors for Finnish, French and Swedish. An important result of this analysis was that only English, which has no front rounded vowels, cannot uniquely have its lip positions represented in a 3-dimensional space. After interpreting the factors of the optimal solutions, we found that in general only n-1 dimensions for solutions having more than one factor accounted for substantial proportions of the variance in the vowel space, given an n-dimensional solution (Swedish was the exception). The underlying parameters found to be important in distinguishing the vowels of the different languages were as follows:

(1) English:	horizontal opening	
(2) Cantonese:	horizontal opening, front view area (and vertical opening)	
(3) Finnish:	(a)	horizontal opening, front view area, vertical opening (and protrusion)
	(b)	the ratio of horizontal opening and front view area to protrusion
(4) French	(a)	the ratio of horizontal opening and front view area to protrusion
	(b)	the ratio of vertical opening and lower lip protrusion to horizontal opening
(5) Swedish	(a)	horizontal opening, front view area and protrusion
	(b)	the ratio of horizontal opening, front view area (and vertical opening) to protrusion
	(c)	vertical opening, front view area and protrusion

Two other results were important in this connection. First, upper lip protrusion (in addition to lower lip protrusion) was found to play a role in the interpretation of the underlying parameters in all four of the languages with front rounded vowels. Second, while protrusion as measured with reference to the upper front teeth turned out to contribute to the underlying parameters, measures of protrusion measured from the corner of the mouth were also shown to be relevant.

With regard to the second question, three methods were used to compare similarly transcribed vowels across languages. First, twelve parameters of lip position (consisting of raw lip measurements and ratios of raw lip measurements) were compared across languages, for the vowels [i], [y], and [u]. An analysis of variance was performed, revealing significant differences for certain of these vowels across languages for the following parameters:

(1) lower lip protrusion measured with reference to the teeth (measure 3)

(2) vertical opening between the lips (measure 21)

(3) horizontal opening between the lips (measure 23)

(4) the area enclosed by the lips in the frontal view (measure 24)

(5) the ratio of upper lip protrusion to vertical opening (measure 1/measure 21) and the ratio of lower lip protrustion to vertical opening (measure 3/measure 21). However, these significant differences were found to reflect the fact that the values for measure 21 for several English subjects were extremely low, compared to the other languages.

(6) the ratio of horizontal opening to lower lip protrusion (measure 23/measure 3), and the ratio of horizontal opening to vertical opening (measure 23/measure 21)

A Newman-Keuls test was performed for every analysis of variance for which the F-ratio was significant, and in this way we were able to ascertain which pairs of languages differed from one another, and in what ways they differed, along the above parameters for the vowels [i], [y] and [u]. For example, it was found that Cantonese and English speakers use significantly less lower lip protrusion in the production of the vowel [u] than do speakers of Finnish, French and Swedish.

The second method used to compare the similarly transcribed vowels across languages was to observe the patterning of the vowel x mean speaker loadings along two factors, for which the lip measurement loading matrices were highly correlated. Because one of these factors turned out not to produce effective separation of the vowels, it was only possible to observe differences and similarities in the vowel patterning along a factor related to the ratio of horizontal opening and front view area to protrusion. Here we saw similarities across the vowel systems in terms of the ordering of the vowels and in terms of their division into "rounded" and "unrounded" groups, but we also observed differences regarding how closely particular vowels clustered together. This result indicates that the languages under study differ with respect to the amount of the above parameter that they use to distinguish their vowels.

Finally, a generalized type of canonical correlation (CANON) was used to find a common factor space, in which to compare the vowels across the four languages with front rounded vowels. Two underlying "canonical" factors, one of horizontal opening and one of the ratio of protrusion to vertical opening, were found to effectively separate the vowels of Cantonese, Finnish, French and Swedish. As with the second method of comparison, we were able to observe similarities across languages in terms of the ordering of the vowels, but differences were found in the way the vowels clustered together. We also saw that the traditional divisions of inrounding/outrounding and tense/lax were reflected in the clustering of the vowels along both canonical factors.

The third question addressed in this study concerned the relationship between lip position and formant frequency in the vowels of the five languages. We found that although it was not possible, at least for English, to predict raw measures of lip position from formant frequency accurately, we saw that a factor of lip shape underlying the English data could be predicted from formant frequency with a correlation of 0.831. We then attempted to predict canonical factors 1 and 2 from formant frequency for Cantonese, Finnish, French and Swedish. Using a constant set of formant frequencies (taken from Terbeek, 1977), the predicted vowel x mean speaker loadings were plotted and compared. Only two common characteristics were found:

(1) To distinguish between [y] and [ø], all languages use relatively higher values of both horizontal opening and protrusion/vertical opening for [y], and relatively lower values of both horizontal opening and protrusion/vertical opening for [ø].

(2) To distinguish between [u] and [o], all languages use relatively higher values of both horizontal opening and protrusion/vertical opening for [u], and relatively lower values of both horizontal opening and protrusion/vertical opening for [o].

Because speakers of different languages would produce acoustically identical vowels with very different lip gestures, it was concluded that the relationship between lip position and formant frequency is to a large degree language-specific.

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Appendix: Data

This appendix consists of (1) 24 measurements of lip position and (2) the first three formants of the vowels of English, Cantonese, Finnish, French and Swedish. Eight speakers are represented for each language. Each set of measurements and formants is preceded by a two-digit identification number: the first digit refers to the speaker, and the second digit refers to the vowel. The key below tells which number refers to which vowel in each language.

The lip measurements are given in the order corresponding to the numbered distances in Figure 1. It should be noted that it is the square root of measures 19 and 24 (side view area and front view area, respectively) that is listed here.

Key to Vowels

ENGLISH

1 i
2 ɪ
3 eɪ
4 ɛ
5 æ
6 ɑ
7 oʊ
8 ʊ
9 u

FRENCH

1 i
2 e
3 ɛ
4 a
5 ɔ
6 o
7 u
8 y
9 ø
10 œ

CANTONESE

1 i:
2 ɛ:
3 a:
4 ɔ:
5 u:
6 y:
7 œ:

SWEDISH

1 i:
2 e:
3 ɑ:
4 o:
5 u:
6 ʉ:
7 ɵ
8 y:
9 ø:
10 œ

FINNISH

1 i:
2 e:
3 æ:
4 a:
5 o:
6 u:
7 y:
8 ø:

English: Calculated Lip Measurements in millimeters x 10^2

11	808.	595.	777.	733.	1392.	1303.	1366.	1094.
	1250.	159.	1176.	796.	942.	728.	1308.	928.
	1062.	595.	709.	780.	650.	740.	5310.	1783.
12	788.	528.	786.	593.	1323.	1238.	1288.	1091.
	1093.	92.	1145.	780.	953.	591.	1208.	843.
	907.	528.	665.	730.	730.	790.	5010.	1766.
13	740.	919.	819.	1046.	1503.	1452.	1482.	1275.
	1460.	189.	1312.	974.	1023.	1034.	1428.	1090.
	1195.	919.	866.	750.	1020.	1120.	5730.	2149.
14	764.	744.	807.	805.	1458.	1389.	1430.	1140.
	1161.	70.	1301.	771.	1066.	805.	1362.	833.
	1059.	743.	725.	790.	590.	730.	5250.	1761.
15	712.	866.	1165.	950.	1546.	1509.	1750.	1300.
	1468.	169.	1389.	769.	1253.	950.	1480.	860.
	1417.	858.	915.	1010.	800.	970.	5120.	1939.
16	750.	796.	800.	862.	1491.	1426.	1419.	1157.
	1197.	66.	1312.	852.	1017.	861.	1377.	917.
	1026.	796.	773.	710.	580.	660.	5300.	1703.
17	791.	153.	971.	466.	1239.	845.	1143.	836.
	999.	397.	641.	590.	618.	295.	976.	925.
	419.	40.	504.	440.	490.	550.	2790.	1091.
18	882.	203.	799.	387.	1234.	1040.	1222.	941.
	1029.	196.	893.	663.	780.	382.	1073.	844.
	738.	202.	591.	850.	660.	820.	3650.	1539.
19	800.	135.	734.	68.	868.	668.	710.	643.
	774.	202.	637.	431.	582.	66.	837.	630.
	613.	134.	303.	170.	140.	220.	3040.	648.
21	630.	628.	945.	624.	1127.	1209.	1294.	1249.
	1389.	217.	1157.	856.	1084.	589.	1119.	818.
	1282.	628.	768.	350.	430.	610.	4070.	1300.
22	651.	508.	860.	739.	1327.	1139.	1126.	1109.
	1382.	275.	1072.	845.	874.	735.	1305.	1078.
	1064.	503.	678.	360.	410.	480.	4120.	1237.
23	629.	541.	1035.	736.	1320.	1163.	1340.	1146.
	1415.	272.	1057.	794.	967.	736.	1278.	1016.
	1165.	514.	779.	400.	480.	590.	3860.	1253.
24	612.	603.	917.	727.	1282.	1198.	1185.	1177.
	1380.	206.	1138.	878.	958.	723.	1265.	1004.
	1145.	596.	727.	380.	350.	460.	3960.	1183.
25	578.	718.	1119.	863.	1415.	1292.	1438.	1194.
	1414.	223.	1229.	723.	1144.	862.	1394.	887.
	1343.	698.	853.	320.	360.	510.	4630.	1253.
26	634.	550.	922.	569.	1196.	1180.	1085.	1027.
	1206.	205.	1064.	863.	708.	561.	1151.	950.
	906.	474.	669.	240.	240.	420.	3850.	964.
27	692.	153.	822.	526.	1217.	835.	898.	822.
	1074.	384.	740.	648.	569.	465.	1099.	1008.
	473.	105.	419.	170.	200.	270.	2670.	721.
28	660.	462.	817.	692.	1271.	1118.	943.	1074.
	1423.	371.	1003.	976.	476.	683.	1252.	1226.
	756.	433.	496.	50.	50.	100.	2540.	447.
29	684.	196.	744.	354.	1037.	529.	766.	588.

