UNIVERSITY OF CALIFORNIA

Los Angeles

Acoustic typology of vowel inventories and Dispersion Theory:

Insights from a large cross-linguistic corpus

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Linguistics

by

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2010

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2010

This dissertation is dedicated to Erika and Armand, with love.

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ACKNOWLEDGEMENTS

This dissertation could not have been written without the help of the following people, to whom I would like to express my utmost gratitude.

I had the pleasure to work with two co-chairs whose scholarship epitomizes their two very different approaches to the study of sound in language. Thank you, Megha Sundara, for accompanying me as the main advisor through most of this journey, for your attention to details and insistence on explicitness and concreteness, and for undertaking the impossible task of improving the clarity of my writing. Even though maternity leave prevented you from being the primary supervisor of the final text, you were the reader I had in my mind. Thank you, Bruce Hayes, for inciting my interest in vowel inventories and helping me to turn vague ideas into testable questions at the very beginning, for stepping in as a fully committed co-chair and at the very end, and for your insistence on the broader context, your ability to immediately conceptualize the essence of every dilemma I ever presented to you in gory details, and for your sheer enthusiasm and positive and encouraging attitude along the way.

The three other members of my advisory committee were also very helpful. Thank you, Patricia Keating, for always knowing what I was talking about even when everyone else (myself included) did not, for always giving the useful advice, and for last-minute editing. Thank you, Jaye Padgett and Sandra Ferrari-Disner, for your passionate involvement and discussions, for your germane commentaries and for your support.

The corpus of acoustic vowel studies that serves as the basis of this dissertation could not have reached its scope and size without the responsiveness and generosity of many scholars and students who brought studies to my attention, sent papers to me, answered my questions, and even shared their raw data with me. These are (alphabetically ordered):

Patti Adank, Kofi Adu Manyah, Coleen Anderson-Starwalt, Rima Bacevičiūtė, Neil Bardhan, Ocke-Schwen Bohn, Mike Cahill, Rod Casali, Yiya Chen, Caleb Everett, Janet Fletcher, Hudu Fusheini, Bryan Gick, Juris Grigorjevs, Susan Guíon, Gwendolyn Hyslop, Shinji Ido, Antti Iivonen, Vladimir Ivanov, Eric Jackson, Allard Jongman, Brian Joseph, Peter Jurgec, Phil King, James Kirby, Yerraguntla Krishna, Susan Kung, Theraphan Luangthongkum, Robert Mayr, Abebayehu Messele, Sylvia Moosmüller, Daniela Müller, Mary Pearce, Bert Remijsen, Carlo Schirru, Patrycja Strycharczuk, Laura Tejada, Christina Thornell, Peter Trudgill, Jarek Weckwerth and Erik Willis. Thank you all. Thanks also to Tomoko Ishizuka, Sun Ah Jun, Jianjing Kuang, Grace Kuo, Craig Melchert and Henry Tehrany for making some foreign-language sources intelligible.

Thank you, Kristine Yu, for the odd reference, the other analysis, the fruitful corridor discussion and the relevant question, and thanks to everyone else at the phonetics lab for never tiring (I hope) from hearing me talking about vowels.

Many thanks to Xiao Chen from the UCLA Statistical Consulting Center, who spent many hours with me (and even some without me), helping me with data mining and gearing me up with the statistical analyses.

Thank you, Melanie Levin, the UCLA linguistics student affairs officer, for always being so helpful (and so cheerful), and a source of peace of mind whenever administrative matters arose (and there were plenty).

Special thanks to Paola Escudero, for being my only close friend who can actually respond when I talk about research, and my only colleague who doesn't just nod when I talk about the things that really matter in life. You are one in a million.

Erika, my wife, my love, my best friend, thank you so much. Thank you for coming after me to Los Angeles, for making our apartment into a cozy retreat, for

enduring 1700 days with endless patience, too often seeing only my profile during the day, going to sleep by yourself at night, only to find me sitting in the same position the next morning. Thank you for tolerating my grumpiness and lifelessness, and for supporting me in every possible way. This dissertation is yours as much as it is mine. Let me just cite what one wise man once said in Jerusalem some 2600 years ago:

"זכרתי לך חסד נעורייך, אהבת כלולותייך, לכתך אחריי במדבר, בארץ לא זרועה." (ירמיהו, ב' ב')

Last but not least, my son Armand. You were born during this dissertation year, so fortunately you will not remember anything from these stressful times, and the one rare privilege I had was to witness every moment in your early life and to always be there for you. Thank you, my little Mandulau, for helping Aba in your little ways: crawling with you on the floor, singing to you, taking you for a walk, making you smile and giggle, hearing you coo and babble, all these reminded me that there is tomorrow.

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2007. Focalization within dispersion predicts vowel inventories better'. *UCLA Working Papers in Phonetics* 105:138-146.

2010. Acoustic structures of vowel inventories and Dispersion Theory: insights from a large cross-linguistic survey. *Talk presented at the UCLA Linguistics Colloquium.*

ABSTRACT OF THE DISSERTATION

Acoustic typology of vowel inventories and Dispersion Theory:

Insights from a large cross-linguistic corpus

by

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Doctor of Philosophy in Linguistics

University of California, Los Angeles, 2010

Professor Megha Sundara, Co-chair

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This dissertation examines the relationship between the structural, phonemic properties of vowel inventories and their acoustic phonetic realization, with particular focus on the adequacy of Dispersion Theory, which maintains that inventories are structured so as to maximize perceptual contrast between their component vowels.

In order to assess this relationship between structure and realization of vowel inventories, formant frequency data were collected from 320 studies describing the acoustic properties of 555 inventories of a wide variety of structures from 230 different languages (many represented by multiple dialects). The formant data of the different inventories in the corpus were normalized with respect to vocal tract and

elicitation method differences, and data from multiple instantiations of the same inventory structure in the same language were pooled. The result of this process is a corpus of normalized formant data from 304 inventories representing unique language-structure combinations. The distribution of structures in this corpus is similar to the distribution attested in studies of structural typology of inventories.

By averaging data from same-structure inventories of different languages, prototypical acoustic realizations of many of the more universally common inventory structures are established, in terms of well-defined ranges of formant frequencies for the component vowels in each structure. In some cases, the emerging acoustic patterns challenge certain previous typological findings. For example, it is shown that instead of the two six-vowel structures [i e a o u ɨ] and [i e a o u ə], which were assumed to be distinct, with the non-peripheral vowel sharing the same height as either the high or the mid peripheral vowels, there is in fact only one structure, which can be broadly transcribed as [i e a o u ɘ]. Its non-peripheral vowel [ɘ] has a distinct height, and is not more variable than the other vowels in the structure.

Rigorous statistical analyses of the corpus data are used to test various principles of Dispersion Theory, and in most cases these principle are shown to operate consistently. Thus, there is clear correlation between the number of vowels and acoustic space sizes of inventories, with the number of peripheral vowels more correlated with the F1 frequency spans of inventories and the number of non-peripheral vowels with the F2 frequency spans. In addition, instantiations of specific vowel categories shift acoustically as a function of structure so as to escape from crowded regions and fill less crowded ones. For example, low vowels vary horizontally between back, central and front when inventory peripheries are respectively front-crowded asymmetrical, symmetrical and back-crowded asymmetrical. This behavior of low vowels is one aspect of a more general push chain shift process, which is initiated by increased local pressure upon the addition of a peripheral vowel, and propagates with gradual decay through the entire inventory periphery. Moreover, vowel height levels in the inventory periphery are evenly spaced perceptually (only when the log(Hz) scale is used).

In order to accommodate non-peripheral vowels in the inventory, the periphery expands horizontally. However, this effect is sensitive to perceptual needs: when there is only one non-peripheral vowel, this vowel tends to occupy a distinct vowel height and thus contrast with peripheral vowels both horizontally and vertically, requiring only limited horizontal expansion of the periphery. Once a second non-peripheral vowel is added, the non-peripheral vowels are forced into the same height levels as peripheral vowels. Consequently, this contrast becomes predominantly horizontal, and peripheral vowels become substantially more extreme. However, in the lower-mid region, where non-peripheral vowels rarely appear, such horizontal expansion is not necessary, and is indeed avoided.

Unlike vertical spacing, horizontal spacing is not even, and non-peripheral vowels tend to be acoustically and perceptually fronter than the midline between front and back vowels. This tendency to be fronter is significantly stronger in higher non-peripheral vowels, where it results in close proximity of F2 and F3, thus providing support for the Dispersion-Focalization Theory, a particular model that combines dispersion with preference of vowels with proximate formants.

All these behaviors are consistent, but at the same time they are too gradient and subtle to surface in typological studies based on phonological, contrast-oriented descriptions. While the corpus data strongly support the concepts and principles underlying Dispersion Theory in general and Dispersion-Focalization Theory in particular, they also point to severe limitations of previous attempts to formalize these concepts in simulations of computational models, implying that accurate prediction of acoustic patterns of inventory structures would require a drastically revised Dispersion-Focalization Theory model. Possible modifications and additional components necessary for such an improved model are discussed.

PREFACE

This dissertation is the result of a one-year project that started as a secondary component in a larger research enterprise, which was the focus of my work during most of my term as a doctoral student at UCLA, and whose goal had been to improve upon previous formal models of Dispersion Theory as studied in computational simulations. The original purpose of the project described in this dissertation was to collect a corpus of a few dozen formant studies of vowel inventories, and use it to create a reference for evaluating the predictions of Dispersion Theory models, by averaging formant data from structurally-similar inventories of different languages.

About two months after I began to work on this project I realized that there were many more formant studies available than I initially expected to find, and that the resulting corpus would thus allow more rigorous analyses of the acoustic typology of vowel inventories, beyond the limited scope of serving as a reference for simulation studies. Moreover, preliminary analyses of the data indicated that the acoustic patterns found in real inventories differ from those predicted by Dispersion Theory models (both mine and others') in certain fundamental ways, but at the same time seem to follow from Dispersion Theory principles that may have not been formalized in such models. As the whole idea behind Dispersion Theory is to derive a model based on phonetic substance in real languages, expanding the analysis of the corpus data became my top priority, as I realized that it would contribute to our understanding of the structure of vowel inventories much more than any revision of a formal model. As more data accumulated and the analyses became more comprehensive, it turned out that including simulation and modeling as part of the dissertation would have actually masked what I consider to be the important output of my work, and so I decided to turn the corpus and its analyses into the sole topic of this dissertation.

During my work on this project I made every effort to ensure the accuracy of the corpus data (as I registered them based on my own interpretation of their sources) and their analyses. However, in particular due to the limited time and to my own misapprehensions and inefficiencies, it is possible that I failed to find some acoustic studies worth of including in the corpus,[1] or that I inaccurately interpreted the data in certain studies, or that I made typos and/or other errors while registering the source data in my own files. Errors may have also occurred during the various transformations applied on the corpus data, and possibly also in the analyses themselves. I take full responsibility for all errors, discrepancies and inconsistencies readers may notice, in the dissertation text or in the corpus, and I apologize to the authors of studies included in the corpus in case they believe that I misinterpreted their studies in any way. Most apparent discrepancies are a result of the need to review and interpret each study in the context of all other studies, and all remaining discrepancies or errors are incidental. Nevertheless, readers are strongly advised not to cite language-specific formant data directly from the corpus collected as part of this dissertation, and to always consult the original studies. Authors and readers alike are welcome to contact me with any question concerning the corpus data, their sources and the analyses.

[1] Studies made available after January 2010 could not be included in the corpus, as I began the final analyses of the corpus in early February 2010.

