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SOME RELEVANT ASPECTS OF VOWEL FORMANT INTERPRETATION

1. THE TRADITIONAL F1/F2 REPRESENTATION

To date, vowels are frequently represented in a two-dimensional F1/F2 chart (for German see e. g. Jørgensen 1969; Kohler 1998; for Austrian German Iivonen 1987) and interpreted with respect to the first two formants. Fig. 1 gives such a representation for one speaker of Standard Austrian German[1]:

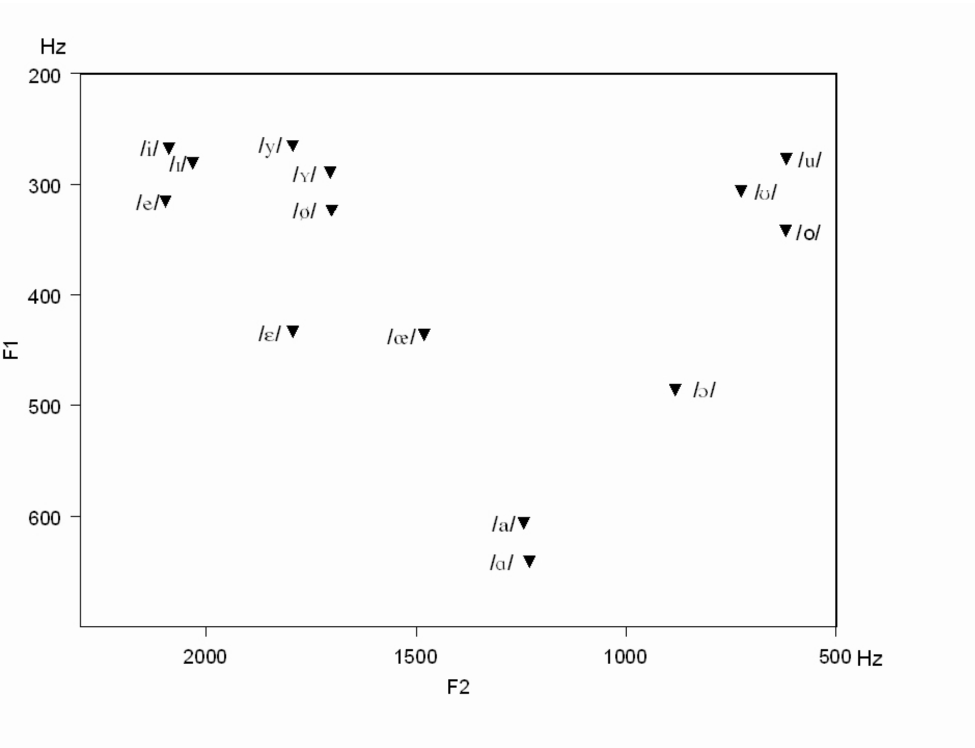

Figure1: F1/F2 plot of the vowels of Standard Austrian German spoken by a male speaker, reading logatomes.

This chart looks quite symmetrical, it suggests, however, a neutralization of /i/ and /e/, of /ʏ/ and /ø/, of /u/ and /o/ and of /a/ and /ɑ/ on the F2 scale, and nearly a neutralization of /i/ and /ɪ /on the F1 scale. A similar observation can be made for the female speaker, as becomes evident from Fig. 2.

1 Standard Austrian German as defined in Moosmüller (1991).

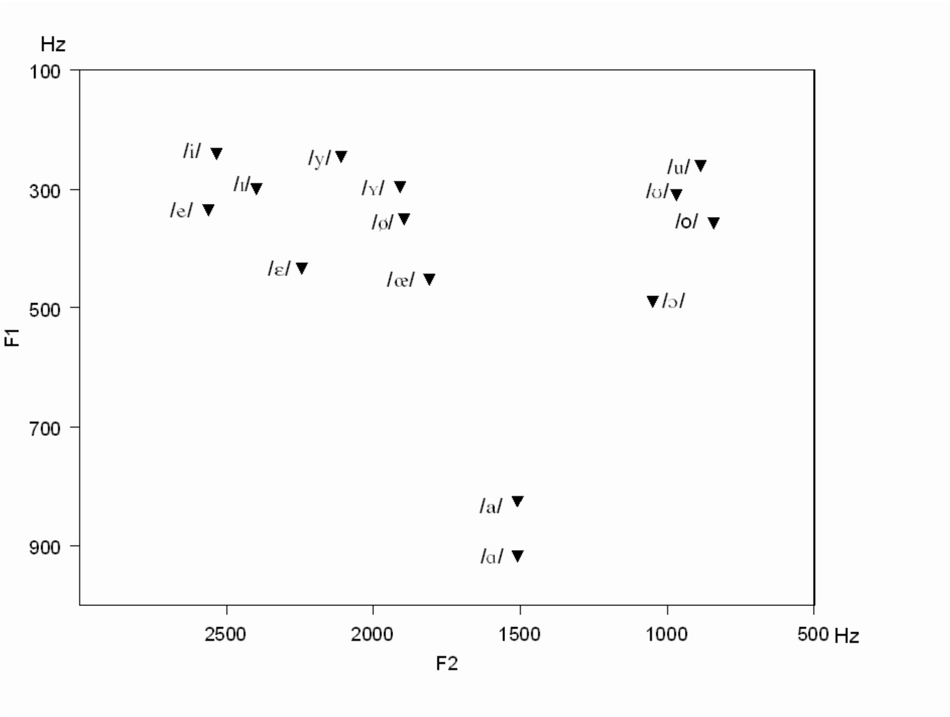

Figure2: F1/F2 plot of the vowels of Standard Austrian German spoken by a female speaker, reading logatomes.