	973.	536.	430.	373.	481.	335.	957.	901.
	431.	194.	308.	0.	40.	30.	2530.	100.
31	654.	676.	889.	741.	1362.	1323.	1086.	1231.
	1389.	182.	1309.	918.	1095.	728.	1362.	971.
	1277.	675.	658.	40.	50.	170.	5120.	361.
32	669.	573.	860.	615.	1262.	1240.	975.	1169.
	1302.	165.	1225.	916.	980.	607.	1262.	953.
	1144.	570.	638.	90.	100.	210.	4640.	742.
33	650.	757.	975.	856.	1485.	1404.	1211.	1268.
	1456.	195.	1379.	929.	1147.	853.	1482.	1031.
	1339.	751.	747.	110.	30.	40.	5280.	387.
34	603.	739.	897.	871.	1449.	1334.	1112.	1244.
	1427.	184.	1321.	911.	1122.	866.	1448.	1039.
	1292.	738.	714.	170.	140.	20.	5860.	520.
35	588.	875.	990.	992.	1515.	1431.	1282.	1414.
	1606.	198.	1421.	969.	1305.	968.	1515.	1063.
	1501.	874.	875.	30.	110.	160.	5460.	787.
36	737.	542.	1088.	658.	1389.	1277.	1275.	1190.
	1400.	211.	1231.	816.	1084.	657.	1376.	962.
	1275.	512.	710.	230.	290.	420.	4640.	1149.
37	631.	151.	773.	465.	1096.	678.	823.	648.
	1041.	467.	624.	382.	613.	462.	1082.	840.
	835.	4.	374.	170.	190.	140.	2750.	671.
38	622.	154.	799.	462.	1084.	738.	826.	747.
	1072.	379.	99.	492.	666.	459.	1071.	865.
	830.	87.	418.	180.	150.	120.	2940.	640.
39	644.	193.	790.	198.	812.	642.	833.	602.
	757.	203.	580.	313.	587.	141.	778.	511.
	693.	57.	356.	100.	130.	90.	2310.	447.
41	920.	406.	778.	514.	1423.	1307.	1085.	812.
	903.	119.	1272.	599.	802.	477.	1390.	718.
	875.	358.	508.	280.	230.	330.	4260.	990.
42	926.	535.	848.	820.	1535.	1454.	1182.	967.
	1624.	793.	1410.	743.	931.	561.	1472.	805.
	1618.	499.	572.	360.	320.	510.	3710.	1105.
43	844.	698.	970.	1155.	1682.	1532.	1349.	993.
	2054.	1236.	1493.	674.	988.	589.	1426.	608.
	1928.	656.	668.	470.	380.	510.	4780.	1285.
44	894.	706.	1031.	956.	1662.	1589.	1447.	1024.
	1836.	925.	1528.	697.	1014.	708.	1589.	757.
	1804.	648.	708.	320.	270.	350.	4250.	1025.
45	884.	799.	1246.	652.	1534.	1672.	1646.	1191.
	1364.	278.	1598.	754.	1178.	649.	1517.	673.
	1364.	730.	890.	320.	210.	360.	4540.	1025.
46	931.	796.	1455.	640.	1568.	1646.	1864.	1044.
	1564.	550.	1470.	554.	1043.	640.	1555.	640.
	1557.	554.	923.	810.	700.	810.	4100.	1606.
47	1071.	363.	919.	531.	1600.	1019.	1169.	556.
	1235.	754.	873.	278.	556.	529.	1579.	984.
	1143.	177.	462.	180.	240.	390.	3010.	812.
48	1006.	264.	880.	242.	1248.	994.	1078.	622.
	993.	390.	914.	339.	622.	240.	1236.	661.
	980.	83.	470.	110.	260.	490.	2710.	825.
49	1020.	426.	841.	277.	887.	717.	969.	496.
	567.	186.	647.	96.	455.	183.	833.	282.

	565.	369.	383.	20.	50.	90.	2040.	173.
51	919.	483.	883.	483.	1389.	1389.	1004.	1242.
	1242.	0.	1388.	913.	1173.	477.	1388.	913.
	1173.	477.	554.	260.	140.	120.	5530.	877.
52	930.	455.	885.	719.	1248.	1382.	889.	1221.
	1569.	747.	1382.	930.	1154.	110.	1040.	588.
	1552.	452.	479.	60.	40.	40.	5680.	141.
53	916.	508.	951.	661.	1221.	1423.	976.	1234.
	1595.	797.	1423.	916.	1183.	99.	1015.	507.
	1556.	507.	532.	90.	50.	40.	5520.	539.
54	802.	726.	807.	874.	1347.	1485.	922.	1429.
	1680.	636.	1472.	1024.	1370.	335.	1132.	684.
	1674.	674.	567.	110.	250.	200.	5930.	933.
55	918.	507.	944.	829.	1601.	1422.	958.	1227.
	1758.	666.	1422.	921.	1173.	542.	1459.	957.
	1758.	505.	531.	80.	10.	20.	5710.	480.
56	969.	416.	960.	965.	1718.	1382.	918.	1198.
	1924.	858.	1382.	891.	1153.	510.	1477.	986.
	1924.	414.	472.	160.	120.	50.	5320.	693.
57	908.	160.	872.	369.	1244.	799.	876.	719.
	962.	445.	797.	291.	705.	335.	1241.	735.
	931.	109.	382.	180.	80.	130.	5240.	787.
58	930.	254.	883.	314.	1235.	700.	852.	690.
	1027.	539.	698.	222.	666.	307.	1235.	759.
	998.	231.	342.	110.	40.	50.	5210.	539.
59	893.	482.	867.	274.	1166.	429.	704.	559.
	1063.	750.	427.	59.	505.	274.	1161.	793.
	1018.	461.	267.	30.	60.	10.	4580.	283.
61	890.	246.	638.	356.	1122.	1067.	971.	863.
	980.	117.	997.	675.	731.	319.	1082.	760.
	835.	234.	551.	330.	330.	510.	4320.	1175.
62	927.	272.	637.	460.	1221.	1151.	1044.	859.
	1079.	228.	1026.	716.	667.	417.	1171.	861.
	878.	272.	546.	400.	500.	420.	4550.	1330.
63	819.	407.	643.	604.	1316.	1173.	1088.	917.
	1128.	213.	1082.	718.	779.	593.	1269.	904.
	938.	407.	618.	450.	460.	630.	4620.	1393.
64	839.	432.	744.	546.	1315.	1256.	1155.	948.
	1142.	201.	1138.	764.	778.	543.	1261.	886.
	968.	420.	656.	530.	580.	550.	4660.	1473.
65	786.	515.	805.	580.	1285.	1271.	1233.	1053.
	1196.	155.	1172.	800.	894.	575.	1236.	865.
	1048.	511.	712.	430.	530.	510.	4660.	1404.
66	901.	403.	796.	568.	1390.	1303.	1209.	908.
	1231.	336.	1146.	745.	738.	560.	1345.	944.
	1059.	362.	690.	720.	750.	740.	4130.	1606.
67	893.	41.	807.	134.	1027.	933.	1038.	827.
	856.	94.	847.	561.	739.	124.	931.	644.
	720.	40.	509.	370.	370.	480.	2630.	964.
68	905.	62.	709.	150.	1040.	857.	954.	731.
	823.	185.	787.	470.	684.	150.	964.	648.
	695.	28.	500.	490.	480.	590.	3070.	1122.
69	903.	267.	745.	24.	927.	637.	770.	620.
	756.	290.	585.	378.	575.	20.	856.	649.
	548.	251.	352.	160.	80.	150.	2040.	469.