1. Introduction

1.1 The goals of this dissertation

This dissertation examines the relationship between the structural, phonemic properties of vowel inventories and the acoustic phonetic realization of their vowels, with particular focus on manifestations of this relationship as predicted by the principles of Lindblom's Dispersion Theory (Liljencrants & Lindblom 1972, Lindblom 1986). The relationship between structural properties and acoustic realization of vowel inventories has been central to research of the interface between phonology and phonetics for decades, and has been addressed in many theoretical, computational and empirical studies. This dissertation adrdresses this relationship on the basis of analyzing a corpus of acoustic descriptions of inventories from 230 different languages (many represented by multiple dialects), collected and constructed specifically for this purpose. At this size, this corpus is comparable to the phoneme inventory corpora in the typological studies of Crothers (1978), covering 209 languages, and Maddieson's (1984) UPSID, covering 317 languages. Just as these two corpora served as data references for various studies dedicated to the structural patterns in inventories (Ferrari-Disner 1984, Lindblom 1986, Schwartz et al. 1997a, 1997b, de Boer 2000, Roark 2001, Carré 2009, among others), the corpus constructed as part of this dissertation is intended to serve as a data reference for studying the acoustic properties associated with these structural patterns.

Using this corpus, this dissertation has two principal goals. First, it establishes prototypical acoustic realizations for many common inventory structures, which together account for the inventories of the overwhelming majority of the world's languages (at least according to Crothers 1978 and Maddieson 1984). This acoustic typology of inventories may serve primarily for evaluating formal models that try to explain and predict vowel inventories and their properties. It might also prove relevant for addressing other major research questions. For example, if the acoustic manifestation (established here) of structural differences between inventory types is found to be correlated with other between-language phonetic differences (established elsewhere) in the vocalic system, e.g. in duration and/or rhythm patterns, we may gain further insights about the behavior of the vocalic-phonetic system as a whole. Implications may reach beyond phonetic and phonological theory. For example, knowing the prototypical phonetic realizations of the most common inventory types, and the differences between them, may prove useful in devising generic pedagogical strategies for improving pronunciation of vowels in foreign languages.

This dissertation also applies standard statistical analyses on the corpus data, from inventories of both common and rare structures, to test various aspects of cross-linguistic acoustic realization of inventories as predicted by principles of Dispersion Theory. Most of these predictions are borne out when the large corpus is properly analyzed. As such, this dissertation provides strong support for Dispersion Theory, and at times provides a basis for refuting previous studies that rejected dispersion principles based on comparative acoustic data from very few languages (often only two). To give a concrete example, Dispersion Theory predicts that inventories with more vowels should cover larger acoustic spaces. Livijn (2000), based on acoustic data from 28 languages, one of the largest acoustic corpora collected prior to this dissertation, concluded that there is little or no correlation between the number of vowels in inventories and the size of the acoustic space they use. The analysis of the much larger corpus in this dissertation suggests that number of vowels and acoustic space size are clearly correlated, but also that the variability of space size is large enough to mask this correlation in small data corpora.

The dissertation also proposes methods necessary in order to render formant data, which were gathered in many different studies, more comparable and more suitable for the analyses. These methods include a normalization procedure for vocal tract differences inherent in acoustic data from different languages, and a model for estimating the F3 frequency of a given vowel based on its F1 and F2 frequencies. These methods have very few predecessors in the literature, as the practical need for them hardly ever arose, and the data that served as the basis for their predecessors were very limited. These methods and their contribution are tentative because, in this dissertation, they are only a tool, not a goal, and as such, the improvements they make are rather modest in most cases, suggesting that there is much room for further improvement.

One other contribution of this dissertation is the availability of its raw data and their source references. It is hoped that researchers will use the corpus data to study theoretical questions related to the acoustic realization of vowel inventories not covered here. The list of references may facilitate future work on the vowel inventories and/or the entire phonetic systems of many languages, including poorly studied ones. It is also hoped that this list of references will encourage researchers to expand it with acoustic studies of many more inventories.

The rest of this introductory chapter is dedicated to a review of the two core areas that constitute both the basis and the goal for this dissertation: Vowel inventory typology literature is reviewed in Section 1.2, and Dispersion Theory and its influence on the study of vowel inventories are reviewed in Section 1.3. Section 1.4 elaborates on the need for a cross-linguistic acoustic corpus. Chapter 2 of this dissertation describes the compilation process of the corpus. Chapter 3 describes the data transformation process, which takes as its input the raw corpus data, and yields as its output formant data that are more suitable for analyses, as wells as a coherent acoustic typology of common inventory structures. Chapter 4 is dedicated to analyses of the corpus data in the context of Dispersion Theory and its predictions. Section 4.7, which concludes Chapter 4, summarizes the insights obtained through the analyses and suggests several ways to enhance existing formal dispersion models so they would better describe and predict the newly available acoustic typology of inventories.

1.2 Structural typology of vowel inventories

Consistent trends in the structure of vowel inventories across languages have been known for many decades. Systematic typological studies of vowel inventories emerged as part of a general enterprise in the mid-twentieth century to establish a representative typology of consistent cross-linguistic facts, as the basis for research within universalistic linguistic theories. The Stanford Phonology Archiving Project, part of the Stanford Project on Language Universals, yielded two publications on vowel inventory universals, based on phonemic transcriptions of inventories from a representative sample of the world’s languages. Seldak (1969) mostly reaffirmed some tentatively held universals, based on 150 inventories. Crothers (1978), based on inventories from a genetically and areally balanced sample of 209 languages, was more comprehensive and laid the foundation for our present understanding of the structural typology of vowel inventories.

Crothers (1978) divided the vowel inventory of a given language into sub-systems based on length (normal/long) and oral/nasal quality, and identified the basic sub-system as 'the arrangement of qualities of normal-length oral vowels' (Crothers 1978:100). His analyses were based on the 209 language-specific basic sub-systems, whose structures were classified according to (a) the number of vowels, (b) the number of peripheral vowels (front unrounded, low and back rounded) vs. non-peripheral or interior vowels (all others), and (c) the arrangement of the peripheral vowels (symmetrical vs. asymmetrical, where symmetrical means the same number of front and back vowels). The analyses showed that, with few exceptions, the basic sub-systems of vowel inventories have between three and nine vowels, and that each inventory size is associated with one or two common arrangements. For example, five vowel inventories are dominated (90%) by the structure /i ɛ a ɔ u/ (two front unrounded vowels, one low vowel, two back rounded vowels), and seven vowel inventories appear mostly either in the form /i e ɛ a ɔ o u/ (three front, one low, three back) or /i ɛ a ɔ u ɨ-y ə-œ/ (two front, one low, two back, two non-peripheral). The ten most common structures accounted for 173 (82%) of the corpus inventories.

Crothers (1978) used his corpus to establish twelve universal generalizations on vowel inventory structure, each violated by very few (or none) of the corpus inventories. Among the more important universals we find: "All languages have /i a u/", "All languages with four or more vowels have /ɨ/ or /ɛ/", "Languages with two or more interior vowels always have a high one" and "The number of height distinctions in front vowels is equal to or greater than the number in back vowels". However, some of these universals, in particular those referring to specific vowel qualities, need to be interpreted with caution. For example, /u/ (which is said to be present in every inventory) may be phonetically [ɯ] or [o], similarly, /ɨ/ may be phonetically [ə] if it is the only non-peripheral vowel in the inventory.

Maddieson's (1984) UPSID (UCLA Phonological Segment Inventory Database) was based on inventory descriptions similar to those used for the Stanford Phonology Archiving Project, but covered many more languages (317 in its original version). UPSID was later expanded to cover 451 languages (Maddieson & Precoda 1990), but all the studies that analyzed its vowel inventory data are based on its original version. When discussing the vowel inventories in UPSID and the typological patterns they fall into, it is desirable to consider not only Maddieson's (1984) own analyses and interpretations, but also those done by others (Ferrari-Disner 1984, Schwartz et al. 1997a, Roark 2001). For example, while Maddieson's (1984) analysis included fine phonetic distinctions and did not attempt to generalize structural patterns in inventories, Schwartz et al. (1997a) and Roark (2001) do so. Schwartz et al.'s (1997a) analyses retain some of the phonetic detail and their UPSID-based typology of inventory structures is finer (and more diverse) than Crothers' (1978), but Roark (2001) abstracts away from phonetic detail and his inventory typology is expressed in terms almost identical to Crothers' (1978). While Maddieson's (1984) analysis tends not to split inventories into sub-systems according to vowel quantity, and consequently recognizes inventories with as many as 17 vowels and more, Schwartz et al. (1997a) treat vowels sharing the same quality but differing in quantity as parts of different sub-systems.

Overall, the typology of inventory structures emerging from UPSID, in particular as analyzed by Roark (2001), resembles Crothers' (1978) typology to a great extent. For example, the ten most common inventory structures in Crothers (1978) account for 245 (77%) of the inventories in UPSID, and are all among the 13 most common structures in UPSID. As such, the larger language sample in UPSID makes it a more reliable source for determining the typology of inventory structures. Moreover, the coarse analysis of UPSID inventory structures in Roark (2001) is complemented by the finer sensitivity to details of the other UPSID-based analyses (Maddieson 1984, Ferrari-Disner 1984, Schwartz et al. 1997a). For example, both Crothers (1978) and Roark (2001) do not distinguish between [u] and [o] in three-vowel inventories or between [ɨ] and [ə] as single non-peripheral vowels. However, Maddieson (1984, Chapter 8), Ferrari-Disner (1984) and Schwartz et al. (1997a) are sensitive to these distinctions. In fact, sensitivity to such distinctions led Ferrari-Disner (1984) to reject Crothers' (1978) universal that all languages have /i a u/.

For the purpose of this dissertation, the most important outcome of these typological studies is that they establish a core of inventory structures that account for the overwhelming majority (above 80%) of the inventories in the world's languages, and that, within this set of inventory structures, different inventory sizes are represented by very few (typically two) structural patterns. Throughout the dissertation, structural typology of inventories will usually be referenced through the newer studies of Schwartz et al. (1997a) and Roark (2001), rather than through the original typological surveys (Crothers 1978, Maddieson 1984), because the newer studies use the larger and more reliable dataset (Maddieson's UPSID) while applying classificational nomenclatures and summaries of inventory structures resembling Crothers (1978).

1.3 **Dispersion Theory**

1.3.1 Dispersion and Structural typology of inventories

The idea that vowel inventories are structured in a manner that enhances contrast, by maximally dispersing vowels in the auditory-perceptual space, is as old as the intuition that vowel inventories follow universal structural patterns. As soon as linguists noticed that inventories always have the vowels /i a u/, and that front vowels are usually unrounded while back vowels are rounded, they also noticed that inventories tend to spread their vowels along the periphery of the acoustic and perceptual space. Further support came from the fact that a phonological front-back contrast is usually absent in low vowels, i.e. precisely where the acoustic correlate of this contrast (F2 difference) is smallest, and that non-peripheral vowels, with intermediate F2 frequencies, tend to appear between front unrounded (high F2) and back rounded vowels (low F2) in the higher regions of the acoustic space, where the range of F2 frequencies is greatest.

Maximization of dispersion evolved into a formal model intended to predict the structure of vowel inventories more or less in synchrony with the development of rigorous structural typologies of vowel inventories, and the two parallel enterprises maintained a 'scientific dialogue' during the course of their development. Thus, Liljencrants & Lindblom (1972) used Seldak (1969) and other sources as the reference for evaluating the predictions of their model, and Crothers (1978), as part of his analysis of his own typological study, referred extensively to Liljencrants & Lindblom (1972) and indeed proposed some refinements for their model. Crothers (1978) was later used as the typological reference in Lindblom's (1986) study of his revised dispersion model, whose earlier version was among the theoretical references in Ferrari-Disner's (1984) analyses of vowel spacing as emerging from the inventories in Maddieson's (1984) UPSID. The UPSID-based typology in Schwartz et al. (1997a) was the typological reference for Schwartz et al.'s (1997b) Dispersion-Focalization Theory.