Moreover, in the upper part of the vowel space, the vowels are located quite closely together on the F1 scale. Similar results have been obtained for Danish (Ejstrup/Hansen 2003), German (Kohler 1998), and Fering (Bohn 2004). Ejstrup/Hansen (2003) propose a sound change in progress, and Bohn (2004), in comparing the vowel spaces of Southern British English, North German, Danish and Fering, asks

> "whether the uneven distribution of vowels in the vowel space is a general feature of languages with large vowel inventories, or whether we are dealing with a *Sprachbund* phenomenon of Fering, North German and Danish, which are spoken in neighboring and overlapping geographical areas." (Bohn 2004: 165)

It will be argued that the traditional F1/F2 space insufficiently represents vowels[2], especially if we have to deal with large vowel systems. Since the frequently cited investigation of American English vowels performed by Peterson/Barney (1952), many studies on vowels conclude that the first two formants are the most important acoustic parameters for vowel quality distinction (Harrington/Cassidy 1999: 60) and, consequently, sufficient to represent the vowels of a given language or language variety.

2 This is nothing new, Jørgensen (1969) e. g. plotted the vowels in an F1/F2' (effective F2 which takes F3 into account) space, but this did not enhance the discrimination of front rounded and unrounded vowels, therefore he returned to the traditional F1/F2 space. See also Pfitzinger (2005) for a critique.

The convention of representing the formant data of vowels in an F1/F2 plot goes back to Joos (1948) who demonstrated the relationship between the F1/F2 representation and the concept of the vowel quadrilateral, as well as showing that F1 and F2 are negatively correlated with vowel height and backness respectively.

> "A brief glance at this diagram shows that the correlation between articulation and vowel color is (at this stage in the investigation) astonishingly simple. Although the vowel samples have here been placed on the chart strictly according to acoustic measurements (made from a phonograph record!), the diagram is practically identical with the classical 'tongue position' chart. … Of course the scales of these diagrams were deliberately set up so as to enhance the resemblance of the acoustic chart to the tongue-position chart. For the directions in which the two scales run–toward the left and downward, contrary to usual graphical practice – the reason was that this puts [i] at top left, [u] at top right, and [a] at the bottom, to agree with the usage of the International Phonetic Association, and for this no apology is needed." (Joos 1948: 53)

The concept of the vowel quadrilateral in turn goes back to Hellwag (1781, cited in Stratka 1978), who represented the vowels in an isosceles triangle according to the placement of the highest point of the tongue. This vowel triangle has undergone many changes and took many shapes[3], till it ultimately resulted in a quadrilateral with a perpendicular line for the specification of the back vowels and a line with an obtuse angle for the front vowels (Handbook IPA 1999). It did not escape Joos' notice that the IPA vowel quadrilateral does not exactly reflect articulatory tongue positions drawn from X-ray data and he drew the conclusion that the IPA representation is actually an acoustic one:

> "Comparison of Figs. 26, 27, and 28 leads to a very interesting tentative conclusion. It appears that the classical or IPA tongue-position quadrilateral rather more closely resembles the acoustic vowel quadrilateral than it reesembles the Carmody X-ray tongue-position quadrilateral. … It should be noted that nowadays the IPA chart officially has an articulatory shape but an acoustic shape." (Joos 1948: 54)

Joos (1948) has especially pointed out the discrepancy in the spacing of [i], [e], and [ɛ] between the articulatory and the IPA chart. The focus later turned to the representation of back vowels in the diverse vowel charts:

> "Mais aucune de ces figures ne correspond, dans sa partie postérieure, à la réalité." (Stratka 1978: 440).

Regardless of whether one takes the highest point of the tongue or the constriction location as a reference point, /o/ is articulated further back than /u/ (see e. g. Stratka 1978; Wood 1979; Pétursson 1992[4]; Ladefoged/Maddieson 1996; Fant 2001). From the point of view of constriction location, /u/ is the only vowel that can be described as velar; the rest of the

3 Though discarded since long in phonetics, Hellwag's vowel triangle persists in other scientific areas, as becomes obvious from the following example: "According to the position of the tongue in the oral cavity vowels are devided into high (i, u), central (e, o) and low (a) – the so-called Hellwag triangle" (Jindra et al. 2002: 91).

4 Pétursson proposes a vowel trapezoid which meets the fact that [ɑ] is located further back than [o], which again is further back than [u] (Pétursson 1992: 45).

back vowels have their constriction in the pharyngeal region. The IPA Handbook circumnavigates this problem by defining the intermediate vowels auditorily:

> "Specifically, two fully front vowels [e] and [ɛ] are defined between [i] and [a] so that the differences between each vowel and the next in the series are auditorily equal; and similarly, two fully back vowels [ɔ] and [o] are defined to give equidistant steps between [ɑ] and [u]. The use of auditory spacing in the definition of these vowels means vowel description is not based purely on articulation, and is one reason why the vowel quadrilateral must be regarded as an abstraction and not a direct mapping of tongue position." (Handbook IPA 1999: 11 f.)

A half articulatorily and half auditorily based representation causes a confusing situation; consequently, Ladefoged/Maddieson (1996) define the classical vowel quadrilateral auditorily, with reference to acoustic mapping (F1 plotted against F2-F1):

> "The acoustic representation corresponds more closely to the auditory phonetic description in terms of height and backness than the articulatory plots in figures 9.2–9.4…..Recognition that the placement of vowels on an auditory chart such as the one in figure 9.1 [the traditional vowel quadrilateral] is supported more readily by acoustic than by articulatory measurements does not mean that articulatory scales can be discarded in the phonetic description of vowels." (Ladefoged/Maddieson 1996: 285)

Lindblom (1986) emphasizes three facets in defining the vowel space for a language: the articulatory stage, the acoustic stage, and the auditory stage. In the theory of adaptive dispersion (TAD; Liljencrants/Lindblom 1972; Lindblom 1986, 2003; Diehl/Lindblom 2004), the focus is directed towards the acoustic-auditory mapping. This theory is based on the concept that "distinct meanings must sound different" (Lindblom 2003) and that consequently, the dispersion of vowels in the "available phonetic space" (Diehl/Lindblom 2004) meets the principle of maximal contrast (Liljencrants/Lindblom 1972). Liljencrants/Lindblom (1972) tested this hypothesis by first defining the shape of a universal vowel space. Secondly, the perceptual contrast between any two vowels was measured. To measure the perceptual contrast, euclidean distances between the formant frequencies in Mel units were calculated. For reasons of simplification, formant frequencies were restricted to two dimensions, M_1 and M_2'[5]. Thirdly, on the basis of intervowel distances, optimal vowel inventories were created. For inventories of up to six vowels, the predicted systems were identical to those of the preferred vowel inventories. For larger inventories, too many high vowels were predicted. Modifications of this early model (Lindblom 1986; Diehl et al. 2003) yielded better results.