71	759.	517.	773.	519.	1268.	1267.	1214.	920.
	922.	3.	1177.	668.	854.	504.	1179.	669.
	857.	503.	660.	120.	100.	180.	4470.	831.
72	802.	295.	726.	406.	1201.	1083.	1159.	837.
	857.	120.	1018.	503.	823.	396.	1121.	605.
	813.	294.	583.	510.	380.	570.	4220.	1311.
73	752.	604.	995.	605.	1357.	1356.	1467.	933.
	935.	3.	1228.	572.	915.	548.	1230.	574.
	917.	546.	757.	390.	350.	390.	4590.	1208.
74	774.	428.	844.	493.	1265.	1200.	1201.	933.
	970.	66.	1117.	652.	867.	468.	1181.	716.
	880.	404.	653.	330.	320.	350.	4330.	1095.
75	741.	558.	998.	555.	1290.	1293.	1461.	1035.
	1032.	4.	1197.	598.	1016.	534.	1194.	594.
	1013.	537.	740.	370.	350.	370.	4160.	1162.
76	843.	433.	920.	431.	1273.	1275.	1329.	954.
	953.	2.	1169.	639.	905.	392.	1167.	637.
	904.	394.	681.	570.	590.	590.	4240.	1404.
77	974.	229.	845.	238.	1107.	911.	1162.	623.
	679.	201.	830.	191.	600.	72.	1027.	388.
	679.	127.	481.	220.	180.	180.	2340.	663.
78	926.	180.	857.	218.	1083.	895.	1106.	678.
	754.	193.	810.	308.	678.	101.	1000.	497.
	731.	89.	480.	330.	270.	380.	2910.	911.
79	919.	307.	874.	239.	866.	714.	1033.	626.
	635.	153.	653.	143.	600.	112.	799.	289.
	634.	258.	403.	390.	300.	310.	3230.	922.
81	773.	621.	730.	623.	1342.	1341.	1178.	1100.
	1103.	3.	1280.	850.	961.	623.	1282.	852.
	963.	621.	745.	420.	650.	520.	4650.	1456.
82	810.	667.	796.	669.	1432.	1431.	1277.	1151.
	1154.	3.	1403.	790.	1114.	667.	1404.	792.
	1116.	665.	717.	520.	760.	620.	4110.	1490.
83	771.	758.	832.	760.	1491.	1489.	1339.	1153.
	1154.	2.	1459.	776.	1130.	759.	1461.	777.
	1130.	758.	757.	550.	830.	850.	4150.	1568.
84	772.	768.	1062.	772.	1517.	1514.	1570.	1247.
	1249.	4.	1466.	731.	1235.	770.	1470.	734.
	1237.	766.	827.	730.	830.	660.	3910.	1530.
85	769.	727.	974.	724.	1461.	1464.	1444.	1238.
	1236.	4.	1425.	785.	1206.	723.	1421.	781.
	1204.	727.	798.	670.	830.	620.	4270.	1594.
86	856.	557.	829.	557.	1376.	1377.	1303.	1111.
	1113.	4.	1326.	767.	1055.	557.	1326.	767.
	1058.	557.	701.	440.	810.	720.	4170.	1533.
87	591.	26.	680.	313.	904.	608.	701.	668.
	861.	298.	603.	338.	661.	313.	901.	636.
	777.	15.	320.	120.	190.	230.	2160.	566.
88	926.	55.	800.	278.	1194.	980.	1219.	796.
	925.	229.	894.	376.	795.	277.	1123.	605.
	891.	48.	570.	660.	780.	700.	3380.	1407.
89	695.	250.	710.	198.	889.	492.	709.	513.
	789.	419.	450.	210.	511.	183.	868.	629.
	661.	236.	278.	230.	220.	130.	4030.	806.

Cantonese: Calculated Lip Measurements in millimeters x 10^2

11	744	522	644	525	1213	1211	875	1086
	1088	03	1186	912	1051	519	1189	915
	1053	516	584	542	603	612	4426	1413
12	756	585	802	588	1304	1301	1131	1176
	1178	03	1272	875	1096	586	1275	878
	1098	584	686	693	848	843	4557	1685
13	710	540	696	542	1227	1224	915	1085
	1087	03	1199	894	1048	542	1201	897
	1050	539	627	666	762	693	4412	1569
14	713	215	618	463	1150	906	800	787
	985	249	869	608	738	462	1118	856
	968	214	429	299	362	373	2777	893
15	640	43	593	384	1013	596	583	572
	923	425	578	399	506	384	1004	825
	912	41	288	101	116	225	2098	524
16	686	121	594	336	1008	566	580	520
	895	454	545	345	458	335	999	799
	889	119	320	259	273	312	2229	749
17	746	262	775	373	1114	1004	989	907
	973	111	972	609	813	371	1082	719
	910	261	482	492	438	435	2995	1061
21	1020	450	881	460	1474	1465	1405	1027
	1034	10	890	1000	978	325	899	1008
	987	317	676	796	1113	827	3705	1675
22	899	640	1007	638	1535	1537	1453	1056
	1057	03	966	1025	1014	378	966	1025
	1013	378	798	1363	1614	1167	4369	2245
23	876	564	1016	570	1437	1432	1384	1014
	1010	08	809	996	962	252	806	994
	960	254	746	1176	1466	1081	4306	2105
24	937	249	893	517	1451	1172	1215	861
	1027	283	732	808	788	302	944	1021
	1012	90	575	941	936	822	2951	1489
25	826	232	788	418	1244	668	964	606
	967	605	395	431	415	296	923	959
	953	232	343	302	329	256	841	451
26	1023	182	817	261	1284	923	1044	645
	957	404	449	604	564	171	801	957
	942	182	436	439	566	550	1600	829
27	895	204	843	409	1304	1076	1121	793
	986	250	610	761	724	253	830	980
	957	33	491	551	783	625	2863	1257
31	818	723	629	725	1481	1476	1204	1049
	1044	11	1288	954	1037	709	1288	954
	1034	709	707	1140	1172	953	5055	2121
32	770	1116	1088	1109	1790	1798	1767	1304
	1303	08	1581	1015	1223	1078	1575	1009
	1220	1084	1036	1903	2204	1724	5766	3006
33	725	975	1395	971	1678	1684	1951	1320
	1327	10	1386	927	1122	863	1386	927
	1124	863	1110	2373	2663	2078	5492	3256
34	964	392	1098	510	1454	1325	1547	937

	979	131	891	752	799	256	994	854
	894	153	710	1735	1894	1657	3085	2193
35	874	477	853	299	944	596	852	429
	632	386	411	182	280	58	785	557
	617	432	300	222	269	139	1021	419
36	948	464	838	192	979	651	893	440
	688	388	433	220	304	60	818	604
	665	445	319	262	400	305	2196	801
37	862	266	847	458	1316	1078	1309	663
	823	271	718	458	544	308	977	718
	783	48	530	1151	1333	1044	2950	1709
41	496	696	731	695	1190	1192	993	808
	801	07	998	746	800	565	993	741
	794	570	566	797	801	429	5124	1695
42	530	765	790	764	1293	1295	1126	878
	879	02	1090	789	863	657	1090	789
	864	657	627	1000	1026	534	5189	1902
43	501	713	815	720	1221	1213	1080	841
	847	08	998	758	820	577	1006	766
	827	570	619	964	1015	537	5101	1902
44	461	540	782	640	1091	987	993	676
	737	106	768	576	633	459	862	670
	717	364	499	865	817	449	4030	1529
45	503	243	600	433	920	728	785	537
	601	193	585	421	481	285	729	565
	595	141	320	427	470	331	2438	908
46	528	203	683	470	984	672	883	530
	672	320	518	309	402	335	810	601
	655	43	340	683	606	345	2288	1004
47	521	273	645	470	963	763	821	549
	607	201	629	414	494	299	779	563
	603	150	366	629	642	354	2897	1124
51	697	593	1057	591	1204	1209	1583	1243
	1248	07	927	946	936	565	927	946
	936	565	798	1570	1916	1229	5382	2594
52	622	974	1084	967	1477	1485	1634	1310
	1309	08	1150	1111	1127	896	1145	1106
	1123	901	911	1814	2323	1543	5633	2935
53	638	704	1063	700	1281	1283	1537	1237
	1227	10	1042	955	998	657	1035	948
	991	663	802	1659	2037	1397	5457	2706
54	617	226	959	379	993	826	1168	870
	955	177	637	587	614	284	805	755
	779	116	509	723	1021	678	3003	1413
55	541	132	705	161	693	579	736	593
	714	144	462	448	455	111	606	592
	599	33	326	229	378	324	2234	734
56	614	132	683	426	1027	744	933	718
	900	295	532	589	562	375	798	854
	836	109	436	540	865	561	2893	1220
57	629	230	743	301	929	859	1011	749
	767	70	611	629	621	208	661	679
	672	158	506	927	1279	842	3338	1669
61	763	545	953	545	1277	1277	1342	1202
	1202	00	1158	913	1040	537	1158	913