1.3.2 Principles of Dispersion Theory and their implications

Dispersion Theory may be used as the generic term for the theoretical approach underlying various formal modeling studies since Liljencrants & Lindblom (1972). It relies on certain principles and makes explicit, but qualitative, predictions. As such it is important to distinguish Dispersion Theory both from the rather vague notions of contrast enhancement that preceded it and from its quantitative formulations in specific models. While most dispersion-related research focused on formal modeling and computer simulations, several attempts have been made to test dispersion principles experimentally or otherwise relate empirical findings to dispersion principles. Following is a description of the principles of Dispersion Theory and of relevant empirical findings in the literature. Formal dispersion models are described in Section 1.3.3.

The first principle of Dispersion Theory is that vowels should be maximally perceptually dispersed from one another (Liljencrants & Lindblom 1972). This means that, articulatory and other considerations set aside, more extreme vowel qualities should be preferred over less extreme ones, because the more extreme the vowel is, the farther it is (and more perceptually distinct) from other vowels. Although limited,direct empirical support for this principle is found in Johnson et al.'s (1993) and Johnson's (2000) studies of the 'Hyperspace Effect'. In these studies, listeners rated vowel stimuli with extreme formant frequencies as more prototypical exemplars of the point vowel phonemes of the inventory than stimuli with more natural formant frequencies, that is, given the choice, listeners preferred a maximally dispersed version of the inventory. However, the hyperspace effect has been demonstrated only with speakers of English, and thus provides only tentative support for the principle of maximization of dispersion. Additional, cross-linguistic, but indirect evidence may be found in findings regarding the vowel space in infant-directed speech. For example, Kuhl et al. (1997) showed that, when speaking to infants, speakers of English, Swedish and Russian pronounce the point vowels with significantly more extreme qualities that when speaking to adults. Regardless of whether or not this tendency to maximize vowel inventory dispersion indeed enhances perception of vowels and vowel contrasts by infants, the fact that speakers choose this strategy while speaking to infants implies that the speakers themselves (subconsciously) associate maximization of dispersion with enhancement of perceptual clarity.

Another principle of Dispersion Theory is that the value of individual vowel qualities and their contribution to the virtue of inventories are relational. Vowels are good candidates for inventories only to the extent that they are perceptually distant from other vowels in that inventory. Thus, no particular vowel quality is favored, and given two different arrangements of all other vowels in the inventory, the same vowel may be optimal for one arrangement and unacceptable for the other. Consequently, vowel qualities are adaptive, that is, minimal structural changes in the inventory may cause the arrangement of vowels in the inventory to be less dispersed, and so vowels have to shift and assume new positions in order to maximize dispersion (Liljencrants & Lindblom 1972). Direct empirical evidence for the relational nature of inventories and the adaptive behavior of their vowels is found in Recasens & Espinosa's (2006, 2009) acoustic studies of inventories of major (regional) and minor (local) Catalan dialects. Contrasts between higher-mid and lower-mid peripheral vowels (/e/ and /ɛ/, /o/ and /ɔ/), which are preserved in the major dialects (Recasens & Espinosa's 2006), are at a stage of near-merger in some local dialects (Recasens & Espinosa's 2009). Whenever a local dialect preserves the contrast, the acoustic qualities of the higher and lower mid vowels are very similar to the same vowels in the major regional dialect. However, if the contrast is being merged (whether it is the front pair, the back pair, or both), this merger takes place somewhere in the middle of the acoustic range between the two vowels, rendering the merged vowel roughly halfway between the high and low vowel, thus maximizing its contrast between the high, mid and low vowels. Recasens & Espinosa (2006) also show that the presence of a mid-central /ə/ as a phoneme in one of the dialects is correlated with more extreme F2 frequencies of the higher-mid and lower-mid vowels in this dialect than in the other dialects, which suggests that the peripheral mid vowels in this dialect are adjusted in order to accommodate the additional vowel.

A third principle is that maximization of dispersion is achieved via even spacing between vowels (Ferrari-Disner 1984). Even spacing essentially refers to a requirement that different pairs of adjacent vowels maintain a particular minimal distance between them. This has been interpreted both as a universal criterion for sufficient contrast between vowels observed in different inventories (Lindblom 1986), and as a language-specific criterion observed by the same language under different circumstances, in particular in the sense that compression of the acoustic space size in unstressed syllables is accompanied by reduction in the number of vowels and vowel contrasts (Flemming 2004, 2005).

The first, cross-linguistic, interpretation of the minimal distance principle makes three predictions. First, there should be an upper limit on the number of vowels in inventories, above which the minimal distance can no longer be maintained because the acoustic space is finite. Empirical support for this prediction is found in the typological finding that nine vowels is the upper limit of viable inventories, above which inventories become extremely rare (Crothers 1978, Schwartz et al. 1997a). Second, in order to maintain minimal distance between vowels, the phonetic realization of the vowels should be rather precise in more crowded inventories, whereas inventories with fewer vowels may allow greater variability in phonetic realization without violating the sufficient contrast criterion. Unfortunately, according to the review and discussion (and novel data) in Recasens & Espinosa (2009), evidence for the correlation between the number of vowels and phonetic precision has usually not been found. Third, inventories with more vowels should cover a larger acoustic space than inventories with fewer vowels. This prediction, which at the same time manifests the principle of vowel adaptiveness in the case of point vowels (they have to shift if the acoustic space size differs as a function of inventory complexity), has been addressed in a variety of studies comparing acoustic data of vowel inventories differing in the number of their respective vowels. Some of these studies support this hypothesis (Ferrari-Disner 1983, Jongman et al. 1989, Guíon 2003, Altamimi & Ferragne 2005, Recasens & Espinosa 2006), but others show null results (Bradlow 1995, Meunier et al. 2003, Recasens & Espinosa 2009). Among the studies with more positive results, Guíon's (2003) study of Quichua (three vowels) vs. Ecuadorian Spanish (five vowels) seems most conclusive, especially as part of the acoustic data is drawn from speakers that are simultaneously bilingual in the two languages. For these speakers all parameters other than language are controlled, and still their acoustic vowel space is greater in Spanish than in Quichua.

It should be noticed that the predicted correlation between the number of vowels and used space size may follow also from the principle of maximization of contrast alone, without the requirement for sufficient contrast, provided that it is combined with an articulatory principle of effort minimization (ten Bosch 1991a,b). According to this view, the more extreme a vowel is acoustically, the more costly its articulation, and acoustic space size is the result of compromise between perceptual pressure to expand the space and articulatory pressure to compress it. Due to the substantially stronger perceptual pressure in more crowded inventories, compromise is reached at a larger acoustic space size. This view is reinforced by the fact that, in all the studies that showed correlation between the number of vowels and space size, the difference in space size was rather small and the inventories did not seem to adhere to the same constraint on minimal between-vowel distance, the inventory with more vowels appearing more spatially crowded. Finally, Livijn (2000), which is the only study that compares data from a large number of languages (28 languages based on a multi-language recording database), reports very weak correlation ($r^2 = 0.075$) between the number of vowels and acoustic space size. While Livijn (2000) does not rule out that this weak correlation is genuine and manifests a tendency to accommodate more complex structure by expansion of the acoustic space, his data imply that variability in space size as a function of structural complexity is too great to manifest any criterion of sufficient dispersion and minimal between-vowel distance.

In the second, within-language interpretation, minimal distance and even spacing principle explains the phenomenon of reduction in the number of vowels and vowel contrasts (phonological vowel reduction) in unstressed syllables attested in many languages (Flemming 2005). In unstressed syllables vowels are shorter and consequently the vowel space is significantly compressed due to undershoot and/or coarticulation. Consequently, maintaining a minimal distance between vowels in a compressed space can be achieved only by reducing the number of vowels. Many acoustic studies have demonstrated the compression of the acoustic space in unstressed syllables, in inventories with or without phonological vowel reduction. However, very few studies directly addressed the issue of maintaining the same minimal distance between vowels in stressed syllables and unstressed syllables with phonological vowel reduction. According to Flemming (2004), such a criterion appears to be operative in Italian, at least in the F1 dimension, according to formant data in stressed vs. unstressed syllables in Leoni et al. (1995). However, in acoustic studies of phonological vowel reduction in Russian (Padgett & Tabain 2005) and Catalan (Herrick 2005) no evidence was found for a consistent between-vowel distance threshold maintained either in different stress conditions or between different vowel pairs.

In summary, Dispersion Theory maintains that inventories are (a) structured so as to maximize dispersion, which is achieved by (b) adaptive behavior of vowel qualities, which tend to be (c) evenly spaced and adhere to (d) constraints on the minimal perceptual distance between them. Some empirical support is found for the first two principles, but not for the other two. However, it should be kept in mind that proponents of Dispersion Theory have so far focused more on attempts to predict the typology of vowel inventories by formal models than on finding anecdotal evidence for its principles in individual languages, because Dispersion Theory is meant to work more at the global, cross-linguistic level. It is plausible that, just as any generalization (in linguistics and elsewhere) is often violated by many individuals and yet holds at the population level, the true test for Dispersion Theory and its principles is only against large amounts of cross-linguistic data. As will be shown throughout Chapter 4, when acoustic data from many inventories are analyzed together, most principles of Dispersion Theory are strongly supported.

1.3.3 Formal dispersion models

Various formal models of Dispersion Theory have been proposed in the literature (Liljencrants & Lindblom, Lindblom 1986, ten Bosch 1991a, Schwartz et al. 1997b, de Boer 2000, Roark 2001, Diehl et al. 2003, Becker-Kristal 2007, Sanders & Padgett 2008b). It is beyond the scope of the current work to elaborate on these models and evaluate them, but as the development of Dispersion Theory as a conceptual framework was always translated into formal models tested in computer simulations, the shared properties of these formal models and some of the differences between them provide a more concrete view of the mechanisms of Dispersion Theory.

All dispersion models share the assumption that possible inventories can be evaluated as better or worse candidates as a function of the spatial arrangement of their vowels. Thus, these models formalize a space of possible vowels, and a vowel inventory is represented as a set of coordinates in this space. They also formalize a distance metric between vowels, as well as a function from these between-vowel distances in the inventory to a global score, or energy function, by which the inventory is evaluated against other possible inventories. A computer simulation searches through possible inventories, and inventories with the lowest energy function (or otherwise best score) are identified as the inventories predicted by the model.

There are many parameters by which individual models may differ, including the dimensions and shape of the space, the acoustic and perceptual representation of vowels, the perceptual distance unit and distance metric, the precise calculation of the energy function, and the incorporation of factors other than dispersion as part of the model, like effort minimization or biases towards certain perceptual representations. It is nevertheless possible to outline a representative formal dispersion model based on attributes that are shared by most models, bearing in mind that each of these attributes may be represented differently in the individual models.