In the Theory of Adaptive Dispersion (TAD), a two-dimensional representation is favoured, a three-dimensional auditory-perceptual space has been proposed by Miller (1989) who transformed the measurements of F0, F1, F2, and F3 into log frequency ratios and plotted them as points in a three dimensional space. The vowels of each category were en-

5 M_2' = F_2 corrected to reflect the spectral contributions of F_3, in Mel units

closed in three dimensional target zones. Miller (1989) analysed the nine monophthongal vowels of American English and could, by this method, create nine non-overlapping target zones which account for 93 % of the data.

This method has also been applied to German and Greek vowels (Jongman et al. 1989). The zones created could differentiate the five vowels of Modern Greek with 100 % accuracy, and the fourteen vowels of German with 94 % accuracy. Jongman et al. (1989) conclude:

> "In general, it would seem advantageous for a given language to have vowels that are maximally distinct acoustically (see, for example, Liljencrants/Lindblom 1972; Stevens 1972; Lindblom 1986) for reasons of communicative efficiency. Greek provides an example with its five vowels being quite far from each other in APS. Interestingly, five-vowel inventories similar to that of Greek are much more frequent than any other type of vowel inventory … The vowel spaces of German and American English are much more dense. It seems that the larger the vowel inventory, the more peripheral the location of the extreme vowels …, relative to vowels of languages with smaller inventories." (Jongman et al. 1989: 239 f.).

An interesting approach is presented by Carré (1996). He modelled vowels by a stepwise deformation of the acoustic tube (front to back constriction and labial command) and plotted the results in an F1/F2 plane, whereby F1 is on the abscissa and F2 on the ordinate. With this representation, he seemingly approached greater articulatory realism. The location of the constriction arises from a combination of F1 and F2; a maximally high F1 combined with a low F2 indicates a constriction location with the lowest X_c from the glottis. This would denote the pharyngeal constriction location for the vowel /ɑ/. The other dimension captured by this representation is labialisation: a maximally low F1 and a maximally low F2 denote a labial back vowel whilst the labial front vowels exhibit a lower F1 and F2 than their respective unrounded cognates. In this approach, /ɛ/ and /œ/ can be represented as a back or as a front vowel. Similar results have been obtained by Boë et al. (1992) for /œ/. For this vowel, "the vocal tract most resembles a cylindrical tube" (1992: 35), and "the area functions reveal two approximately equal and symmetric minima around $X_{c.g}$[6] = 5 cm and $X_{c.g}$ = 11 cm" (1992: 36). As concerns the unrounded vowel, it is /æ/ rather than /ɛ/ which is described as having a narrowing just above the glottis (Fant 1980 = 2004; Wood 1979; Fant/Båvegård 1997). Fant/Båvegård (1997) illustrate that this vowel can be considered either as a front vowel with a wide constriction area or as an extreme back vowel. Two typical versions for this vowel are (from: Fant/Båvegård 1997: 7, Fig. 7):

/æ/	**X_c[7]**	**A_c**	**F1**	**F2**	**F3**
Front configuration:	4 cm	6 cm^2	648	1595	2450
Back configuration:	13,5 cm	2 cm^2	654	1588	2452

6 $X_{c.g}$ = constriction coordinate from the glottis.

7 X_c = constriction coordinate from the incisors, A_c = constriction area

In Figure 3, the data presented in Figure 1 are plotted in the same way as proposed in Carré (1996):

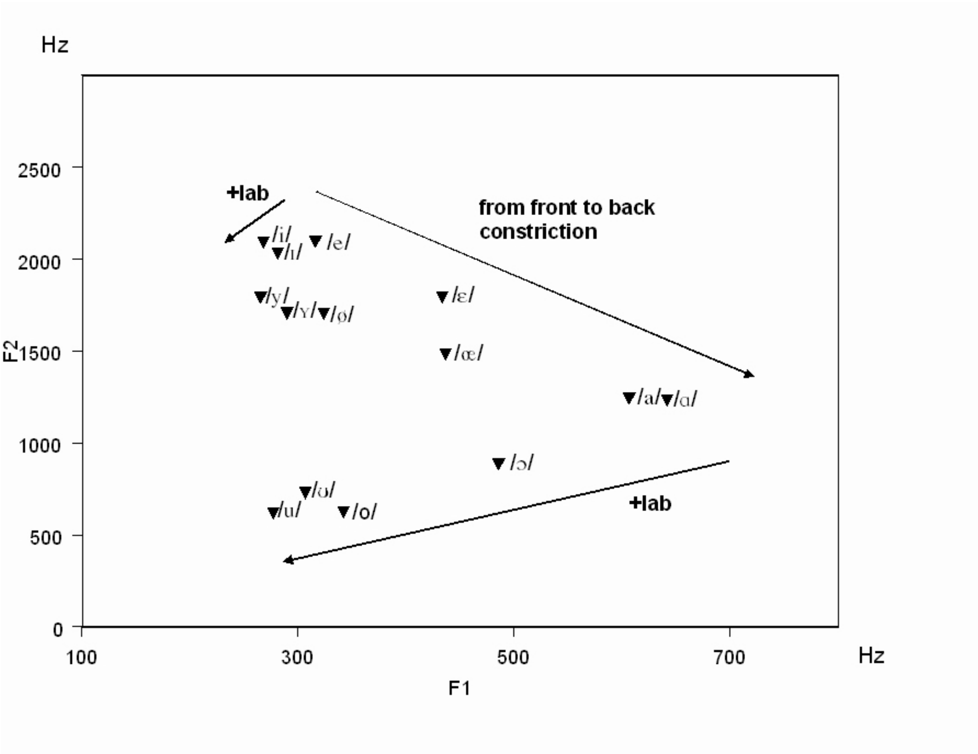

Figure3: F1/F2 plot of the vowels of Standard Austrian German as proposed in Carré (1996), spoken by the same speaker as in Figure 1.