	1040	537	695	883	1270	1256	4757	2074
62	646	768	1029	771	1380	1377	1440	1283
	1282	05	1300	889	1116	765	1302	891
	1117	762	792	1116	1471	1003	5392	2266
63	725	672	1177	672	1394	1394	1618	1177
	1177	00	1234	761	990	616	1234	761
	990	616	829	1372	1690	1374	4865	2407
64	795	134	825	221	1005	811	1093	693
	796	211	661	371	513	153	869	578
	703	54	428	598	719	555	2631	1159
65	823	249	872	177	953	677	1072	673
	783	296	535	260	411	63	824	550
	674	227	355	347	425	341	1892	749
66	879	273	854	82	890	667	1006	659
	781	246	536	309	433	25	780	553
	663	269	376	439	503	471	1951	869
67	783	143	891	297	1074	848	1197	760
	871	244	695	366	535	232	936	607
	755	08	451	637	754	639	2623	1225
71	772	345	753	348	1119	1116	1181	792
	793	03	737	714	721	245	739	716
	723	243	555	939	1135	1112	3691	1791
72	795	348	836	378	1170	1143	1329	784
	859	77	746	635	671	293	817	706
	745	222	589	1023	1132	1059	3638	1813
73	781	410	841	405	1181	1186	1338	867
	870	06	651	798	756	266	651	798
	755	266	593	974	1200	1102	3806	1870
74	814	154	728	502	1313	968	1167	731
	881	348	578	618	604	349	829	868
	863	98	524	805	932	759	3531	1563
75	734	81	679	407	1136	784	967	620
	746	352	505	499	502	227	745	738
	739	13	426	536	775	543	2968	1221
76	785	117	723	298	1083	892	1117	671
	764	201	543	532	536	201	713	702
	705	31	468	620	795	656	2928	1281
77	785	146	722	408	1192	931	1136	715
	818	264	623	562	585	304	830	769
	783	96	508	776	904	795	3510	1525
81	735	880	791	876	1358	1361	1440	1320
	1316	04	1083	1169	1130	868	1079	1165
	1126	872	828	1356	1688	1314	5790	2663
82	625	841	878	843	1382	1381	1395	1152
	1153	02	1119	995	1043	797	1121	997
	1045	795	796	1324	1534	1122	5739	2511
83	589	912	1016	917	1454	1451	1511	1129
	1136	07	1138	956	1022	823	1144	963
	1028	817	860	1678	1838	1392	5391	2740
84	707	250	871	434	1122	892	1153	691
	792	240	637	461	534	255	853	677
	732	39	495	898	1006	710	2844	1426
85	794	283	725	277	1005	662	802	450
	683	364	411	351	371	58	733	673
	680	264	312	361	501	334	1621	719

86	816	278	791	147	948	619	1003	605
	767	364	392	308	350	67	736	653
	684	277	373	425	605	414	2015	895
87	677	161	802	359	1029	790	1037	690
	801	246	582	478	526	240	804	700
	736	19	437	675	779	579	2825	1255

<u>Finnish: Calculated Lip Measurements in millimeters x 10^2</u>

11	821	455	971	473	1261	1241	1257	871
	878	20	1115	622	811	345	1133	640
	825	327	671	855	1123	856	4116	1781
12	837	456	1002	458	1227	1226	1263	828
	826	03	1077	591	769	269	1077	591
	768	269	646	791	1044	927	4153	1758
13	851	510	1190	516	1339	1334	1457	1092
	1090	06	1163	788	956	367	1166	791
	957	365	794	1448	1662	1344	4326	2307
14	807	509	1115	505	1265	1267	1356	962
	969	08	1111	683	862	339	1113	685
	867	336	708	1032	1346	1275	3958	1951
15	962	318	1005	297	1119	811	1111	705
	827	317	677	345	513	49	978	646
	770	252	471	815	923	854	2295	1296
16	902	309	831	216	1039	675	1001	604
	724	373	574	196	397	66	932	554
	689	292	382	406	587	450	1610	786
17	898	250	898	287	1050	772	1018	662
	726	278	646	362	502	31	883	600
	690	207	437	642	724	690	2076	1083
18	902	197	958	250	1102	890	1116	762
	881	222	772	441	606	130	991	660
	804	89	496	847	1086	997	2413	1377
21	729	318	754	321	1033	1032	915	973
	980	07	846	918	890	304	852	923
	895	299	608	787	855	783	4863	1832
22	590	584	830	584	1174	1174	969	1051
	1051	00	974	1003	993	480	974	1003
	993	480	609	933	725	566	4805	1737
23	614	614	859	618	1231	1227	1053	1073
	1075	04	1024	1005	1012	520	1026	1008
	1014	517	682	1028	951	906	4878	1996
24	579	638	989	642	1173	1170	1002	1011
	1013	04	932	967	956	392	935	970
	959	389	606	850	838	757	4456	1775
25	1129	601	1119	335	1031	695	940	575
	801	368	489	373	424	230	843	727
	763	584	391	610	591	546	1588	902
26	963	626	1024	438	847	480	710	458
	629	375	348	264	307	269	681	597
	616	602	268	297	318	174	1431	557
27	1091	635	1116	325	904	537	793	582
	793	380	431	347	395	268	794	710

	743	631	336	455	488	468	1972	919	
28	1151	631	1221	301	1042	673	1011	673	
	927	411	465	423	445	222	865	822	
	840	621	437	1108	1082	978	2769	1619	
31	875	309	861	307	1123	1125	1274	675	
	676	02	617	587	595	12	617	587	
	595	12	539	1117	1292	1105	3803	1914	
32	832	386	827	387	1216	1215	1336	744	
	746	02	693	663	671	188	695	665	
	672	186	609	1283	1639	1350	4896	2390	
33	829	423	926	420	1215	1217	1369	720	
	724	04	715	612	639	124	716	614	
	641	122	614	1266	1505	1164	4571	2208	
34	806	182	776	182	951	953	1080	685	
	682	03	589	600	597	13	585	597	
	593	17	496	940	1161	956	3990	1816	
35	987	286	968	303	1057	944	1250	685	
	681	113	507	512	510	177	572	577	
	575	242	502	1264	1532	1333	2771	1772	
36	858	303	753	263	968	634	893	522	
	577	335	334	384	363	112	522	572	
	567	300	342	459	535	477	1927	886	
37	938	233	858	336	1068	868	1118	631	
	578	209	479	493	488	162	532	546	
	543	215	460	899	1146	888	2836	1524	
38	961	245	962	324	1154	992	1320	718	
	709	161	536	529	532	79	624	617	
	619	167	512	1188	1594	1448	2845	1827	
41	603	596	1018	591	1146	1150	1030	1020	
	1020	05	1020	894	947	426	1018	891	
	945	428	575	650	728	691	3323	1367	
42	668	783	1076	784	1436	1435	1176	1238	
	1241	03	1284	1122	1183	649	1286	1125	
	1186	647	692	731	966	821	3940	1659	
43	581	678	961	677	1225	1226	982	1069	
	1070	02	1081	992	1024	518	1081	992	
	1024	518	582	631	888	866	3485	1533	
44	605	716	920	724	1300	1292	950	1086	
	1089	08	1133	1037	1064	556	1138	1042	
	1068	551	546	579	763	760	3080	1342	
45	803	338	1128	560	1173	819	1052	812	
	923	355	675	567	624	166	955	848	
	880	114	513	570	698	627	2086	1034	
46	760	283	1002	627	1304	806	1018	743	
	995	500	638	531	583	341	1067	960	
	982	88	435	258	304	253	1486	585	
47	799	293	966	613	1337	773	961	679	
	1019	570	640	450	542	387	1167	977	
	1015	139	420	295	342	254	1575	641	
48	872	471	1311	775	1378	850	1176	851	
	1035	528	700	513	614	273	1144	957	
	1008	171	544	703	907	713	2204	1196	
51	592	552	1019	551	1132	1132	1236	956	
	953	03	965	728	833	422	962	726	
	831	424	670	1080	1371	966	4659	2074	