In one such generic model, vowels have acoustic representations that include the frequencies of the first four formants in Hz units, and a two dimensional perceptual representation (F1xF2', where F2' is based on F2 but may be corrected for F3 and F4 when F2 is high), on an auditory frequency scale (typically the Bark scale). The perceptual distance between two vowels is the two-dimensional Euclidean distance between their coordinates on the F1xF2' plane. This Euclidean distance is often weighted such that the contribution of F1 is greater. The inventory energy function is based on the distances between all the vowel pairs in the inventory, in a formulation that substantially enhances penalty (increases the energy level) for smaller distances, thus militating against vowel pairs that are very close together. The formulation of the energy function is:

$$E = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{1}{d_{i,j}^{2}} \tag{1.1}$$

(n = the number of vowels; $d_{i,j}$ = distance between the two vowels i and j)

Certain settings of Schwartz et al.'s (1997b) Dispersion-Focalization Theory model (settings where the optional 'focalization' component of their model is neutralized and F2' is weighted relative to F1 by a factor of about 0.3) may be regarded as the model most similar to the generic model just outlined (see Schwartz et al.'s 1997b for more detail). Examples of alternative model architectures include representation of vowels based on entire spectra rather than only formants (Lindblom 1986, Diehl et al. 2003), frequency representation in Mel units (Liljencrants & Lindblom 1972) or log(Hz) units (ten Bosch 1991a, Roark 2001) and calculation if the inventory energy function based on the least dispersed pair only (ten Bosch 1991a, Becker-Kristal 2007).

The differences between any pair of models and their implementations usually involve two or more components, which makes it difficult to directly compare the contribution of specific components to the differences in models' predictions. While it is nevertheless possible to compare between the typological predictions themselves, and prefer one model over the other strictly based on predictive accuracy, such comparison is intentionally avoided here. As will be explained at length in Section 1.4, such a comparison is meaningless until the known structural typology of vowel inventories is assigned acoustic values on which predictions of dispersion based models can be tested, which is one of the goals of this dissertation.

It is interesting to note that, although virtually all proponents of dispersion models adopt even vowel spacing as a principle of Dispersion Theory, this principle has never been explicitly formulated as part of the energy function in any formal model, e.g. by favoring a narrow distribution of the set of shortest between-vowel distances in the inventory (one for each vowel). It has not been explicitly shown that even spacing (in numerical terms) is indeed achieved by the existing energy functions either. Nevertheless, impressionistic observation of the inventories predicted by various dispersion models suggests that, more often than not, these inventories are characterized by even spacing.

1.3.4 Other theories

Dispersion Theory is the only theory that was fully formalized to predict vowel inventories and explain their typology (see Section 1.3.3). While no other theory has ever been developed to this level with respect to vowel inventories, it is worth recognizing the fundamental aspects of major rival theories and how they differ from Dispersion Theory.

According to Distinctive Feature Theory (Jakobson et al. 1952, Chomsky & Halle 1968), inventory structures are determined by the combinations of features with discrete values: each feature combination forms a sound, and all the sounds form the inventory. Feature values can be unmarked (default) or marked, and inventories tend to maximize the use of unmarked values, hence certain vowels are expected to be more common than others. For example, since [-round] is unmarked while [+round] is marked, unrounded vowels should be more common in inventories, which is expressed by the fact that low vowels and central vowels are seldom rounded, and that while there are some inventories with no rounded vowels (e.g. /i a ɯ/ in Nunggubuyu and Jaqaru according to Crothers 1978, /i a ɨ/ in a dialect of Hakka according to Zee & Lee 2007), all inventories have unrounded vowels. Distinctive Feature Theory thus treats certain inherent properties of vowels as preferred over others, and differs from Dispersion Theory, which recognizes only relations between vowels. Another, related, difference between the two theories has to do with phonetic implementation and vowel quality. Dispersion Theory maintains that vowel quality is adaptive and is regulated by perceptual distances from other vowels. Conversely, Distinctive Feature Theory maintains either that the phonetic implementation of vowel features like [+high], [-back] etc. should be rather precise (hence not variable as a function of the nature of other vowels in the inventory) or that it is language-specific and not part of the core linguistic system. Dispersion Theory and Distinctive Feature Theory are thus rather incompatible with one another (but see Boersma 1998 for criticism of both theories and a preliminary attempt to reconcile them).

According to Stevens' (1972, 1989) Quantal Theory, some speech sounds are also preferred because of their inherent, absolute properties and not by their relations to other speech sounds. However, unlike Distinctive Feature Theory, the preferred inherent properties are not discrete feature values but concrete phonetic qualities that render the sounds in question stable and impervious to contextual effects. In fact, Quantal Theory maintains that these stable phonetic qualities are the basis for discrete feature values, because they quantize the phonetic continuum, i.e. impose a quasi-discrete partition on it. With respect to vowels, Quantal Theory views within-vowel formant proximity as a quantal property, because those vowels are characterized by minimal acoustic sensitivity to articulatory variability. According to Quantal Theory, this property explains the cross-linguistic popularity of the three point vowels [i ɑ u], as [i] is preferred because of F2-F3-F4 proximity, and [ɑ] and [u] are preferred because of F1-F2 proximity (at different frequency ranges). These vowels are predicted to be preferred, and to the same extent, regardless of other vowels in their vicinity, and are not expected to shift around in response to structural changes.

One major development within Quantal Theory with respect to vowel inventory structure was the view that formant proximity within a certain distance range has a quantal effect at the perceptual level. Based predominantly on experimental findings by Chistovich & Lublinskaya (1979), proponents of Quantal Theory maintained that formants that are less than 3-3.5Bark apart are integrated into one perceptual component, and that this component is relatively stable across different distances between formants as the 3-3.5Bark distance threshold is maintained. However, most work within this approach did not try to explain vowel inventory structures and predict their typology, and focused on providing phonetic basis for phonological, feature-based distinctions in inventories, by applying the 3-3.5Bark distance threshold on formant pairs as determining the threshold between feature values: F1-f0 for [±high], F2-F1 for [±back] and F3-F2 for [±front] (e.g. Fant 1983, Syrdal & Gopal 1986, Stevens 1998).

Dispersion Theory and Quantal Theory are not entirely incompatible with one another because Quantal Theory is not designed to predict entire inventories but only specific sounds or sound contrasts, and it does not preclude that dispersion may explain the organization elsewhere in the inventory. Such a combined approach is manifested in Roark's (2001) model, which practically fixes the phonetic qualities of the three point vowels and lets dispersion determine the rest of the inventory structure. Another such approach is Schwartz et al.'s (1997b) Dispersion Focalization Theory, which views the preference of maximal perceptual distances between vowels and of formant proximity within vowels as two independent factors.

According to Carré's Distinctive Region Model (Mrayati et al. 1988, Carré 2009), vowel inventories are organized such that minimal articulatory differences between vowels yield maximal acoustic and perceptual differences. While this theory recognizes the role of perceptual dispersion, its emphasis is on economy and efficiency during connected speech. Since vowels occur in the dynamic context of connected speech, there is always transition from one vowel to another. These transitions are more efficient if their articulatory trajectories are short while the acoustic and perceptual distances between their endpoints are large. Most efficient are the three trajectories between the three point vowels [i a u], and as such they are the most suitable trajectories to be further divided to intervals and form series ([i e ɛ a], [a ɔ o u], [u ɯ ɨ i]). Although this theory has not been fully formalized, from its descriptions it particularly disfavors individual vowels that require new trajectories just for themselves. For example, assuming a six-vowel inventory [i e a o u ɨ], with three trajectories each with two intervals – two endpoints and one midpoint (front [i e a], back [a o u] and high [u ɨ i]), accommodation of a seventh vowel should be achieved by adding a vowel to one of the three trajectories (e.g. [ɛ], [ɔ] or [ɯ]), not by adding a vowel requiring a new trajectory (e.g. [ø]). The Distinctive Region Model also much prefers acoustic-perceptual series involving monotonous articulatory transitions like [i y ʉ u] (with increasing lip rounding as the tongue goes back) over series with very similar acoustic-perceptual values but involving 'articulatory zigzag' like [i y ɯ u]. Conversely, Dispersion Theory is indifferent to such considerations, and prefers vowel combinations solely based on maximization of perceptual dispersion, regardless of the articulatory trajectories between them.

Since none of the theories described in this section has ever been fully formalized to make falsifiable predictions of the typology of vowel inventory structures, there is very little sense in using typological corpora to make a comparative evaluation between each of them and Dispersion Theory (or between themselves). Therefore, only sporadic reference will be made to these theories through the rest of this dissertation.

1.4 The need for an acoustic typology of vowel inventories

Our present understanding of the relationship between the structural properties of vowel inventories and their acoustic realization is rather limited. On one hand, the established typological facts suggest that perceptual contrast enhancement plays an important role in inventory structure. On the other, support for Dispersion Theory, which translates the notion of contrast enhancement into more concrete principles, is rather inconclusive. In this regard, it is important to highlight a long term paradox in the development of Dispersion Theory. Since the inception of this theory, its proponents put emphasis on formal models of dispersion, and on computational simulations that served for testing these models, as described in Section 1.3.3. These formal models rely heavily on numerical representations, as they evaluate and predict inventories based on the formant frequencies of vowels, which are translated to numerical scores. However, when inventories predicted by these models are compared against typological data, their component vowels are not considered based on their acoustic qualities but on phonetic transcriptions assigned to them, because the typological reference consists only of transcribed inventories.

For example, both Lindblom (1986) and Schwartz et al. (1997b) commonly predict inventories with a high-back vowel labeled [u], with F1 frequency at around 300Hz and a F2 frequency close to 600Hz, the lowest F2 frequency possible in those simulations. In both simulations, a vowel with the same F1 frequency but F2 frequency at around 875Hz ([ɯ] in Lindblom 1986, 'V1' in Schwartz et al. 1997b) is never predicted. Clearly, the extremely low F2 frequency contributed to the preference for [u] over the vowel with the slightly higher F2 frequency in these simulation studies. Both studies treat the overwhelming preference for inventories containing a vowel labeled as /u/ in their respective typological references as evidence for successful modeling. However, suppose that the F2 frequency of a vowel labeled as /u/, though often lowest in the inventory, tends in fact to be around 875Hz across different languages, and hardly ever reaches below 750Hz. Should those model predictions still be regarded as just as successful because a vowel labeled [u] with a relatively low F2 frequency was predicted? Or should they be regarded as inadequate, because a vowel with the appropriate F2 frequency was never predicted? Thus, although coarsely defined inventory typologies are crucial for establishing general structures the models should aspire at predicting, they are inadequate for testing gradient phonetic models if they are not assigned more precise, numerical qualities of the same type as the predictions of these models.

In her evaluation of a pre-publication version of Lindblom (1986), Ferrari-Disner (1983:4-5) expresses criticism along the same lines. In reference to Lindblom's claim that Crothers' (1978) data support his model, she asserts that "such proof [of aspects of Lindblom's model] would require more phonetically detailed data, preferably a large sample of acoustic data drawn from multiple speakers of a wide range of languages". Lindblom (1986:30) is clearly aware of this type of criticism, and comments: "Regretably, we are unable to present a comparison between predictions and facts in terms of acoustic measurements".

Substantial advancement in our understanding of the relationship between structure and realization of vowel inventories can be achieved only through the collection and analysis of a large corpus of acoustic data from many languages. It is worth mentioning that Ferrari-Disner (1983), who was the first to express this view, undertook the initiative and presented acoustic vowel data from 11 different languages, with many speakers for each, based on both existing sources and novel recordings she made herself. Unfortunately, too few scholars followed Ferrari-Disner's initiative, and although acoustic data for dozens of languages had already been available at the time, no attempt was made to translate the newly established structural inventory typologies of Crothers (1978) or Maddieson (1984) into an acoustic typology. Two initial attempts to accumulate larger corpora of cross-linguistic acoustic data and use them to analyze the relationship between structure and phonetic realization of vowel inventories have been reported in the literature. One is Livijn's (2000) brief analysis of distances between point vowels based on formant data from 28 languages, and the other is a bibliography of existing formant studies of 55 languages reported in Sonderegger (2005) but with no analyses and no follow up.