In this model, the labial command always results in a lower F1 for the labial vowel. This does, in fact, not hold for the front labial vowels, as can be seen from Figure 3 and as has also been exemplified by Wood (1986). It seems that constriction location is not accurately modelled either, since F3 also substantially contributes to the determination of constriction location, especially in the /i/ and the /u/-vowels.

The non-linear relationship between acoustic data and articulation, as shown above for the vowel /æ/, was also known to Joos (as well as the non-conformity of the IPA vowel quadrilateral with the X-ray data) – "Two vowels might sound different and yet have the same two formants (…), but the reverse is not possible: if the formants differ, the sounds are not alike" (1948: 61) – however, despite his observations he seemed to have been fascinated by the possibility of correlating F1 and F2 with tongue height and backness respectively. Up to date, vowels are represented in a two-dimensional, mostly F1/F2 plane and interpreted in the way proposed by Joos. For small vowel systems, or better, for vowel systems whose most peripheral constriction location on the front end of the vocal tract is indeed the hard palate, as stated in the IPA Handbook, the correlation of F2 and backness can be upheld as long as the degree of constriction is sufficiently small, preventing acoustic coupling of the front and the back cavity as well as possible. This holds generally for the so-called "tense" vowels, i. e. /i/ and /e/, in vowel systems which lack front rounded vowels. As soon as the cavities are coupled through widening of constriction degree, F2 becomes more a function of constriction degree than of backness (Carré 2004; Beckman et al. 1995; Hoole 1999). In other words, a lowering of F2 in front vowels does not necessarily point to a centralization or retraction of the constriction location, nor does a rising F2 value of the back vowels necessarily point to a centralization or fronting of the constriction location, as the concept of Joos suggests and as has been assumed in many studies. If this concept of centralization were adopted for Standard Austrian German, /i/ of the speaker in Figure 4 would have a more retracted tongue position with respect to /e/, an interpretation that is definitely wrong.

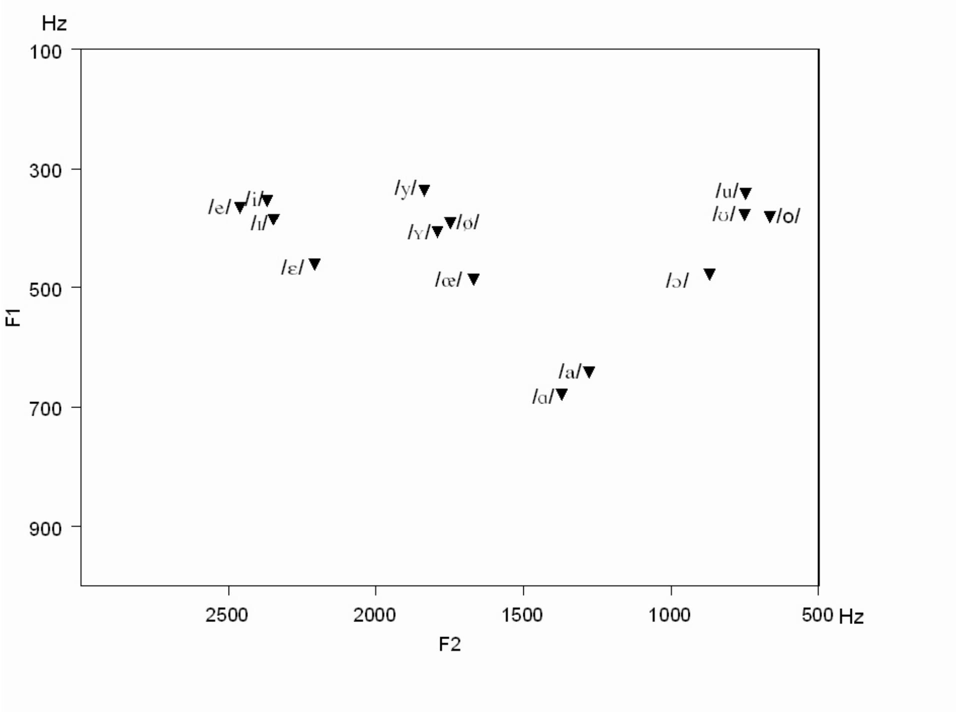

Figure4: F1/F2 plot of the vowels of Standard Austrian German spoken by a female speaker, reading sentences.

A brief look at the mean values of F3 of /i/ and /e/ (see Table 1) reveals that /i/ has, on the contrary, a more fronted constriction location than /e/. As soon as the constriction location transgresses the critical point of about 2/3 of the vocal tract length, a shift in cavity affiliation of F2 and F3 takes place, which causes F2 – now associated with the cavity behind the constriction – to drop or at least to stay constant and F3 – associated with the cavity in front of the constriction – to rise substantially (see e. g. Fant 1970, 2004; Stevens 1999; Johnson 1997; Badin et al. 1990; Gay et al. 1992). This shift in cavity affiliation is responsible for the equal or higher values of F2 for /e/ in Figures 1, 2 and 3 and might also be responsible for the same results in Iivonen 1987.

	Fig.1	Sp012	Fig.2	Sp180	Fig3	Sp129	Iivonen	men	Iivonen	women
	/i/	/e/	/i/	/e/	/i/	/e/	/i/	/e/	/i/	/e/
F1	269	315	240	335	357	367	234	326	261	386
F2	2074	2092	2533	2566	2374	2458	2287	2256	2738	2712
F3	3263	2797	3410	3189	3113	3001	3103	2818	3423	3276

Table 1: Median[8] values for F1, F2 and F3 for the speakers represented in Figure 1 (male), 2 (female) and 3 (female) and mean values of F1, F2 and F3 for the data presented in Iivonen 1987.