52	661	646	951	650	1307	1303	1297	1096
	1090	10	1173	851	996	605	1173	851
	993	605	747	1188	1438	979	4781	2171
53	633	575	1062	579	1203	1198	1317	1259
	1256	08	1092	957	1036	553	1094	959
	1037	551	740	1266	1472	1288	4857	2322
54	659	494	1065	494	1132	1132	1222	1018
	1018	00	986	786	881	367	986	786
	881	367	676	1100	1294	880	4409	2004
55	936	392	1041	332	804	701	1079	697
	715	106	513	369	445	268	608	464
	532	363	412	706	1001	792	2244	1251
56	841	360	988	188	889	594	979	689
	840	317	452	357	412	35	759	665
	711	343	338	262	451	282	1535	650
57	862	427	908	344	621	562	892	558
	609	85	418	250	339	323	501	334
	424	407	328	384	537	405	1839	816
58	885	347	994	285	737	680	1009	680
	722	72	527	374	456	241	599	445
	527	313	428	812	1109	1028	2444	1417
61	808	386	944	389	1185	1177	1224	894
	920	26	997	696	813	287	1017	716
	836	267	598	737	873	769	3473	1523
62	825	434	993	444	1249	1242	1194	1003
	997	13	1104	812	931	334	1106	814
	930	332	684	932	1062	922	3783	1734
63	880	603	1260	609	1434	1428	1534	1078
	1079	06	1186	825	965	370	1190	829
	968	366	792	1334	1492	1290	3899	2090
64	804	399	979	403	1180	1175	1135	957
	962	06	994	819	886	263	1000	825
	892	257	636	778	952	740	3743	1591
65	1049	278	1013	282	1150	891	1200	764
	792	260	689	456	566	57	887	654
	728	256	506	664	857	737	2354	1212
66	964	245	918	191	1058	755	1011	740
	807	304	610	485	551	10	845	719
	759	245	408	189	331	353	1849	682
67	978	290	899	217	986	727	998	696
	702	262	623	368	507	93	820	565
	652	289	448	403	515	532	1817	875
68	968	181	975	259	1145	934	1175	794
	846	212	757	516	629	57	933	692
	777	119	515	550	809	649	2628	1214
71	726	692	878	697	1413	1407	1198	907
	913	07	1126	848	899	503	1133	855
	906	496	626	1003	1180	857	4777	1993
72	723	721	992	719	1406	1409	1234	936
	930	06	1119	867	920	457	1114	862
	915	462	635	922	1223	752	4771	1963
73	699	915	1063	915	1598	1598	1423	964
	966	03	1174	911	953	592	1176	913
	955	591	752	1396	1721	1279	5039	2469
74	744	682	951	684	1387	1384	1191	892

	893	02	1072	842	883	404	1074	844
	884	403	614	947	1221	925	4354	1938
75	744	409	928	701	1383	1081	1107	772
	887	304	834	658	714	367	1043	867
	886	158	517	777	907	610	3646	1505
76	844	444	1012	499	1090	666	1012	590
	709	432	470	276	371	18	838	645
	689	350	363	421	467	320	1851	772
77	711	285	871	572	1207	720	969	588
	819	495	515	372	435	276	939	795
	816	147	383	527	594	473	2370	1016
78	756	332	935	666	1348	958	1106	699
	857	391	730	521	600	338	1036	827
	854	32	487	842	908	577	3280	1442
81	928	177	959	177	1103	1104	1086	1014
	1008	06	929	888	906	135	925	884
	901	139	703	1268	1232	1012	4333	2033
82	905	284	954	258	1159	1176	1132	972
	1009	53	955	865	898	194	970	880
	917	180	731	1293	1368	1122	4519	2190
83	888	341	1116	345	1202	1200	1278	1071
	1069	04	910	949	933	165	910	949
	934	165	755	1354	1545	1281	4056	2160
84	927	268	958	265	1144	1147	1007	930
	929	03	890	886	887	90	888	884
	885	92	607	874	963	809	3809	1669
85	1052	244	990	124	998	834	867	780
	868	164	711	652	680	100	855	795
	817	244	463	692	640	441	1953	968
86	1206	575	1094	234	1022	679	912	655
	866	358	528	444	486	231	867	784
	814	570	401	283	257	222	1262	530
87	1178	541	1049	258	993	699	935	628
	796	309	503	441	469	252	787	725
	745	537	411	358	391	336	1441	670
88	1089	273	1005	159	1029	845	918	778
	850	185	693	646	667	128	836	789
	804	272	483	742	731	535	2143	1096

French: Calculated Lip Measurements in millimeters x 10^2

11	940	491	1190	498	1029	1023	1331	709
	702	08	685	447	538	202	685	447
	537	202	546	915	947	880	3517	1636
12	926	490	1171	494	986	993	1249	696
	689	11	712	452	552	194	701	441
	541	183	542	690	911	747	3596	1534
13	923	608	1269	623	1148	1141	1395	710
	696	15	795	465	578	107	789	459
	570	102	577	867	1000	887	3639	1653
14	909	676	1433	681	1218	1212	1567	818
	815	06	803	518	625	72	805	521
	626	75	661	970	1357	1286	3948	1997

15 978 575 1316 675 1293 1072 1391 756
790 222 747 468 578 28 923 644
722 203 581 928 1006 964 3120 1585
16 952 561 1255 642 1142 893 1271 695
692 250 593 376 470 153 774 556
619 334 469 592 709 611 2885 1230
17 944 590 1253 757 1375 845 1202 664
866 542 530 392 451 56 975 836
856 389 441 393 561 485 2572 1009
18 911 594 1184 780 1311 868 1132 592
739 447 566 375 447 14 910 719
737 330 441 439 523 431 2589 985
19 1094 855 1369 835 1291 985 1379 535
610 347 499 199 302 265 808 507
569 574 424 554 664 585 1830 955
10 964 518 1191 619 1268 979 1294 675
737 294 692 373 500 03 938 619
699 243 513 596 706 635 3042 1283
21 726 621 1269 620 1344 1346 1556 1270
1260 11 968 1112 1050 417 959 1103
1042 426 877 1639 1894 1367 4780 2514
22 676 741 1542 737 1383 1387 1708 1390
1390 04 1052 1135 1095 455 1049 1132
1092 458 990 1984 2217 1674 4511 2698
23 603 1027 2086 1040 1605 1594 2350 1564
1553 15 1046 1063 1055 541 1046 1063
1055 541 1180 2879 3316 2471 4410 3270
24 631 996 2061 997 1544 1542 2244 1496
1498 03 1067 981 1024 487 1070 984
1027 484 1134 2677 3104 2349 4210 3107
25 870 1209 2465 1361 1885 1679 2586 1374
1367 217 774 829 805 109 932 986
966 49 961 2925 3325 2876 2441 2490
26 1179 868 1955 775 1291 1136 1963 1100
1189 225 534 537 536 367 755 758
756 588 607 1581 1724 1672 1432 1396
27 807 582 1134 415 937 577 840 553
902 440 413 343 378 46 852 783
817 394 308 272 384 259 1441 603
28 911 611 1272 443 958 657 999 665
921 364 451 415 433 94 814 778
795 457 377 472 730 506 1815 903
29 1322 896 1732 659 1263 1074 1700 877
1076 323 487 466 475 427 810 789
798 749 537 1193 1384 1293 1102 1197
20 972 1216 2278 1285 1802 1658 2335 1167
1222 173 810 756 777 24 966 912
931 132 894 2682 3118 2730 2304 2371
31 535 459 929 456 967 972 1076 846
837 09 686 753 727 234 678 744
719 242 527 691 1076 662 4646 1727
32 555 360 915 359 883 884 1024 828
829 02 647 714 685 171 647 714
685 171 515 763 1225 853 4928 1919
33 509 601 987 609 1109 1102 1156 961

959 09 848 848 848 418 850 850
850 416 624 780 1365 1027 5058 2120
34 529 597 978 595 1119 1122 1151 1006
1002 04 847 917 890 413 843 913
886 417 607 595 1258 939 5441 2064
35 600 335 895 663 1259 916 1078 816
1015 349 627 707 675 441 914 993
975 155 502 617 942 630 4043 1551
36 597 227 877 393 947 651 948 661
815 311 403 501 453 161 670 768
736 106 397 515 841 526 2886 1203
37 619 261 838 313 830 539 831 580
705 301 314 433 374 17 556 675
638 225 312 343 542 433 1599 751
38 732 399 937 479 997 605 862 541
716 401 375 377 376 04 698 700
700 319 339 421 664 394 1603 803
39 676 286 859 375 985 660 891 575
794 352 383 456 426 111 698 771
752 203 368 431 799 507 2696 1126
30 575 407 968 624 1169 899 1038 785
999 293 621 683 659 382 896 958
939 107 508 654 1066 785 3710 1598
41 661 578 714 573 1222 1225 860 1119
1111 09 1027 1103 1082 521 1020 1096
1076 528 519 468 638 395 5486 1542
42 594 818 687 818 1346 1346 963 1295
1295 00 1194 1249 1228 798 1194 1249
1228 798 664 858 936 721 5797 2051
43 597 695 734 703 1289 1280 956 1133
1135 11 1096 1094 1095 641 1101 1099
1099 636 592 578 844 508 5651 1802
44 598 826 778 827 1417 1416 1009 1223
1226 03 1230 1184 1197 755 1232 1187
1199 752 670 821 1019 664 5584 2030
45 638 264 791 467 1104 895 884 831
1005 219 726 749 739 392 936 959
951 182 465 659 779 643 3311 1365
46 847 324 911 387 1062 650 934 619
722 412 386 466 429 69 637 717
707 319 368 504 689 418 1791 889
47 1062 561 1060 415 1043 656 901 556
710 392 364 430 403 285 639 706
698 561 355 380 585 349 926 567
48 1032 567 1052 403 1089 621 907 557
761 478 393 358 374 172 782 746
752 560 331 368 533 427 867 557
49 1042 596 1071 371 936 781 1030 496
702 257 400 344 363 290 657 601
620 547 414 744 900 661 1376 941
40 836 321 1049 461 1175 927 1189 752
834 251 577 593 587 50 763 780
776 137 544 1427 1570 1194 2602 1735
51 830 447 879 442 1270 1275 1297 980
975 06 955 871 898 354 949 865