Accordingly, this dissertation constitutes the first major attempt to construct and analyze a sufficiently large corpus of acoustic studies, covering at present 320 studies and 230 different languages. Since Ferrari-Disner's (1983) work, hundreds of new acoustic studies have become available, not merely due to the 27 years of research that naturally would have yielded new studies. More importantly, the development of user-friendly acoustic analysis software has made the task of performing a descriptive acoustic study of the vowel inventory of a given language very easy. In recent years, such a study no longer requires advanced expertise in phonetics, and many fieldwork linguists today accompany their description of the vowel inventory of a language with reliable formant frequency data. The exponential growth in the volume of such studies is represented by the fact that, although formant measurements can be traced to the middle of the previous century, more than 80% of the studies included in the corpus collected for this dissertation had not been written at the time of Ferrari-Disner's dissertation in 1983.

2. Compilation of the corpus

This chapter describes the compilation of the corpus. Section 2.1 defines the scope of inventories and their representation levels. Section 2.2 describes the collection of studies and the review process. Section 2.3 discusses the classification of structural properties of inventories, which are the basis for the independent variables in dispersion-related analyses. Section 2.4 describes and illustrates how the corpus data were tabulated.

2.1 **Assumptions and scope**

2.1.1 Vowel inventory as a set of phonemes with specified phonetic targets

Virtually all dispersion-oriented models share the assumption that a language's vowel inventory is a set of phonemes with prototypical phonetic qualities, or targets. Given the default realization context and the ideal between-speaker normalization procedure, vowel phoneme targets should be realized, by all speakers sharing the same language variety, with the same phonetic quality at least at some level (probably perceptual). This assumption was standard among phoneticians, phonologists and linguistic typologists at the time when Dispersion Theory evolved. Thus, in inventory typology studies, vowel phonemes were represented by their 'major realizations' (Crothers 1978:103) or 'most representative allophones' (Maddieson 1984:162). The idea that vowel phonemes have precise prototypical percepts received empirical support in studies like Kuhl (1991) and Iverson & Kuhl (2000). In these studies, vowel exemplars subjectively ranked as more prototypical in a rating task also invoked more phonemic (categorical), rather than auditory (gradient), mode of perception in a discrimination task, implying that the phoneme as a category is associated with certain phonetic qualities more than with others within its acceptable range of realizations.

The phoneme and prototype assumption is adopted here, with the following consequences. First, the survey is limited to acoustic descriptions of prototypical realizations of vowel phonemes, as defined or implied by the study authors. Vowels identified in a given study as non-prototypical allophones, like vowels in a specific segmental context (e.g. adjacent to nasal or pharyngeal consonants) or weak prosodic context (e.g. in unstressed syllables), were excluded from the inventory and their data were ignored. Second, the acoustic realization of the prototypical allophone is assumed to be represented by average formant frequencies (or median, if reported instead). When data were reported only as formant ranges, range midpoints were used. Standard deviations and other distribution statistics were ignored.

2.1.2 Place-specified plain oral modal monophthongs

In the dispersion-oriented model tradition, vowel inventories are restricted to sets of monophthongs (no diphthongs), which are modal (no creaky, breathy or otherwise non-modal phonation), oral (no nasalization) and plain (no secondary articulation in the form of apicalization, rhoticization or pharyngealization). For example, in their typological analysis of vowel inventories appearing in Maddieson’s (1984) UPSID, Schwartz et al. (1997a) treat all plain oral modal monophthongs in a given inventory as the primary system, and all other monophthongs as the secondary (and sometimes also tertiary) system, but only the primary systems are the object of their modeling attempt in Schwartz et al. (1997b). The same practice will be followed here, and only plain oral modal monophthong data were included in the survey.

Vowels not inherently specified for place, i.e. the features front/back and rounded/unrounded, likewise stay outside the scope of most dispersion-oriented models. Such vowels often occur both under contextual neutralization of phonemic contrast, typically in unstressed syllables as in English and Dutch, and in 'vertical' vowel systems as in Marshallese and Kabardian, where according to standard analyses vowel place features are determined by the secondary articulation of the adjacent consonants. While these vowels are commonly transcribed phonemically as central unrounded, their realizations are too variable to suggest a specific phonetic target (see e.g. acoustic phonetic data of American English unstressed /ɨ/ in Flemming & Johnson 2007 and of Marshallese /ɨ/, /ə/, /ɐ/ in Choi 1992). Therefore, vertical vowel systems are excluded from this corpus, as are vowels emerging from contextual contrast neutralization. Of course, central unrounded vowels with fully contrastive phonemic status are treated as place-specified phonemes and are included (e.g. /ə/ and /ɨ/ in Romanian).

2.1.3 Quantity contrasts as orthogonal to timbre contrasts

Treatment of vowel quantity contrasts, typically between short and long vowels, has been somewhat complicated in the dispersion literature. No dispersion-oriented model has so far incorporated quantity considerations and/or dealt with quantity contrasts. At least implicitly, this means that quantity should be treated as orthogonal to timbre, and that dispersion is expected to explain only timbre contrasts within a system of vowels sharing the same quantity, so short and long vowels of the same inventory should be treated as separate systems. This approach was exercised by Crothers' (1978) analysis of his corpus. However, Schwartz et al. (1997a,b) consider the set of all independent vowel timbres in a language's inventory, regardless of whether they belong to a short or a long vowel, as timbre-contrastive. For example, the inventory of Arabic, with three short vowels /ɪ a ʊ/ and five long vowels /iː eː æː oː uː/, was analyzed in Schwartz et al. (1997a) as an eight-vowel primary system /i ɪ e æ a o ʊ u/, and as such did not contribute to the evaluation of three- and five-vowel inventory predictions in Schwartz et al. (1997b).[2]

Schwartz et al.'s (1997a) approach cannot be applied to the current corpus, where vowel timbres are represented by formant frequencies. For example, while Schwartz et al. (1997a) distinguish the eight-timbre /ɪ a ʊ iː eː æː oː uː/ inventory of Arabic from the five-timbre /i a u iː ẹː aː ọː uː/ inventory of Dagomba, it is impossible to set a priori formant frequency criteria that would treat Dagomba /iː/ and /i/ as sharing the same timbre, but Arabic /iː/ and /ɪ/ as different. The only possibilities here are either to treat all vowel timbres, regardless of quantity, as one inventory, or to split the inventory to two parallel inventories.

Formant studies of inventories manifesting quantity contrasts far more often follow the second practice, reporting formant data separately for short and long vowels, while seldom expressing the formant difference between related short and long vowels in transcription. For example, in both Norlin's (1984) and Altamimi et al.'s (2004) studies, respectively of Egyptian and Jordanian Arabic, the short vowels are transcribed as /i a u/ and the long vowels as /iː eː aː oː uː/, even though the formant data suggest that the high short vowels /i u/ are significantly lower than their long correspondents /iː uː/ and could have been duly transcribed as [ɪ ʊ]. As this

[2] Schwartz et al. (1997b) do not present inventory predictions for eight-vowel inventories.

common practice in formant studies is also consistent with the view of timbre and quantity as orthogonal, this approach was adopted here. Thus, whenever inventory data are provided separately for short vs. long vowels, the two subsets are treated as separate inventories. Quantity interpretation of inventories is explained in more detail in Section 2.3.1.

2.1.4 Adult male data

To date, all dispersion-oriented modeling studies used an acoustic vowel space of a typical adult male speaker, characterized, for example, by an F1 frequency range between 250Hz and 800Hz and an F2 frequency range between 600Hz and 2400Hz. This practice was probably adapted from the better understanding of the acoustic properties of the adult male vocal tract, on which Fant's (1960) Acoustic Theory of Speech Production has been based. Accordingly, the corpus consists exclusively of data drawn from native adult male speakers. Acoustic descriptions of vowels elicited from female speakers, children and non-native speakers are excluded.

It is worth mentioning that including acoustic data from women and children studies would have contributed very little novel typological data, because, with very few exceptions, if an acoustic description exists for a given language's inventory, then it is based on vowels pronounced by adult males (with women and children data possibly found in the same studies or elsewhere). At the same time, inclusion of data drawn from women and children would have severely complicated the corpus, due to inherent differences in the shape and proportions of the vocal tract between adult males and other populations (Fant 1975, Fitch & Giedd 1999). In addition, adult male data are often more reliable, because the lower fundamental frequency provides a greater number of harmonics, and thus a finer resolution of the harmonic spectral pattern, essentially ensuring that formant bandwidths always span at least one harmonic. In women and children's spectra, formant peaks (and at times entire formant bandwidths) might fall between the more widely spaced harmonics, which often results in miscalculations of formant frequencies by automatic algorithms. Nevertheless, future research should extend the current work to cover at least female data as well, in particular given the important role of adult female speech in language acquisition. Not less importantly, adult males are the 'marked' human population, in terms of vowel spectra, due to the male-specific vocal tract transformation at puberty. In children, anatomical differences between female and male speakers are limited, and consequently their formant patterns are similar and resemble adult female patterns (see e.g. Bennett 1981 for English child vowel data and discussion and comparative Hebrew vowel data for girls, boys, women and men in Most et al. 2000).

2.1.5 Structural configuration

The term 'structural configuration' refers to the general arrangement of the vowel phonemes in the inventory, possibly shared with other inventories. Two or more inventories that share the same structural configuration may differ in the actual phonetic symbols used to transcribe their component vowels, yet it is possible to intuitively map the inventories onto each other such that each vowel in one has its own matching vowel in the other. Thus, by definition, to be matched, the two inventories must have the same number of vowels, and these vowels should be organized in the same fashion. For example, two four-vowel inventories respectively transcribed as /i e a o/ and /i ɛ ɑ u/ follow the same configuration and allow one-to-one mapping of their respective vowels (/i/⇔/i/, /e/⇔/ɛ/, /a/⇔/ɑ/, /o/⇔/u/), even though only one pair of corresponding vowels share the same phonetic symbol.

The question of what counts as similar or different organizational configurations is a matter of subjective interpretation and its resolution. However, as mentioned in Section 1.2, a coarse division of the phonological vowel space into four regions – front, low, back and non-peripheral – is a common denominator in structure-oriented typological sources (Crothers 1978, Ferrari-Disner 1984, Schwartz et al. 1997a, Roark 2001). Inventories with the same number of vowels in each of these four regions can be treated as sharing the same structure, and it is usually possible to map each vowel in each of these inventories to its corresponding vowel in any of the other inventories. The classification of inventories into structures is described in detail in Section 2.3.2.

The importance of structural configurations is that they allow us to efficiently establish the properties of vowel inventories in the world's languages. As mentioned in Section 1.2, the ten most common structures account for 75%-80% of the inventories in both Crothers (1978) and Maddieson's (1984) UPSID. Expanding this set with the next 10-15 structures, which are not as common but still surface consistently in unrelated languages, creates a core of 20-25 structures that cover 85%-90% of attested inventories.

It is very likely that, among the 7000 languages of the world, and their many more dialects, there are hundreds of unique structures, most of which are extremely rare (at least 20 such rare structures surface once or twice in any survey of a few hundred inventories). As in the case of many other typological patterns in languages, it stands to reason to distinguish between the core of relatively few common patterns that account for the vast majority of languages, and the periphery of many rare patterns. Accounting for the entire set of patterns (inventory structures in this case) is not feasible, and universalist theories, like Dispersion Theory and its formal models, should be expected to account for the core patterns only, with the hope that this core be extended as the theory improves. It is therefore a primary goal of the current work is to establish the acoustic properties of as many structures as possible, thus creating the proper reference for evaluating present and future dispersion models.