Assuming F3 to be a quarter wavelength resonance of the front cavity for /i/ and F2 to be a quarter wavelength resonance of the front cavity for /e/, the calculated constriction locations would be 2.7 and 4.2 cm from the incisors respectively for Sp012, and 2.6 and 3.4 cm from the incisors respectively for Sp180, distances which are in accordance with the measurements presented in Fant (2001) for Swedish vowels. Therefore, for the front vowels, Standard Austrian German discerns two constriction locations, and this result cannot be accounted for by a traditional F1/F2 representation.

As concerns the negative correlation of F1 with vowel height[9], physiological realism is not met either, since e. g. the tongue has in most cases a higher position for /a/ than for /ɔ/ and even /o/ (Wood 1987; Bohn et al. 1992; Hoole/Kühnert 1996; Hoole/Mooshammer 2002).

Apart from the fact that an F1/F2 representation cannot capture articulatory adjustments in a satisfactory way, it additionally suggests that vowel articulation is gradual, i. e. a vowel can be articulated anywhere within the defined extreme points of the vowel quadrilateral. This is exactly the position the Handbook of the IPA takes:

> "Since the vowel space is continuous, it is a matter of chance whether a vowel in a language exactly coincides with one of the reference points symbolized on the quadrilateral. In particular, languages may use vowels which are similar to, but not as peripheral as, the reference points indicated by the cardinal vowels." (Handbook IPA 1999: 13)

8 The median has been chosen in order to meet the high standard deviation of F3 for sp129, which is caused by the less formal task of reading sentences as compared to reading logatomes. For sp012 and sp180, there are hardly any differences between mean values and median, whereas for sp129, F3 shows substantial differences.

9 Kohler (1998) uses the term "openness" as correlate with F1.

2. VOCAL TRACT CONFIGURATIONS FOR VOWELS: DISCRETE OR GRADUAL?

> "The classical vowel model, originally introduced by Bell in 1867 (4) and modified into various versions by other authors, is characterized by the class of central vowels. The model was designed around the single resonance theory, according to which the upper surface of the tongue narrows the mouth channel locally in order to delimit the buccal cavity and tune its natural resonance. Bell postulated a configurative aperture that 'may be shifted to any part of the back or front of the palatal arch' (p. 71). He held that the horizontal and vertical position of the tongue arch relative to the roof of the mouth set the size a location of this aperture, so that the natural resonance of the mouth cavity would rise progressively as the tongue moved from low to high at the back, central and front locations in turn." (Wood 1987: 53)

This model acts on the assumption that tongue movements are gradually and constrictions can, therefore, take place anywhere on the roof of the mouth. Since a constriction can take place anywhere, central vowels are incorporated into this model. However, investigations based on x-ray studies suggest three or four discrete places of constriction[10] according to the classification. Stratka (1978) classifies the vowels in three categories: alveolar vowels, which include the i-vowels, the y-vowels, the e-vowels, ø and schwa, pharyngeal vowels, which include the a-vowels, the o-vowels, œ, nasalized œ, ɛ, a, ɔ, and schwa and velar vowels, which include the u-vowels.

The x-ray studies performed by Wood (1979, 1982) on several languages, yielded 4 prominent constriction locations: a palatal one, a velar one, an upper pharyngeal one and a lower pharyngeal one. These tongue gestures are available for both vowels and consonants (Wood 1996): as far as the central vowel is concerned, Wood states: "The articulation of so-called central vowels obviously needs clarification" (Wood 1991b: 64). Fant (2001), on modeling Swedish vowels, assumed 3 areas of constriction:

- a "front" region of X_c[11] located less than 4 cm from the teeth
- a "mid" region at coordinates between X_c = 4 cm and X_c = 7 cm and a
- a "back" region at X_c greater than 7 cm. (Fant 2001: 45f)

The region of midvowels was designed to provide a suitable transition between the very different front and back regions (Fant 2001), which is necessary for sequences like e. g. [ja], where a neutral state is involved but not completely reached (Lin/Fant 1989). For the Swedish vowels, with the exception of [u] at X_c = 6.5 cm from the teeth (Fant 2001) and the neutral vowel [ə] at X_c = 6.4 cm from the teeth (Fant/Båvegård 1997), no vowel was found well in the mid-range. The central vowels [ɨ] and [ɵ] have moved towards the front and the back respectively. The constriction location for [ɨ] is even more front than the one for [i] (X_c = 2.8 cm vs. X_c = 3.1 cm from the teeth respectively), and [ɵ] has its location

10 The highest point of the tongue as reference point is abandoned.

11 X_c is the constriction coordinate.

near [o] (X_c = 8.8 cm vs. X_c = 8.2 cm respectively) (Fant 2001). On the whole, Fant's results are in agreement with the constriction locations spotted by Wood (1979).

Russian is described as having a high central vowel [ɨ] as well. The area function[12] created in Fant (1980 = 2004) shows a constriction at about the same location as for [i] which is, however, wider and shorter. The difference between [i] and [ɨ] lies in the specific cavity affiliation of the first and second formant: in [i], F2 is affiliated with the cavity behind the constriction and F3 with the cavity in front of the constriction, whilst in [ɨ], the cavity affiliations are reversed, F2 is affiliated with the cavity in front of the constriction and F3 with the cavity behind the constriction.

In the same way as in Fant (2001), schwa-vowels are described as either front or back vowels by Stratka:

> "Pour la voyelle ə, la langue semble pouvoir se placer, selon les idiomes et les locuteurs, d'un côté ou de l'autre de la limite entre les voyelles alvéolaires et les voyelles pharyngales. En anglais le ə apparaît tantôt alvéolaire, tantôt pharyngal …, tandis que dans d'autres langues, il est plutôt pharyngal: ainsi en allemand …, en catalan …, en bulgare …, en chinois …, et peut-être aussi en français …." (Stratka 1978: 450)

The so-called "indeterminate" vowel of Bulgarian, which is often denoted as /ə/ is described as exposing the same low pharyngeal tongue body gesture as /a/, but with a small mouth opening (Wood/Pettersson 1988; Wood 1996). The vowel is therefore characterized as "close pharyngeal".