892 360 607 924 1032 690 4312 1759
52 852 445 905 445 1296 1296 1298 1009
1009 00 959 916 929 347 959 916
929 347 638 838 1049 694 4493 1768
53 808 630 1097 626 1425 1434 1622 1078
1127 52 1073 856 936 527 1099 883
968 501 812 1468 1925 1555 4642 2479
54 804 495 880 499 1296 1293 1278 1033
1036 04 996 929 951 423 1000 933
955 418 655 865 1144 970 4269 1867
55 1099 253 1076 286 1320 1205 1558 839
895 130 779 561 642 39 901 683
757 84 625 1818 2111 1905 2865 2171
56 977 418 898 285 997 673 1051 600
633 329 454 266 358 149 719 531
584 415 349 384 445 344 1729 734
57 1043 562 905 264 1017 591 1064 595
648 447 350 164 262 176 736 549
601 561 274 170 212 160 1085 405
58 1001 489 910 227 1024 634 1098 612
700 417 403 180 295 105 785 562
635 488 312 247 319 266 1353 555
59 966 429 869 237 1043 646 1004 566
692 413 450 229 337 52 824 603
663 425 334 296 333 239 1667 630
50 889 124 902 322 1207 971 1243 812
906 241 673 604 634 199 876 807
829 04 535 746 801 676 3218 1398
61 725 410 837 412 1137 1135 1242 830
831 02 870 665 738 316 872 667
740 314 617 996 1153 1081 3551 1789
62 706 562 875 562 1267 1267 1335 877
877 00 1019 690 803 472 1019 690
803 472 662 1071 1284 1173 3835 1937
63 678 544 741 550 1218 1212 1122 920
919 08 935 852 875 467 937 854
877 465 618 855 1016 928 3685 1710
64 702 530 809 528 1229 1230 1208 894
889 05 1014 752 839 453 1010 749
835 456 625 978 1085 988 3872 1780
65 692 491 744 641 1327 1180 1102 873
982 152 909 803 832 540 1047 941
964 401 600 858 955 972 3509 1673
66 749 51 737 289 1035 699 938 740
882 337 554 536 546 251 836 819
825 31 448 468 629 598 2906 1171
67 750 125 702 214 964 634 903 643
762 332 472 430 452 155 746 704
717 119 387 369 515 516 2604 1003
68 749 35 697 292 1040 743 942 662
815 304 550 494 519 239 816 760
776 27 439 431 526 456 2809 1083
69 754 61 708 349 1101 806 923 687
890 306 620 554 581 305 906 839
858 19 445 422 490 497 2883 1079

60	755	115	789	380	1129	869	1053	800
	965	270	655	639	646	332	904	889
	894	83	505	652	803	813	3056	1394
71	726	593	1173	593	1269	1270	1244	1124
	1122	02	911	1068	1016	280	909	1066
	1014	282	718	1262	1337	1421	4123	2181
72	770	620	1271	618	1181	1124	1162	925
	1017	95	810	842	831	150	903	935
	924	57	617	978	1125	1002	3726	1785
73	754	805	1294	804	1362	1361	1145	1134
	1136	03	1102	1080	1086	354	1104	1082
	1088	352	695	981	1299	1030	4411	2012
74	750	853	1472	852	1388	1390	1375	1168
	1166	02	1077	1057	1064	331	1075	1055
	1062	333	808	1520	1787	1550	4101	2345
75	912	498	1171	758	1431	926	958	739
	1089	509	641	680	668	169	1050	1089
	1089	240	466	800	860	970	3158	1506
76	1034	679	1205	483	1133	572	892	577
	911	588	368	356	362	110	900	888
	891	642	349	562	585	688	2337	1088
77	1227	828	1281	496	1096	594	913	550
	834	533	387	304	344	318	878	795
	815	809	357	373	425	421	1737	767
78	1039	693	1133	502	1207	570	825	486
	919	671	330	326	327	78	922	917
	918	670	321	349	363	404	2027	801
79	1122	726	1253	577	1263	686	986	566
	905	606	429	347	383	125	970	888
	900	666	398	579	675	724	2062	1075
70	1036	588	1271	593	1368	861	1060	684
	1076	545	535	565	554	43	1033	1064
	1059	456	475	910	1013	1168	2902	1576
81	908	441	1154	438	908	913	1149	725
	726	06	559	586	576	271	557	584
	574	269	507	1072	1237	1124	4221	2017
82	696	736	1008	733	1406	1408	1182	1062
	1064	06	1013	1042	1036	432	1015	1043
	1038	430	679	1005	1258	1062	5198	2186
83	688	723	1066	721	1361	1362	1152	1075
	1075	02	1009	1049	1040	395	1009	1049
	1040	395	714	1099	1409	1126	5519	2340
84	750	649	1093	650	1321	1320	1184	993
	995	02	902	968	955	248	904	970
	956	246	676	1058	1277	1081	4971	2137
85	806	423	1077	557	1178	961	1047	755
	862	218	606	694	667	32	762	850
	835	123	524	982	1107	945	3634	1774
86	959	426	1061	432	1086	766	968	639
	769	322	529	488	505	117	780	739
	747	368	434	480	750	487	2431	1068
87	1103	541	1119	393	1031	700	933	629
	759	334	515	433	471	252	791	710
	731	529	384	353	525	444	1821	812
88	918	458	1031	389	982	584	845	615

	755	399	453	392	425	113	776	716
	731	436	336	365	451	290	1987	782
89	1086	564	1149	427	1084	650	980	669
	790	435	497	376	441	194	851	731
	762	549	408	386	545	432	1813	811
80	910	438	1130	489	1196	903	1109	704
	892	313	563	577	572	05	840	854
	851	271	509	775	1119	839	3222	1569

Swedish: Calculated Lip Measurements in millimeters x 10^2

11	591	610	930	605	1162	1167	1000	962
	960	05	981	891	920	419	977	887
	917	423	613	780	1109	859	5263	1961
12	609	881	1259	880	1396	1399	1403	947
	938	09	1088	807	890	491	1080	799
	881	499	811	1498	1990	1609	5061	2658
13	1063	528	1436	555	1312	1183	1654	917
	948	138	783	530	638	79	906	653
	751	202	676	1936	2183	2108	2874	2322
14	1052	602	1179	462	1067	806	1228	628
	735	304	455	297	366	243	740	582
	635	528	462	1835	1204	1124	1869	1433
15	739	428	935	400	790	479	832	554
	591	313	312	295	304	163	547	530
	535	398	310	280	426	271	1475	619
16	713	370	885	368	845	479	752	542
	665	367	355	332	345	40	652	629
	635	338	308	285	393	277	1742	673
17	1127	494	1241	389	1268	983	1359	758
	936	329	734	377	537	23	1061	704
	841	350	582	1447	1764	1496	2855	1961
18	1160	601	1181	424	1140	884	1370	671
	760	304	477	278	364	273	764	564
	632	559	484	1267	1491	1382	1955	1596
19	1094	471	1229	417	1290	1076	1537	764
	874	260	737	317	495	21	995	575
	733	279	580	1250	1459	1454	2448	1720
10	1119	466	1210	375	1276	1013	1497	770
	890	310	748	249	478	10	1056	557
	757	318	566	1101	1402	1298	2607	1688
21	800	523	1128	527	1185	1182	1007	1023
	1025	04	1062	906	969	268	1065	908
	971	265	626	666	948	785	5054	1822
22	750	492	1152	498	1152	1147	1000	1129
	1128	06	1083	948	1022	337	1086	950
	1024	334	664	606	644	571	3834	1391
23	848	445	1112	480	1040	673	929	668
	842	372	518	447	483	08	847	777
	799	322	399	381	458	436	2737	990
24	900	645	1202	659	1023	709	987	558
	681	326	435	363	393	187	707	635
	651	459	384	536	729	668	2947	1274