2.1.6 Acoustic geometry

The term 'acoustic geometry' refers to absolute and relational numerical properties of the formant pattern of the inventory. Such properties may be systemic, like the span of F1 and F2 frequencies for the entire inventory, or involve one vowel or two, like the absolute F2 frequency (or its relative position within the F2 span) of the lowest vowel, or F1 difference between corresponding front unrounded and back rounded vowels.

Establishing prototypical acoustic geometries for common inventory configurations will be achieved by averaging acoustic geometries of same-structure inventories of different languages. This is analogous to the prototypical acoustic geometry of the inventory of a particular language, which is established by averaging formant data from different speakers. Pursuing this analogy further, the acoustic geometries of structural configurations may be regarded as coherent to the extent they mimic the distribution of formant data in acoustic inventory studies of acceptable standards, in terms of the number of speakers participating in the study and the standard deviations of formant frequencies.

In studies published in peer-reviewed phonetics journals in recent years, the number of speakers varies greatly, and although at least a dozen speakers are required for high reliability, 4-6 speakers appears to be sufficiently representative of a speech community (Bradlow 1995, Deterding 1997, Fourakis et al. 1998, Fulop et al. 1998, Johnson & Martin 2001, Guíon et al. 2004, Hawkins & Midgley 2005, Nishi et al. 2008, Recasens & Espinosa 2006, 2009). Standard deviations, if reported in such studies, also vary, but as a rule of thumb they are at about 10% of the formant frequencies. For example, Escudero et al.'s (2009) study of Portuguese vowels describes a novel method that substantially reduces formant estimation errors, in order to reduce standard deviations in multiple-speaker data to about 8% of the frequencies. Thus, applying the same criteria to structural configurations, acoustic geometries based on five different languages or more, and with average formant standard deviations of around 10% (typically 50Hz for F1, 150Hz for F2), may be regarded as sufficiently coherent.

It is important to note that the corpus is not confined to inventories manifesting common structural configurations, and covers many additional inventories, which share their structures with very few other inventories or none at all. Such inventories are included and participate in various dispersion-oriented analyses that target general structural properties, like the effects of the number of vowels or front-back asymmetries on properties of acoustic geometries.

2.2 Data collection

2.2.1 Sources and review

As mentioned in Section 1.4, there are studies of formant data available for hundreds of languages, written by scholars of varying degrees of phonetic expertise and experience, and available in many types of publication venues. However, for the corpus to be as comprehensive as desired, it has to include as many studies as possible, as long as their formant data appear reliable. Screening studies based on other criteria (e.g. studies with five speakers or more, published in an international peer-reviewed journal etc.) would result in a corpus too small to allow either the establishment of reliable cross-linguistic geometries or meaningful statistical analyses.

In an attempt to accumulate the largest possible corpus of studies, a systematic keyword-based search was carried out for relevant papers, monographs, theses, squibs etc., covering (a) all international phonetic journals, (b) working-paper periodicals of phonetic labs, (c) proceedings of phonetics conferences, (d) all journals of general linguistics, areal linguistics and working-paper periodicals listed on the LinguistList, (e) the Linguistic and Language Behavior Abstract database, (f) dissertation and thesis databases, (g) the Melvyl inter-library catalog of the University of California[3], and (h) the World Wide Web. Additional search initiatives included (a) following relevant references in studies already collected, (b) a LinguistList query asking readers to send papers or references, (c) contacting scholars who had written papers or books that seemed relevant but were inaccessible, and (d) sporadic yet intensive search through grammar books and dialectology or philology journals available at the UCLA library.[4]

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[3] The University of California Melvyl inter-library search system was used for systematic searching books on languages for which no acoustic study had been found. One Melvyl query looked for titles listed under the subject 'phonetics'. Another set of hundreds of queries looked for titles listed under 'subject: X', where X is a language belonging to a language family for which little data had been found. Among the thousands of items returned by these queries, any item whose title indicated that it was dedicated to the phonetics of a specific language (or languages), and which was available, either from the UCLA library or via a successful inter-library loan request, was individually inspected in search for formant data.

[4] The various searches and queries were tried not only in English but in many other languages as well, and titles found were inspected regardless of the languages in which they were written. In this regard it

Although the goal was to use as many studies as possible, some studies were excluded. One reason for exclusion was that it was impossible to obtain formant data for adult males, either because the study did not use adult male speakers at all, or because the reported data from males and females (or adults and children) were pooled together. Another reason was if formant data were available only for some vowels, but not the entire inventory (e.g. studies describing only the behavior of the point vowels /i a u/ in various contexts). However, coverage of only one quantity constituent of a quantity-contrastive inventory (e.g. a study of only the long vowel phonemes) was acceptable. Absence of data for one vowel phoneme in the inventory was also accepted, and the missing vowel was still recognized as part of the structure of the inventory, only without acoustic data (this never happened with inventories with less than five vowels). Yet another reason for exclusion was if the study described only non-prototypical vowels, like unstressed vowels, nasalized vowels, pharyngealized vowels, breathy vowels etc.

Probably the most important and most robust criterion for exclusion was the reported formant data. Although great leniency was exercised and somewhat atypical formant frequencies were generally tolerated, highly implausible data were rejected. Examples of excluded inventory descriptions are (a) an inventory whose entire F1 span was only 100Hz, (b) inventories with front vowels whose F2 frequencies are below 1300Hz, or back vowels whose F2 frequencies exceed 2000Hz and so on, (c) inventories where the F1 frequency of /i/ is higher (or the F2 frequency of /i/ is lower) than that of /a/, (d) inventories whose formant data are reported only in frequency

is worth noting that, thanks to the rather consistent structure and technical nature of formant study reports, and to the availability of online dictionaries for many languages, it was relatively easy to inspect, understand and retrieve the relevant details from reports written in almost any language.

ranges, and these ranges cover most of the vowel space (e.g. F1 of /i/ between 200Hz and 700Hz, F2 of /e/ between 1000Hz and 2700Hz), (e) inventories whose F1 data seemed appropriate for typical adult males (200Hz<F1<900Hz) but their F2 data often reached child-like frequencies (F2>3000Hz). If data seemed flawed for only one vowel, the study was accepted and this particular vowel was ignored (treated like a vowel whose data were missing). Also, in principle, if a study with apparently flawed formant data explicitly addressed those peculiarities, it would have been included, but this never happened. Independent corroboration of apparently peculiar data was also sufficient. One concrete example is the existing formant data for Kazakh. In two independent studies of Kazakh (Kenesbaev et al. 1969 and Dzhunisbekov 1972), /i/ was at the same height (same F1 frequency) and more retracted (significantly lower F2 frequency) than /e/. The formant frequencies of /i/ in these studies suggest that this vowel is a higher-mid central vowel, and that there is in fact no [i]-like vowel in Kazakh at all, a feature never otherwise attested in inventories with more than three vowels (Kazakh has nine). Nevertheless, once the two independent studies were found to corroborate each other, both were included.

Special attention was given to understanding the elicitation method, or the procedure by which speakers were prompted to pronounce vowels in each study. Five different elicitation methods were identified: sustained isolated vowels (*isolation*), vowels embedded in isolated words (*wordlist*), vowels embedded in words placed in a constant sentential framework (*carrier sentence*), vowels embedded in words placed in a variable, and meaningful, sentential framework (*meaningful sentence*) and vowels pronounced as part of speech flow, which may be a read passage or spontaneous conversation (*running speech*).

Elicitation methods differ in the speech rate they impose on the utterances and on the test vowels embedded in them, in the segmental and prosodic contexts in which the test vowels are placed and in speakers' awareness of the purpose of the study. All of these aspects affect the pronunciation of vowels and, consequently, their acoustic qualities. As a result, inventories studied using different elicitation methods cannot be compared without minimizing the inherent acoustic effects of elicitation methods. In order to devise a procedure for minimizing elicitation method effects, multiple studies of the same inventory in different elicitation conditions were very valuable, and even more valuable were certain studies where multiple methods were used for eliciting the same inventory with the same speakers. For this reason, formant datasets from different elicitation methods in such studies were included separately in the survey. Section 3.3 describes elicitation method normalization in detail.

Of course, the segmental material surrounding the target vowels is not less important than elicitation method. F2 frequencies are particularly sensitive to co-articulatory effects of adjacent consonants. However, as the vast majority of studies elicit vowels in naturally occurring words, perfect control of segmental context is seldom possible and is often not taken into account in the first place, as in studies of running speech or studies based on words elicited as part of language documentation fieldwork. Moreover, even those studies where such segmental material is fully controlled do not agree on the identity of the segmental context. For example, while nearly all studies of the vowels of English use a /h_d/ immediate context, and the virtually identical /h_t/ context was used in Pols et al.'s (1972) study of Dutch, Ferrari-Disner (1983) used a /d_d/ context for her Norwegian data (and other contexts for other languages), Fourakis et al. (1999) chose a /p_s/~/p_ts/ context for Greek vowels, Most et al. (2000) elicited Hebrew vowels in a /p_p/ context, and Adank et al. (2004, 2006) and Escudero et al. (2009) preferred vowels flanked by coronal sibilants in their studies of Dutch and Portuguese vowels. Thus, given the unlimited variability of segmental context across studies, this aspect was neither taken into account in the review process nor in the data normalization procedures.

After the review process, 320 studies remained, covering 447 inventory instances of 230 languages (with independent ISO 639-3 codes).

2.2.2 Language coverage

Since a primary goal of the survey was to accumulate as many formant studies as possible, no selection was made according to genetic or geographical basis. Thus, unlike the typological studies of Crothers (1978) and Maddieson (1984), language coverage in the corpus is not typologically representative. Table 2-1 summarizes the geographical distribution of languages and inventories covered in the corpus, in absolute numbers and proportions, as well as the proportional geographical distribution of the world's languages according to Ethnologue (2010).

Continent	**languages**	**inventories**	**Ethnologue (2010)**
Languages of Africa (including Maltese, excluding Afrikaans and colonial languages)	70 (30%)	84 (19%)	30%
Indigenous languages of the Americas	35 (15%)	38 (9%)	15%
Languages of Asia (including Caucasian languages and non-Indo-European languages of Russia, excluding Turkish, languages of Indonesia and indigenous languages of Taiwan)	53 (23%)	104 (23%)	23%
Languages of Europe (including Afrikaans, Turkish, Yiddish and European languages in other continents, excluding Maltese and non-Indo-European languages of Russia)	52 (23%)	199 (44%)	3%
Indigenous languages of Oceania (including languages of Indonesia and indigenous languages of Taiwan)	20 (9%)	22 (5%)	29%
World	**230**	**447**	

Table 2-1: Geographical (continent-based) distribution of languages and inventories in the corpus.

Clearly, the geographical distribution of languages covered is skewed. While African, American and Asian languages are represented proportionally to their respective share of the world's languages, European and Oceanic languages are respectively over- and under-represented. This typological skew is probably less extreme as suggested by language coverage, because vowel inventory is often more a function of dialect rather than language, and European languages tend to have many dialects, whereas most languages of Oceania are limited to very small speech communities with one or very few dialects. Nevertheless, for a more typologically representative distribution, the numbers of European and Oceanic languages included in the survey should have been reversed.