It seems that constriction locations in the mid range of the vocal tract are avoided and that at least phonological central vowels have an active constriction gesture either in the front or in the back of the vocal tract. Given the high and context-independent variability of both phonemic and allophonic "central vowels" (e. g. Eastern Arrernte, see Ladefoged/ Maddieson 1996; or Albanian, see Granser/Moosmüller 2002; Moosmüller/Granser 2003, 2006), it has been proposed that central vowels are not specified for constriction location (Bates 1995) and can consequently take either a front or a back configuration. Schwartz et al.'s (1997) evaluation of the UPSID phoneme inventory concludes that phonemic "/ə/ is a 'parallel' vowel which exists because of intrinsic principles (probably based on vowel reduction) different from those of other vowels" (p. 251) and does not seem to interact with other vowels. As a consequence, its presence or absence should not modify the structure of the vowel system. This seems to be the case in Québécois, where the schwa has merged with [œ] (Martin 1998).

The observation that allophonic schwa vowels exhibit a high level of context-dependency (van Bergem 1994; Bates 1995) and that they are more readily assimilated (e. g. in

12 It has to be considered that an area function is not in itself an articulatory parameter (Boë et al. 1992, Wood 1991a)

Danish, Jensen 2001) or deleted (Gheg variety of Albanian, Camaj 1969) than other unstressed vowels, led to the concept that schwa vowels are vowels without a target (van Bergem 1994) or that they are vowels with an active gesture that is overlapped by the gesture of the following full vowel (Browman/Goldstein 1992). However, Hála (cited after Stratka 1978) could show that the schwa in English has either an alveolar or a pharyngeal constriction. More recent studies (Gick et al. 2000; Gick 2002) could prove a pharyngeal constriction for American English schwa. In sequences where adjacent phonemes exhibit conflicting articulatory targets (e. g. a tongue root advancement followed by a retraction of the tongue root), the tongue passes through a neutral space, rendering a schwa-vowel (Lin/Fant 1989; Gick/Wilson 2001, 2005). But the concept of targetless schwa cannot be completely abandoned: Davidson/Stone (2003) could demonstrate that in cases where phonotactically illegal consonant clusters have to be dissolved, the tongue does not coarticulate with the epenthetic/excrescent[13] schwa, but with the following consonant. However, an excrescent schwa is perceived. They conclude:

> "the production of the preceding consonant … it has been shown that speakers' tongue motion during their production of /zC/ sequences is not consistent with movement toward a *schwa* target."
>
> (Davidson/Stone 2003)

These examples demonstrate that a vowel[14] can, in principle, be articulated without a target. However, where a constriction is intended for the production of either an epenthetical schwa, an allophonic schwa or a phonemic central vowel, it seems to be located either in the front part of the vocal tract, or in the pharyngeal region. Therefore, it might be useful to differentiate between a "neutral vowel (configuration)" and a "schwa-vowel".

Since the central region of the vocal tract does not seem to be a preferred target for a constriction for vowels, it can be assumed that the tongue does not move gradually from front to central or from back to central, but that the tongue aims at discrete locations for the articulation of vowels.

3. The acoustic-articulatory relationship

Paradoxically, it was also Joos (1948) who pointed at the non-linear relationship between acoustic output and articulatory adjustments (i. e. different articulatory adjustments can trigger the same acoustic output). In 1972, Stevens put forward his widely discussed "quantal theory of speech". This theory not only gives evidence for the non-linearity of articulatory-acoustic mapping, but also links these observations to perception. Stevens (1972,

13 Davidson/Stone (2003) differentiate between "epenthetical schwa", i. e. a schwa having a target, and "excrescent schwa", i. e. vowel without target.

14 It might be perhaps confusing to name a truly excrescent vowel "schwa".

1989) found three zones – a palatal, a velar and a pharyngeal zone –, where vowel spectra are relatively insensitive to small displacements in constriction location, whereas in other regions of the vocal tract, small displacements render drastical spectral changes. These detected stable areas, which are in good congruity with the results of Wood (1979), ensure not only a relative stability of the formant frequencies with respect to displacements in constriction location, but constrictions in these areas additionally induce a narrow spacing of two spectral peaks, which – according to Stevens – lead to perceptual enhancement.

For example, the location of constriction for the low vowels is situated in the lower pharyngeal region. The low vowels strive either for a proximity of F1 and F2 with a constriction located about 7 – 9 cm from the glottis rendering the back vowel /ɑ/, or for a proximity of F2 and F3 with a back cavity length of about 4 cm rendering the front vowels /a, æ/.

For the non-low front vowels, this perceptual enhancement is achieved through narrow spacing of F2 and F3, or F3 and F4. In varying the length of constriction (5 cm vs. 6 cm), Stevens in both cases observes

> "a broad maximum of F_2 for configurations having a back-cavity length in the range 6.5 to 9 cm. In this region where F_2 is a maximum, this formant is relatively close to F_3. When the constriction is even farther forward, F_3 becomes close to F_4, while F_2 remains relatively high. The exact location in the maximum in F_2 and the distance between the formants in this cluster of F_2, F_3, and F_4 depend on the length and cross-sectional area of the constriction between the tongue dorsum and the hard palate. When the length of the back cavity decreases to the left of the F_2 maximum in Fig. 8, there is a substantial decrease in F_2, and F_2 becomes quite sensitive to changes in l_1[15]." (Stevens 1989: 11)

The non-low back vowels are usually accompanied by lip-rounding. The reason for rounding is to bring F1 and F2 closer together as would be the case without rounding. Furthermore, rounding ensures a greater degree of freedom as concerns the placement of the constriction location:

> "Another potential advantage of using a rounded configuration for non-low back vowels is that F2 passes through a minimum value as the position of the tongue body constriction is displaced along the upper pharyngeal and velar region of the vocal tract … When the tongue body is in this position that yields a minimum F2, both F1 and F2 are relatively insensitive to changes in the constriction position. Thus the precision with which the constriction must be located to give a stable and low value of F2 is relatively lax." (Stevens 1999: 290)

Contrary to Wood (1979), who discerns an upper pharyngeal and a velar constriction location for the /o/ and /u/ vowels respectively, Stevens (1989) unifies this area for acoustic reasons:

15 l_1 = back cavity length.