25 987 643 1276 620 931 611 928 650
725 321 421 432 426 318 661 672
669 559 335 414 444 458 1812 823
26 910 595 1213 477 892 506 881 658
812 394 367 386 375 190 715 734
726 538 345 478 572 567 2208 986
27 878 527 1192 424 824 527 841 682
822 302 442 401 427 151 727 687
708 436 364 489 585 614 2114 1000
28 1139 836 1332 509 955 634 949 536
840 418 410 282 341 309 828 700
756 727 385 818 902 759 2893 1408
29 1158 762 1422 473 1099 748 1169 703
985 436 489 370 429 220 924 804
858 655 445 1246 1207 983 2805 1652
20 1035 655 1325 490 1020 745 1030 674
903 325 530 449 487 177 852 772
806 500 462 1229 1215 1083 2903 1683
31 671 1098 1047 1086 1748 1760 1222 1383
1368 15 1469 1360 1377 850 1453 1345
1362 865 880 1110 1541 1387 5640 2568
32 709 1063 1100 1070 1760 1753 1292 1307
1311 07 1457 1271 1301 811 1462 1276
1306 806 891 1144 1516 1347 5422 2508
33 778 921 1172 1085 1737 1583 1077 1274
1355 163 1291 1264 1267 621 1382 1355
1355 530 733 1122 1187 865 4256 1948
34 874 402 1149 692 1365 728 915 749
1111 638 542 616 579 192 1037 1111
1105 303 459 563 669 576 2217 1041
35 819 422 874 574 1268 480 570 472
1055 788 402 360 381 288 1094 1052
1044 405 245 94 129 127 2203 483
36 795 311 894 729 1396 667 556 604
1200 730 587 555 568 436 1227 1195
1187 204 308 217 233 232 2299 656
37 783 302 933 620 1295 882 707 780
1090 413 710 759 744 289 1040 1088
1090 41 418 421 476 523 3379 1147
38 791 332 966 782 1410 784 830 668
1038 626 650 546 590 362 1142 1038
1029 130 463 541 683 650 3018 1263
39 805 367 1050 754 1421 801 938 708
1091 622 599 581 588 331 1108 1090
1091 178 485 714 777 785 2906 1344
30 781 477 1017 899 1539 1083 800 930
1257 459 936 894 906 523 1299 1257
1254 160 510 654 724 759 3308 1400
41 477 591 844 594 1045 1043 965 804
801 06 931 661 763 466 931 661
761 466 524 558 968 502 5640 1827
42 483 729 792 721 1194 1204 963 885
870 15 1080 795 874 607 1067 781
860 620 543 517 844 341 5690 1675
43 781 559 1364 765 1379 1165 1577 919

	867	219	786	588	672	176	895	697
	756	67	627	2054	2194	1965	3199	2336
44	792	602	1115	562	874	625	876	513
	664	277	387	340	360	145	646	599
	614	404	367	647	708	516	1524	864
45	851	666	1078	536	796	485	671	416
	648	343	361	245	299	140	699	584
	623	479	274	174	226	177	744	344
46	720	458	929	445	834	593	762	471
	618	257	416	330	366	61	655	569
	592	300	332	63	86	71	854	230
47	812	515	979	451	927	656	900	469
	631	305	401	284	330	104	688	570
	601	390	341	939	914	778	1894	1312
48	882	583	1036	503	1029	787	995	453
	650	299	446	304	349	115	736	594
	626	405	336	926	875	729	2425	1310
49	938	615	1153	585	1161	862	1143	539
	720	343	550	294	388	41	880	625
	689	371	412	1030	1130	1105	1945	1458
40	994	620	1154	575	1036	876	1201	543
	596	182	519	273	363	270	687	441
	514	439	407	1460	1495	1460	2374	1731
51	740	729	831	726	1459	1462	1187	1137
	1133	04	1103	1114	1112	591	1100	1110
	1108	594	697	809	1361	776	5190	2038
52	685	778	786	757	1414	1446	1244	1026
	1062	70	969	1012	1006	622	992	1035
	1026	599	767	1070	1600	1171	5562	2469
53	988	403	1227	542	1389	1129	1460	854
	939	267	433	765	659	83	592	924
	863	242	636	1142	1456	1104	2681	1643
54	885	493	996	354	923	603	894	538
	706	344	313	386	354	186	606	678
	660	478	340	401	471	310	1158	606
55	823	412	939	308	919	597	898	559
	719	342	348	378	364	94	646	676
	668	392	316	308	442	309	1007	532
56	683	338	837	324	905	536	787	510
	745	396	357	332	344	82	728	703
	710	289	291	224	330	243	1042	475
57	772	376	958	482	1163	852	1157	586
	760	349	469	384	415	120	785	701
	720	196	463	869	1086	985	2506	1415
58	846	272	931	387	1180	819	1124	659
	845	383	444	495	475	101	764	814
	804	219	442	606	871	589	2516	1179
59	852	370	954	421	1159	867	1142	584
	753	325	453	424	434	31	739	710
	716	256	420	714	1120	709	2639	1356
50	824	233	872	553	1374	957	1259	664
	911	453	569	454	497	359	978	863
	886	50	513	1058	1503	1036	3059	1709
61	526	760	911	761	1287	1286	1125	1076
	1075	02	1152	935	1020	679	1152	935

	1020	679	717	1046	1155	998	4754	2025
62	549	758	992	759	1305	1304	1244	1008
	1011	03	1173	798	947	666	1175	800
	949	664	733	1103	1242	1149	4715	2123
63	684	1079	1827	1211	1672	1519	1714	1356
	1434	155	1164	1138	1149	614	1299	1273
	1283	480	1003	2500	2628	1795	3988	2748
64	989	494	1212	408	1028	764	1015	721
	883	280	596	488	542	110	865	757
	801	379	454	581	803	713	2084	1098
65	969	574	1104	394	741	538	822	585
	711	224	412	345	382	324	631	564
	598	544	329	251	320	216	1291	521
66	1033	546	1003	346	820	601	879	550
	660	237	493	236	371	289	728	471
	586	523	366	23	309	252	1175	506
67	960	560	1323	585	1128	888	1044	791
	942	249	702	616	655	24	935	848
	880	257	522	935	1158	1016	2487	1538
68	1063	639	1375	565	1198	888	1128	738
	977	348	659	519	580	58	1001	861
	912	400	547	1223	1376	1213	2234	1625
69	1235	454	1141	262	1181	938	1209	732
	885	268	755	414	567	153	1021	680
	812	419	520	1186	1168	1231	2512	1613
60	923	310	1222	428	1293	1014	1352	940
	1125	306	816	590	704	244	1119	893
	995	58	627	1434	1582	1457	3214	2023
71	977	593	1219	601	1572	1564	1667	1169
	1176	10	1162	996	1052	401	1172	1005
	1061	391	779	1220	1655	1397	4493	2264
72	988	674	1347	675	1659	1658	1861	1248
	1244	04	1229	1009	1089	457	1227	1007
	1086	458	871	1439	1918	1619	4733	2509
73	1023	321	1061	688	1674	1278	1404	903
	1063	397	871	774	804	330	1144	1047
	1057	56	634	1040	1440	1177	3358	1807
74	873	303	1054	633	1408	852	1181	751
	950	558	609	479	540	254	1051	920
	941	188	500	813	1137	854	2403	1324
75	883	323	969	534	1290	719	966	658
	906	572	545	438	490	175	1001	894
	905	281	378	501	671	450	2089	952
76	1005	216	996	582	1540	959	1333	785
	941	582	607	521	558	224	1011	926
	935	181	416	414	609	381	2562	1006
77	899	120	921	557	1453	921	1281	802
	1011	539	624	531	573	372	1062	969
	988	66	453	466	672	570	3100	1186
78	1040	185	1008	545	1529	1045	1270	826
	981	485	736	638	677	213	1065	967
	977	115	530	771	1039	829	2924	1446
79	1027	260	1135	675	1638	1159	1508	909
	981	479	827	604	698	285	1148	926
	964	37	556	838	1085	883	3198	1563

70	1038	244	1093	609	1585	1145	1399	885
	1007	441	843	642	723	271	1160	960
	993	47	609	1054	1365	1218	3110	1749
81	664	743	890	742	1399	1400	1081	1075
	1072	03	1234	1000	1062	617	1232	998
	1059	619	589	751	898	747	4821	1779
82	636	905	970	907	1530	1528	1152	1157
	1159	02	1372	1071	1148	768	1374	1073
	1150	766	660	961	1129	799	4860	1947
83	707	512	974	734	1380	1144	1095	839
	964	236	915	740	794	439	1105	930
	959	249	556	951	1136	965	4073	1847
84	696	242	799	573	1197	659	855	557
	823	540	509	362	429	302	960	813
	823	149	338	429	481	391	2507	969
85	705	297	724	521	1168	554	630	428
	906	626	399	352	369	290	952	904
	898	262	258	241	248	138	2292	620
86	712	337	760	503	1189	545	774	445
	929	688	321	295	306	317	953	927
	929	315	255	225	309	223	1968	637
87	844	316	984	500	1299	881	1100	678
	985	454	590	513	543	266	1018	941
	959	162	474	1087	1194	973	3557	1809
88	769	304	853	407	1123	703	840	550
	889	453	480	444	457	203	907	871
	878	225	369	542	692	559	2935	1205
89	749	280	850	618	1341	686	888	570
	1052	683	519	377	441	461	1170	1028
	1050	190	412	555	724	498	2912	1201
80	839	315	1025	481	1286	823	1097	712
	1068	511	612	467	534	327	1115	970
	1021	176	485	1011	1099	865	3434	1682