The skew towards European languages, which is even more pronounced in the distribution of inventories, is only of minor concern. First, multiple studies of better studied languages are of great importance, because, as will be seen in Sections 3.1-3.3, they are crucial for the normalization procedures devised and applied on the survey data as part of its preparation for analysis. At the same time, multiple studies for the same language affect the analyses very little because, as will be explained in detail in Section 3.5, all inventories pertaining to the same language and sharing the same structure are collapsed into one data entry prior to the analyses. Third, it has to be kept in mind that the purpose of this survey is not to establish a typology of inventory structures, but to take such structures as given and establish their prototypical acoustical geometries. As such, the relative structural diversity of European inventories results in a contribution well distributed between the various structural configurations, while very few structures are dominated by European languages. In the cross-structure analyses that might be sensitive to the European bias, this bias will be taken into account (Section 4.6.2).

The skewed distribution of languages and inventories is nevertheless lamentable because certain structures that are rare in Europe but common elsewhere are poorly represented. For example, the four-vowel structure with one front, one low, one back and one non-peripheral vowel (e.g. /i a u ə/), which is common in e.g. indigenous languages of Australia, Papua and Canada, is represented in the survey by only seven languages. It is hoped that, as many more formant studies of presently less-studied languages are accumulated, future versions of this survey or its like would represent such structures more comprehensively.

2.2.3 Processing and modifying source data

For the majority of studies, formant data and additional information about an inventory were registered into the survey unchanged. However, many studies required corrections, described in this section. As such, the survey data should be viewed as 'based upon' the studies covered, rather than as entirely faithful to their original data.

The primary source for corrections and modifications of original data was the study authors themselves.[5] An attempt was made to contact the author(s) of every study published since 1990, whose data appeared to be limited, inconsistent or otherwise unsatisfactory for the purposes of the survey. Authors were contacted in order to obtain clarifications (about the language, methodology, peculiar results,

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[5] I would like to again express my gratitude to each of the following authors: Patti Adank, Kofi Adu Manyah, Coleen Anderson-Starwalt, Rima Bacevičiūtė, Ocke-Schwen Bohn, Mike Cahill, Janet Fletcher, Bryan Gick, Juris Grigorjevs, Susan Guíon, Gwendolyn Hyslop, Shinji Ido, Antti Iivonen, Vladimir Ivanov, Eric Jackson, Peter Jurgec, Phil King, James Kirby, Yerraguntla Krishna, Robert Mayr, Sylvia Moosmüller, Daniela Müller, Mary Pearce, Bert Remijsen, Carlo Schirru, Patrycja Strycharczuk and Peter Trudgill.

possible typos, verification of crucial contents of a study written in a foreign language etc.), additional formant data (partitioning of male and female speakers, F1 and F2 frequencies in numerical form when the text had only charts, formants above F2, formant frequencies for additional speakers etc.), and even the raw data (original numerical measurements and/or original recordings). Whenever data were modified as a consequence of correspondence with the authors, this fact was noted by adding "personal communication" to the source reference registered for these data.

In some studies, the original data were modified without correspondence with the authors, as the data in the study were perfectly satisfactory except for their form of presentation. Some studies reported formant data individually for different participants, for different phonetic contexts, or for individual recordings, with no general summary. For such studies, it was necessary to calculate the average formant frequencies, and if the data of a participant, a particular phonetic context or even one token had to be excluded due to implausible formant frequencies, the calculated averages are no longer transparently derived from the original data. Some studies reported individual participant data as well as average data pooled from both male and female participants, or specific segmental context data as well as average data pooled from stressed and unstressed syllables together. In such cases, average formant frequencies had to be re-calculated only for male participants or stressed syllables, yielding values that differ from those appearing in the original summary. Certain studies reported formant data in scales other than Hz (Bark, Mel etc.), and/or in terms other than absolute values (e.g. F2-F1, F3-F2), making it necessary to perform certain arithmetical conversions in order to obtain absolute formant frequencies in Hz. A few studies reported formant frequency ranges, rather than average frequencies. Range midpoints were interpreted as average frequencies in such cases. In various studies, the entire formant report was satisfactory except for local oddities that were most likely the result of a superfluous formant, e.g. F3 frequencies lower than 1800Hz for back vowels, or a missing formant, e.g. F2 frequency of /i/ close to 3000Hz (when F2 for /e/ is below 2000Hz and all other formant frequencies are typical for adult males). Superfluous formants were ignored, while in the case of missing formants, existing formants were interpreted as formants of higher order (so F2 at 3000Hz was interpreted as F3), leaving a blank placeholder for the missing formant.

Many studies do not provide formant data in numerical form, but only as coordinates on charts. In most of these studies, it was impossible to obtain the original numerical data from the author(s), and formant frequencies had to be graphically estimated from the charts. This process, which was performed carefully either by graphical software or by ruler and pencil, involved magnifying the charts, adding finer notches to the scales along the axes, determining the precise position of the vowel on the chart (e.g. the center of the symbol or of the ellipse), and obtaining coordinates of points relative to the axes. Coarsely marked data points (e.g. standard-deviation ellipses or arbitrary-size shapes), coarse, non-linear and/or irregular scaling of the axes, overlapping data markers and other graphical obstacles may have occasionally degraded the accuracy of the estimates, and it can never be known with certainty that the charts were faithful to the original numerical data in the first place.

2.3 **Structural Classification**

2.3.1 Splitting inventories into quantity-contrastive constituents

As mentioned in Section 2.1.3, the corpus should be constructed so as to represent spectral contrast in inventories, which is viewed as orthogonal to quantity contrast. It was therefore necessary to split entire inventory data into quantity-contrastive constituents whenever relevant. In the vast majority of inventories, such division is either non-existent, in which case the inventory has only one constituent of *uniform* quantity, or explicit, that is, the inventory consists of *long* vs. *short* vowels.[6] In the latter case, most studies provide separate reports for either constituent of the inventory (or only report one and ignore the other), but in certain inventories, where the two constituents are structurally identical, some studies report the data in a *combined* form, with long and short variants pooled together. Such combined-constituent inventories were registered in the survey unsplit.

There were also a few inventories where between-vowel contrasts are based on a combination of quantity and quality. Though a small minority, some of these inventories, in particular those of American English and Dutch, are represented by many studies. Such inventories were interpreted as split between long and short constituents if the study explicitly suggested this split, and as a single constituent of *mixed* quantities otherwise. Explicit indication of short-long split could be (a) contrastive length marks in the transcription of the vowels, (b) anywhere in the text,

[6] Three languages covered in the survey, Estonian, Võru and Southwestern Dinka, have inventories with tertiary quantity contrast – short, long and overlong. In Estonian, Southwestern Dinka and one dialect of Võru it was possible to merge long and overlong subsets, because they had the same structures and nearly identical formant frequencies. Only in Navi Võru the long and overlong had to remain split.

or (c) dichotomously-split vowel duration data. If duration data were controlled and reported, and suggested a clear split between phonetically long vs. phonetically short vowels, such a split was preferred over a different, phonologically motivated split.

This approach is best explained by the specific example of North Midwestern American English vowels, as described in Hillenbrand et al. (1995). According to their data, the vowels /ɛ/ and /æ/ have near identical acoustic qualities (/ɛ/: F1=580Hz, F2=1799Hz, F3=2605Hz, F4=3677Hz; /æ/: F1=588Hz, F2=1952Hz, F3=2601Hz, F4=3624Hz). Phonologically, the two vowels are considered short, as neither can appear word-finally in English. Phonetically, however, /ɛ/ is the second shortest vowel (189ms) and belongs to a set of four short vowels /ɪ ɛ ʌ ʊ/, whose average durations are virtually identical (188-192ms). Conversely, /æ/ is the second longest (278ms), and belongs to the set of long vowels /i e æ ɑ ɔ o u ɝ/, which occupies a range of durations between 237ms and 283ms. Such data leave little room for doubt that /ɛ/ and /æ/ are distinguished primarily by duration, which also explains how the fractional spectral contrast between these two vowels is tolerated. This perhaps 'unorthodox', yet well motivated, duration-based division of American English into long vs. short constituents, is balanced by other studies of American English (e.g. Peterson & Barney 1952), where there are neither duration data nor any other reference to quantity differences, and so the inventory was interpreted as a single quantity constituent.

Out of the original 447 inventories in the corpus, 108 were split into two quantity-contrastive inventories, making the total number of listed inventories 555.

2.3.2 *Discerning structural configurations*

The 555 inventory constituents had to be classified to structural configurations. As already mentioned in Section 2.1.5, structural configuration refers to the distribution of the vowels in the inventory along the division of the vowel space into four coarse regions: front, low, back and non-peripheral.

This particular division of the vowel space is motivated not only by its use in previous studies of vowel inventory typology (Crothers 1978, Roark 2001), but also by the basic tendencies of vowel inventory structures. With few exceptions, most of which involve vertical systems where vowel phoneme targets are only partially defined, all the vowel inventories in the world's languages have at least one front (unrounded) vowel, at least one (and typically at most one) low vowel and at least one back (rounded) vowel. With very few exceptions among these inventories, the number of front vowels and the number of back vowels in any given inventory are balanced: they are equal, or differ by at most one. Both sets of vowels are organized as vertical series, with F1 frequency as the major acoustic correlate of contrast in the series.

Although non-peripheral vowels come in many forms, it is sensible to group them together for two reasons. First, they are relatively rare, such that further dividing them would not yield sufficiently frequent patterns across languages. Second, in inventories with seven or more vowels, where the co-occurrence of two or more non-peripheral vowels is common, the non-peripheral vowels often form a third vertical series between the front-unrounded and back-rounded vowels. The non-peripheral vowels usually agree in frontness and rounding and differ in height (significant F1 frequency difference), and even when they differ in frontness and/or rounding, height is still the major dimension of contrast between them.

As far as low vowels are concerned, it was decided that each inventory, without exception, would be interpreted as having exactly one low vowel, the vowel with the highest F1 frequency. In inventories with two low vowels, the low vowel with the lower F1 frequency was forced into either the front or back region, according to its F2 frequency relative to the lowermost vowel. In many cases, this forced an classification as asymmetrical upon inventories whose front and back regions are in fact symmetrical. For example, in studies of the Finnish inventory /i e æ ɑ o u y ø/, low front /æ/ is forced into the front region, and the entire inventory is forced into a structure with three front vowels and two back vowels, essentially the same as the structure of the German long vowel inventory /i e ɛ a o u y ø/.

This approach might do injustice to inventories with two low vowels (like Finnish), but unfortunately no objective criterion or threshold could be established for distinguishing inventories with two low vowels from inventories with one low vowel, either according to transcription symbols or according to F1 frequencies or frequency differences. For example, in Kaukeniene's (2004) study of the inventory of Standard Lithuanian, the difference between the lowest vowel /a/ and second lowest /æ/ is 100Hz for sustained isolated vowels, which is sufficient for treating /a/ as a single low vowel, but in wordlist elicitation with the same speakers the difference shrinks to merely 20Hz. While a vowel transcribed as /a/ nearly always has an F1 frequency much higher than a vowel transcribed as /e/, in Pharris' (2006) study of Molalla, long /e/ has a higher F1 frequency than long /a/.

Moreover, both peripherally-symmetrical inventories with two low vowels and peripherally-asymmetrical inventories with one low vowel are relatively infrequent. In most of the structural configurations in question, distinguishing between these very similar structure types would result in the different structures being represented by less than the required minimum of five languages. The decision to merge such structures may be understood as similar, in both nature and purpose, to the decision to group all non-peripheral vowels as one region. Nevertheless, in certain cross-structural analyses sensitive to the status of peripheral symmetry (Sections 4.3.2 and 4.3.3), the possible symmetrical interpretation of inventories with two low vowels will be taken into account.