> "The figure[16] shows a broad minimum for F_2 over a range of length of the back cavity. F_2 is within 100 Hz of its minimum value for l_1 between 2 and 7.5 cm. Within this range of l_1, the spacing between F_1 and F_2 is 400-500 Hz, and, while F_1 does not achieve a maximum value, it varies by only about 80 Hz."
> (Stevens 1989: 13)

For the /u/-vowels two constriction locations are generally reported: a front configuration with X_c at about 6,5 cm (with a low F2 and a low F3) and a back configuration with X_c at about 10 cm (with a higher F3 and occasionally higher F1) (see Boë et al. 1992; Fant/Båvegård 1997; Wood 1979 on Southern British). The back configuration of the /u/-vowels has its constriction near /o/ (X_c = 11 cm according to Fant/Båvegård 1997). This range of possible constriction locations for the /u/-vowels justifies a unification of Wood's velar and upper pharyngeal regions. The fact, however, that this whole range is a quantal region, does not mean that the whole region is exploited for constrictions. For the /u/-vowels, two locations have been spotted so far. This leaves the question of whether constrictions are intended in the region which separates the upper pharyngeal region for the /o/ and occasionally the /u/-vowels from the velar region for the /u/-vowels.

> "Published nomograms give the magnitude of a formant shift that can be attributed to a gesture, although the three-parameter models … are difficult to understand in gestural terms, as they are really models of the area function, and not of the manœuvres that created it." (Wood 1991a: 215)

Steven's quantal theory implies that articulation strives for a maximum of freedom in the positioning of the articulators. This implication is in contradiction with Wood (1982) who proved that all vowels are articulated with precision. Wood's results as concerns articulatory precision have been confirmed by Hoole/Mooshammer (2002) in their work on German vowels and by Boë et al. (1992) for American English vowels. Therefore, the observation of acoustically stable regions need not necessarily imply that the whole of this stable region is utilized in production. Given the observed precision in vowel articulation, it is at least just as comprehensible that speakers utilize the possibility of varying the acoustic output by the means of small displacements of the articulators. The Distinctive Region Model (DRM; Mrayati et al. 1988; Carré/Mody 1997; Carré 2004) makes use of the principle of creating a maximum acoustic contrast between two sounds for a minimum area deformation (Carré 2004: 230). This, on first view, is the exact opposite of the quantal theory:

> "…it has to be noted that a characteristic of stability in the articulatory-acoustic relation is the exact opposite of the characteristic of least effort, and thus of efficiency." (Carré 1996: 434)

The Distinctive Region Model (DRM) is based on the sensitivity analysis of formant frequencies in vocal tract constriction (Fant/Pauli 1974). The distinctive regions are specified

16 i. e. the nomogram calculated for the configuration of a non-low back rounded vowel. l_1 = back cavity length.

by the zero-crossings of the sensitivity function of a specific formant. Dependent on how many formants are incorporated into the model, the vocal tract is divided in either 2, 4 or 8 distinctive and symmetrical regions of unequal length. The constriction is located preferably in the middle of each region in order to produce the most distinctive formant transitions. This also means that the vocal tract is quantal in its nature.

It has been put forward that the DRM model implicitly assumes that a linear relation between articulation and acoustic output exists (Boë/Perrier 1990). Linearity is, however, more a goal of the model than an assumption; the constriction locations are placed at the midpoints of each region, where transversal displacements guarantee maximal formant frequency changes, so as to optimize the principle to achieve maximal contrast with minimal area deformation (least effort principle):

> "An important property of the model is that variation in the values of the regions' cross-sectional areas around the unifrom-tube configuraion generates maximal formant frequency variations. In other words, if we look for places in the vocal tract having the best modulation of formant frequencies around the uniform configuration, and the largest dynamics of these modulations, these places are around the midpoints of the regions. Nonlinearities and saturations occur only near the borders of the vocalic space."
> (Carré/Mrayati 1991: 436 f.)

Areas of stability, in this model, are not exploited in production. In order to examine whether areas of stability are exploited or not, one has to know which area functions result in an identical acoustic output. Atal et al. (1978) introduced the concept of fibers, which defines vocal tract shapes with identical acoustic properties. The authors conclude:

> "Large changes in the shape of the vocal tract can be made wihout changing the formant frequencies. These changes are consistent with the hypothesis that compensatory articulation is a possibility – that is, different people can produce the same sound with different vocal-tract shapes." (Atal et al 1978: 1555)

Although "an area function is not in itself an articulatory parameter" (Boë et al 1992: 29; but see also Wood 1991a), it is possible to derive to a certain extent vocal tract adjustments from the speech signal (Boë et al 1992; Ladefoged et al. 1978). Boë et al. (1992) reduced the possible area functions to meaningful configurations and could classify 7 out of 10 vowels uniquely. The vowels [i, e, a, y, o, ɔ] show a relatively precise control of the constriction location and of constriction degree. [i, y, e] show a strong constraint and maintain a small constriction degree (A_c < 1 cm^2). The vowels [ɛ, ø, œ] exhibit a large variation in constriction degree (from 0.2 cm2 to 4.0 cm^2). The authors conclude:

> "The parameters X_c, A_c and A_l thus seem to be good candidates for use in inversion procedures. It must be noted though that the precision of control necessary for each parameter depends on acoustic sensitivities, which vary according to the vowel under consideration … Thus [i] requires precise control of X_c, but no precision at all for A_l. The case of [u] is different, requiring a very small and accurate lip opening, but granting more latitude for A_c." (Boë et al. 1992: 36)

Again, the degree of freedom guaranteed for either A_l in [i] or A_c in [u] need not be reflected in actual articulatory adjustments. On the contrary, Wood (1982: 46) could show that A_l is precisely controlled in the front vowels: the jaw opening is smaller than 8,9 mm for the i-vowels, but greater than 8,9 mm for the e-vowels. These results were confirmed by Hoole/Mooshammer (2002).