English: Formant Frequencies in Hertz

	F1	F2	F3
11	274	2005	2901
12	359	1857	2516
13	395	2103	2552
14	516	1848	2525
15	677	1753	2552
16	700	1153	2457
17	457	870	2350
18	471	1502	2292
19	305	1062	3000
21	264	2354	3269
22	399	1874	2592
23	399	2058	2552
24	453	1807	2596
25	623	1691	2489
26	673	1135	2762

27	359	897	2498
28	399	1404	2511
29	274	646	2179
31	322	2247	3213
32	295	1895	2858
33	393	2188	2962
34	565	1954	2912
35	828	1812	2582
36	850	1227	2769
37	791	1121	2272
38	352	1331	2502
39	322	833	2209
41	270	2490	3186
42	384	1920	2711
43	430	2133	2753
44	513	1795	2620
45	886	1772	2620
46	817	1148	2810
47	460	905	2487
48	447	1004	2510
49	285	848	500
51	285	2377	3031
52	444	2079	2770
53	444	2151	2722
54	524	1964	2687
55	524	925	2599
56	539	968	2516
57	464	1000	2722
58	480	1040	2722
59	361	925	2639
61	287	2459	3149
62	471	1920	2789
63	464	2287	2843
64	659	1889	2789
65	774	1774	2751
66	808	1234	2774
67	479	1038	2732
68	467	1375	2571
69	360	916	2693
71	350	2404	3039
72	442	1804	2650
73	492	2539	2923
74	500	1827	2635
75	758	1785	2539
76	712	1115	2615
77	504	1019	2458
78	477	958	2496
79	369	962	2431
81	269	2362	2885
82	431	1881	2519
83	458	1962	2535
84	500	1777	2465
85	727	1731	2404
86	723	1173	2689
87	458	915	2577

88	462	1000	2519
89	269	827	2454

Cantonese: Formant Frequencies in Hertz

	F1	F2	F3
11	286	2095	3095
12	414	1894	2262
13	696	1171	2680
14	449	989	2391
15	411	753	2304
16	396	1989	2544
17	451	1498	2110
21	220	2620	3244
22	360	2060	2528
23	684	1200	2360
24	480	900	2796
25	240	648	2448
26	244	2016	2392
27	360	1420	2316
31	272	2112	3154
32	499	2058	2919
33	790	1291	3127
34	326	734	2881
35	345	804	2707
36	253	2000	2765
37	499	1578	2074
41	269	2004	2850
42	442	1654	2615
43	685	1081	2519
44	442	727	2962
45	296	673	2769
46	289	1800	2308
47	423	1342	2050
51	238	2462	3304
52	534	2135	3004
53	811	1461	2380
54	570	924	2404
55	249	761	2546
56	208	2058	2730
57	496	1480	2615
61	232	2643	3068
62	506	2186	2658
63	779	1422	2319
64	502	886	2335
65	262	791	2540
66	240	2057	2506
67	373	1498	2338
71	247	2194	3046

72	525	1726	2555
73	722	1122	2525
74	563	935	2403
75	274	738	2692
76	274	1973	2426
77	388	1437	1852
81	278	2472	3247
82	502	2114	2890
83	856	1373	3003
84	608	954	2757
85	297	791	2608
86	278	1997	2730
87	464	1445	2354

Finnish: Formant Frequencies in Hertz

	F1	F2	F3
11	256	2140	2916
12	392	1820	2620
13	644	1684	2484
14	684	1104	2372
15	516	964	2128
16	320	796	2400
17	324	1780	2296
18	364	1620	2324
21	271	2197	2835
22	366	1803	2484
23	610	1594	2480
24	704	1177	2413
25	511	884	2275
26	354	733	2271
27	311	1721	2279
28	433	1511	2252
31	281	2158	2684
32	530	1877	2544
33	677	1684	2463
34	681	1211	2347
35	544	962	2488
36	319	737	2274
37	383	1772	2316
38	523	1614	2298
41	287	2113	2771
42	467	1790	2512
43	666	1474	2418
44	635	1181	2169
45	519	887	2113
46	297	925	2075
47	542	1677	2207
48	474	1406	2192
51	252	2228	2815
52	436	1811	2501

53	652	1595	2621
54	629	1189	2455
55	470	923	2632
56	306	688	2568
57	248	1540	2139
58	463	1428	2231
61	341	1950	2495
62	464	1773	2503
63	675	1572	2463
64	568	1116	2730
65	501	900	2463
66	316	823	2463
67	343	1605	2312
68	463	1613	2355
71	309	2000	2482
72	351	1751	2384
73	731	1465	2192
74	695	1157	2307
75	463	946	2349
76	307	751	2365
77	324	1572	2115
78	501	1466	2123
81	266	2622	3244
82	378	2189	2753
83	631	1736	2709
84	649	1157	2635
85	505	915	2643
86	301	728	2930
87	281	1953	2497
88	497	1689	2622

French: Formant Frequencies in Hertz

	F1	F2	F3
11	316	1756	2831
12	361	1793	2455
13	485	1495	2302
14	688	1150	2053
15	508	1041	2041
16	400	900	2000
17	316	917	2642
18	290	1662	2312
19	399	1188	2113
10	470	1262	2075
21	273	2111	3131
22	403	1981	2597
23	646	1708	2515
24	765	1217	2750
25	619	1093	2429
26	362	944	2265
27	310	776	2504

28	273	1772	2213
29	355	1429	2280
20	541	1328	2205
31	258	1901	3156
32	380	1852	2662
33	601	1552	2308
34	741	1228	2186
35	570	1054	2080
36	304	704	2152
37	316	867	1894
38	465	1531	2156
39	365	1452	2262
30	620	1220	2095
41	231	2300	2812
42	312	2158	2842
43	458	1992	2996
44	750	1308	2312
45	539	1081	2842
46	292	808	2146
47	227	762	2000
48	227	1885	2385
49	289	1504	2119
40	531	1481	2654
51	297	2015	3107
52	278	1992	2764
53	559	1730	2939
54	627	1080	2460
55	525	1186	2437
56	304	730	2304
57	183	578	2304
58	308	1840	2262
59	342	1498	2304
50	540	1380	2437
61	232	2107	2943
62	346	1695	2438
63	476	1689	2613
64	722	1425	2524
65	476	1114	2659
66	495	1091	2430
67	300	1152	2385
68	274	1943	2695
69	360	1619	2581
60	425	1471	2510
71	210	2069	3417
72	312	1882	2466
73	564	1775	2503
74	698	1381	2637
75	576	1099	2076
76	312	843	2287
77	217	931	2275
78	236	1771	2191
79	313	1388	2306
70	350	1465	2306
81	248	1915	3081
82	459	1856	2537

83	463	1724	2506
84	611	1214	2475
85	514	1210	2078
86	381	891	2031
87	241	864	2175
88	265	1689	2117
89	339	1451	2163
80	471	1413	2237

Swedish: Formant Frequencies in Hertz

	F1	F2	F3
11	258	2401	3032
12	273	2424	2951
13	578	982	2297
14	408	784	2281
15	273	673	2231
16	273	1711	2347
17	442	1335	2366
18	270	2304	2732
19	384	1809	2348
10	442	1458	2347
21	281	2272	3497
22	420	2311	3000
23	697	1210	2622
24	343	724	2304
25	320	720	2117
26	315	1715	2121
27	417	1747	2254
28	301	2108	2747
29	453	1675	2337
20	534	1670	2393
31	312	2440	3740
32	360	2460	3560
33	672	1100	2316
34	324	676	2240
35	304	672	2252
36	316	1780	2220
37	552	1172	2124
38	360	2128	2444
39	340	1752	2184
30	556	1460	2240
41	314	2180	3511
42	302	2359	2721
43	637	1000	2797
44	342	725	2483
45	202	609	2630
46	202	1716	2120
47	406	1271	2535
48	287	1980	2549
49	283	1769	2152

40	471	1781	2303
51	253	2284	3176
52	298	2147	2867
53	565	951	2211
54	312	726	2560
55	312	702	2354
56	309	1793	2414
57	611	1312	2298
58	302	2053	2653
59	354	1825	2400
50	583	1323	2151
61	239	2231	3362
62	301	2289	2653
63	659	983	2821
64	255	618	2571
65	282	657	2380
66	248	1823	2201
67	482	1197	2351
68	274	2120	2568
69	343	1861	2270
60	495	1788	2325
71	266	1924	2460
72	270	2004	2430
73	498	958	2061
74	487	829	1943
75	247	734	1818
76	297	1768	2152
77	414	1308	1985
78	251	1806	2380
79	422	1658	2057
70	464	1384	2076
81	205	2187	3153
82	293	2008	2420
83	459	829	2508
84	329	729	2424
85	287	713	2417
86	255	1675	2199
87	401	920	2390
88	236	2023	2566
89	367	1604	2191
80	599	1535	2317