Regions of stability, which in principle allow for a certain degree of freedom of articulatory adjustments, exist. Given the high degree of precision in the articulation of (vowel) phonemes, it is not quite clear what their function is. In quantal theory, regions of acoustic stability are separated by regions of acoustic instability, and these natural boundaries define the opposition between distinctive features (Stevens 2003). The boundary, e. g. between [+back] and [-back] vowels, occurs at a location where F2 is near the lowest frequency of the subglottal system and the interaction between the sub- and supraglottal resonances cause discontinuous jumps in the spectrum (Stevens 2003). This is certainly a conclusive explanation for the rough division of [+back] and [-back] vowels. Such a natural boundary is not always provided by quantal theory however (e. g. within the front region). On the contrary, quantal theory predicts a high stability of the vowel /i/. This has already been confuted by Abry et al. (1989). The current investigation reveals that in Standard Austrian German, the /i/ vowels are located exactly at or slightly before such a natural boundary where formant frequencies converge and a slight displacement of the tongue position or a reduction in constriction length causes a considerable change in formant frequency values, especially F3. Therefore, the stability of the /i/-vowels only holds for languages which do not expose a high amount of front vowels, including front rounded vowels. like e. g. English.

Acoustic stability is, therefore, not necessary for the creation of vowel systems (see also Lindblom 2003), although a positive correlation between the locations of vowels from a small vowel inventory and the regions of stability might be observed. Yet, the vowels of smaller vowel inventories are articulated with no less precision than the vowels of greater inventories (Jongman et al. 1989; Flege 1989). I. e. the potential freedom of movement is not exploited in small inventories either. As soon as the number of vowels exceeds the number of the most frequent vowel system in the languages investigated so far (Maddieson 1984; Ladefoged/Maddieson 1996), namely five, further locations or adjustments have to be exploited in order to gain distinctiveness. Jaw opening, for example, can be combined with constriction degree in such a way that four distinct vowels can be produced (Wood 1982):

	/i/	/ɪ/	/e/	/ɛ/
open	–	–	+	+
constricted	+	–	+	–

A displacement of the constriction location is not necessary for the creation of these four phonemes. Standard Austrian German, however, discerns eight phonemes in the front region. As has already been pointed out by Wood (1982, 1986), languages with front rounded vowels exploit an additional pre-palatal region to differentiate the /i/ and /y/-vowels from the /e/ and /ø/-vowels, and this pre-palatal region is highly sensitive to small articulatory displacements. Therefore, the more vowels that have to be discerned, the more problems they pose for vowel models.

Regions of acoustic stability might be useful in allophonic variation, in order to guarantee perceptual invariance. However, Stevens' regions of stability only refer to constriction locations and not to degree of constriction. Allophonic variation affects the degree of constriction rather than the constriction location, and variation in constriction degree renders a monotonic change in formant frequency values (Gay et al. 1991, 1992; Carré 2004). The overshoot and undershoot simulations performed by Gay et al. (1991, 1992) clearly show that shifts in perception for /i/ were more dependent on A_c than on X_c and shifts in perception for /u/ were highly dependend on A_l. Therefore, it can be concluded that quantal regions neither serve the creation of phonological oppositions nor are exploited in allophonic variation. Consequently, one can ask, what are they good for?

Inter-speaker differences in articulation have been documented in many investigations. It is assumed that these inter-speaker differences render different acoustic output. E. g. Apostol et al. (1999) report inter-speaker differences which are caused by speaker specific strategies used to control the speech apparatus. In the production of the vowel /a/, one of their speakers exposed a short back cavity and a long constriction zone, whereas the other speaker had a short constriction, but a rather long back cavity. These articulatory differences are of course reflected in the acoustic output, which excelled by a higher F2 for the first speaker. In a similar way one speaker had a long front cavity in the production of the vowel /i/, whose quarter-wavelength resonance is F2, whereas the other speaker had a very short front cavity, but a long constriction zone (Apostol et al. 1999: 446).

Maeda (1991), however, reports that articulatory variability was higher than acoustic variability in the production of French /ɑ/ for *pâte* ('pastry') vs. /a/ for *à* (PREP., 'to') (two vowels which have merged acoustically in some modern French variants). Whereas formant frequencies measured at the center of the vowels were quite similar, articulatory differences could be observed: the jaw was clearly open during the vowel /ɑ/, whereas during the vowel /a/ the jaw was at an average position. The vowel /ɑ/ exhibited a falling pattern (i. e. a fronting gesture) of the tongue dorsum position, the vowel /a/ indicated a peak (i. e. backing followed by fronting). These results indicate not only that a considerable articulatory variability for the same vowel exists, but also, and more importantly, that articulatory gestures are applied in a way that compensates articulatory differences in order to produce invariant acoustic patterns.

The most obvious differences in vocal tract shape is that between children, women and men. These differences should lead to different formant frequency values. However, despite the difference in vocal tract length, F1 and F2 of the vowel /u/ and F3 of the vowel /i/ of women are very similar to those of men (Fant 1980 = 2004). Fant states that differences in perceptually important formants are minimized by compensations.

> "Differences in perceptually important formants may thus be minimized by compensations in terms of place of articulation and in the extent of the area function narrowing. Such compensations are not possible for all formants and cannot be achieved in more open articulations. The great difference in F2 of [i] is in part conditioned by tha relatively short female pharynx but can in part be ascribed t the retracted place of articulation." (Fant 2004: 44)

The differences in vocal tract shape between men and women are of course an extreme example, but even here compensatory strategies can be observed. Between the sexes, slight differences in vocal tract shapes have to be assumed, and these slight differences may be compensated. Regions of stability ensure or facilitate such compensations. From this perspective, it makes sense that constriction locations are less sensitive to small displacements, whereas displacements in constriction degree yield monotonous changes in formant frequencies.

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