Assigning a given inventory's vowels to the four regions was done using IPA transcription symbols. In studies where a different annotation system was used (e.g. orthography or a language-specific scholarly convention), annotations were converted to IPA symbols first, based on other descriptive sources on the language. However, the IPA symbols, regardless of whether they appeared in the study or were applied as interpretation based on other sources, were inspected for their acoustic qualities. If the two were incompatible, they were re-interpreted with a different IPA symbol. For example, in the many dialects of English where the vowel transcribed as /u/ had too high F2 frequencies for a high back rounded vowel (e.g. F2>1250Hz, often more than 400Hz above lowest F2 frequency in the inventory), it was re-interpreted as /ʉ/, or even /y/ when necessary. Table 2-2 describes the coarse-region interpretations of vowels as a function of transcription symbols and formant information.[7]

[7]It should be noted that, at the time of writing, a careful scrutiny of the corpus revealed about 20 odd cases, out of 3755 vowels in the entire corpus, where vowel interpretation was inconsistent with the criteria described above. These inconsistencies involve interpretation of front-unrounded or back vowels as non-peripheral and vice versa, and they occurred almost exclusively either with vowels properly transcribed as /ɪ/ or /ʊ/, whose peripheral status is ambiguous to begin with, or vowels in the half-back region transcribed as /u/ or /ʌ/ (in particular in some studies of varieties of English). Such inconsistencies have resulted in inappropriate structural interpretation of their respective inventories, because every incorrectly interpreted vowel changes the distribution of vowels between the four regions of the vowel space. Since it was too late to perform all structure-based analyses using corrected interpretations, the analyses reported in this paper are affected by these inconsistencies, but these effects should be very slight and random.

IPA	Region	Exceptions
i ɪ e	Front	Non-peripheral, if clearly indicated by absolute and relative formant frequencies, as in the case of Kazakh /i/ described in Section 2.2.1.
ɛ æ	Front	Low, if the vowel had the maximal F1 frequency in the inventory.
a	Low	Back, if there was /æ/ with higher F1 frequency, in which case /a/ had to be interpreted as /ɑ/ or /ɒ/ in the first place, due to too low F1 frequency and/or too small F2-F1 difference.
ɑ ɒ	Back	Low, if the vowel had the maximal F1 frequency in the inventory.
ɔ o ʊ u	Back	Non-peripheral, if clearly indicated by absolute and relative formant frequencies, as in the case of English /u/ in many studies.
y ʏ ø œ ɶ ʉ ɵ ɞ ɨ ɘ	Non-peripheral	None.
ə ɜ ɐ	Non-peripheral	Low, if the vowel had the maximal F1 frequency in the inventory.
ɯ ɤ	Non-peripheral	Back, if F2 was very low in absolute value (e.g. F2<1100Hz) and relative value (within 150Hz from the minimal F2 frequency), and the vowel did not contrast with a back-rounded vowel of the same height.
ʌ	Non-peripheral	Low, if the vowel had the maximal F1 frequency in the inventory. Back, if F2 was sufficiently low (<1250Hz) and the vowel did not contrast with a back-rounded vowel of the same height.

Table 2-2: Interpretation of vowels into vowel-space regions as a function of IPA symbol and formant frequencies (the word 'inventory' refers to quantity-specific inventory constituent whenever relevant).

With all their vowels attributed to the four regions, inventories were assigned structure labels, based on the following nomenclature:

- The number of peripheral vowels.
- The balance between the front and back regions:
    - "S" = symmetrical, the same number of front and back vowels.
    - "L" = left-crowded, more front vowels than back vowels.
    - "R" = right-crowded, more back than front vowels.
- The number of non-peripheral vowels.

For example, 5S0 stands for an inventory with a symmetrical periphery of five vowels with no non-peripheral vowels, e.g. Spanish /ie-a-ou/, 6L2 stands for an inventory with a left-crowded six-vowel periphery and two non-peripheral vowels, e.g. German /ieɛ-a-ou-yø/, and 10R4 stands for an inventory with a right-crowded ten-vowel periphery and four non-peripheral vowels, e.g. Northern Khmer /iɪeɛ-a-ɒɔoʊu-ɯɤəʌ/. Since there is always one low vowel, peripherally-symmetrical inventories can only have odd-numbered peripheral vowels. Even-numbered peripheries are always asymmetrical, with their more crowded side outnumbering the other side by one vowel. In the very few inventories with odd-numbered asymmetrical peripheries, the more crowded side outnumbers the other by two vowels.

In a few odd cases it was necessary to denote fundamentally distinct configurations of multiple vowels in the non-peripheral region, and therefore a letter index was added. There are many hypothetical arrangements for three or more non-peripheral vowels, but in practice, only a distinction between a vertical series and one other configuration was ever necessary, represented respectively by the indices ‘a’ and ‘b’. For example, 7S3a denotes a structure with a non-peripheral vertical series, as the Standard French /ieɛ-a-ɔou–yøœ/, while 7S3b denotes a structure with a non-peripheral triangle, like the (Old) Seoul Korean /ieɛ-a-ʌou–yøɨ/.[8]

Table 2-3 lists the inventory structures occurring in five languages or more in the survey. For the individual languages for these and other structures see Appendix B.

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[8] In this regard, it is worth noting that inventories were also interpreted according to the number of sonority (height) and chromaticity (frontness and rounding) degrees. There have been various inconsistencies during this process, which tries to artificially tabularize a non-square structure, and so this interpretation is not described here further and is not used in the analyses. Nevertheless, information registered as part of this process was helpful, when it was necessary to distinguish certain structures that would otherwise be labeled the same, as in the case of Standard French (three chromaticity degrees) vs. Old Seoul Korean (four chromaticity degrees).

structure	languages	inventories	structure	languages	inventories	structure	languages	inventories
3S0	20	29	5S2a	14	38	7S1	6	9
3S1	7	12	6L0	8	16	7S2	12	22
4L0	7	12	6L1	8	14	7S3a	5	11
4L1	7	20	6L2	9	23	9S0	12	15
5S0	42	92	6R0	12	22	9S1	8	10
5S1	26	32	7S0	34	64			

Table 2-3: Generalized inventory structures that occurred in five or more different languages in the survey, with the number of languages and the number of inventories in which each structure is represented.

Finally, inventories that participate in robust vowel harmony patterns, in particular ATR, pharyngealization or register harmony, received special attention. Such inventories are split into two subdivisions, and their most characteristic phonological behavior is that, in the same word, all vowels belong to the same subdivision. Phonetically, one subdivision is typically shifted down and/or back relative to the other. Transcription conventions for such inventories often manifest neither the split nature of such inventories nor the systematic positional relationship between the two subdivisions, and label all the vowels as if they belong to a single-division inventory. The systemic properties of such split inventories are too language-specific, and are further complicated when the split is incomplete (e.g. when the two subdivisions share one vowel) or when one subdivision has more vowels than the other. Therefore, it was impossible to devise a unique procedure of structural classification for such inventories. It was nevertheless important to mark these inventories as inherently different even though they were classified in the same manner as others. This was done by a binary indication, for each inventory, whether or not its vowels participated in robust vowel harmony patterns, as indicated by the study itself or by other descriptive sources about the language.

2.3.3 *Multiple classifications of the same inventory*

At times, interpreting multiple studies of the same inventory (same language, same dialect) yielded different structures. One study may have explicitly distinguished long from short vowels in a mixed-quantity inventory, leading to interpretation as two smaller inventory constituents (e.g. American English in Hillendbrand et al. 1995), while another ignored it altogether, and the inventory was consequently interpreted as one large constituent (e.g. American English in Peterson & Barney 1952). Vowels that were treated as monophthongs in one study may have been treated as diphthongs in another (e.g. /e/ vs. /eɪ/ in American English). Vowels that were treated as distinct in one study may have been treated as merged in another (e.g. /ɑ/ vs. /ɔ/ in American English). A vowel with unclear phonemic status (e.g. /ɨ/ in Russian) may have been included as a phoneme in one study but treated as an allophone in another.

The approach chosen here is simple and straightforward: If an inventory can be interpreted and classified in more than one way, then all clasifications are valid, and the same language thus may participate in different structural configurations. In the case of near-merger of two vowels, which, in some studies, was the motivation for research in the first place, the decision regarding the interpretation of the vowels as merged or split (and hence of the number of vowels in the inventory and its structure) depended on the conclusions of the authors.

2.4 **Data registration**

The corpus data were registered in an Excel file as ‘entries’, where each entry is a single description of a quantity constituent of an inventory (often the only constituent) in a given study.[9] Following are the details registered for each entry:

a) Language information: ISO 639-3 code; language name; dialect name (if available); genetic lineage of the language as appearing in Ethnologue (2010).
b) Source information: Reference; number of speakers and elicitation method (isolation, wordlist, carrier sentence, meaningful sentence or running speech).
c) Structure information: Quantity constituent (uniform, long, short, combined or mixed); number of vowels; structure label; number of sonority degrees; number of chromaticity degrees; a binary indication of robust vowel harmony in the language.
d) Vowel information: original vowel symbol; IPA interpretation of the vowel symbol; F1 frequency; F2 frequency; F3 frequency; F4 frequency (means across all speakers).

Appendix A lists the 555 survey entries, grouped by language. Each entry appears with the dialect name, source reference, elicitation method, quantity constituent, structure label and elicitation method. Table 2-4 illustrates one of the 555 entries, based on Teodorescu’s (1985) study of the vowels of Standard Romanian.

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[9] The registered corpus data are available at the following URL:
http://www.linguistics.ucla.edu/faciliti/facilities/databases/databases.html
In several entries, unpublished or corrected formant data received from authors via personal communication were omitted from this publicly available file per authors' request.

Language info:	ISO 639-3: **ron** Language: **Romanian** Dialect: **Standard**							
	Genetic affiliation: **Indo-European > Italic > Romance > East Romance**							
Source info:	Reference: **Teodorescu, M. (1985). Descrierea acustica a vocalelor din limba romana literara.** ***Studii şi Cercetari Lingvistice*** **36:463-477.**							
	No. speakers: **3** Elicitation method: **wordlist**							
Structure info:	Quantity: **uniform** No. vowels: **7** Structure: **5S2a**							
	Robust vowel harmony: **no** No. sonority degrees: **3** No. chromaticity degrees: **3**							
Vowel info:	Original symbols:	**i**	**e**	**a**	**o**	**u**	**î**	**ă**
	IPA interpretations:	**i**	**e**	**ɐ**	**o**	**u**	**ɨ**	**ə**
	F1:	**232**	**443**	**657**	**465**	**260**	**260**	**495**
	F2:	**2123**	**1823**	**1217**	**805**	**695**	**1533**	**1388**
	F3:	**2768**	**2547**	**2333**	**2250**	**2035**	**2208**	**2390**
	F4:	**---**	**---**	**---**	**---**	**---**	**---**	**---**

Table 2-4: A registered entry in the survey, based on Teodorescu's (1985) study of the vowels of Standard Romanian.

3. Data normalization and transformation

For the purpose of meaningful analyses, the raw formant data of the 555 registered inventories had to be normalized and brought to the same frequency ranges. In particular, statistical noise introduced by variable vocal tract size of speakers and by variable elicitation methods had to be reduced. Such formant frequency manipulations rely on spatial reference points, typically at the center of the vowel space. Section 3.1 describes the *universal centroid*, a reference point devised for the purpose of vocal tract normalization across inventories, which is described in Section 3.2. Elicitation method normalization is discussed and described in Section 3.3. During the normalization process, whose ultimate goal was to reduce variance of F1 and F2 frequencies within cross-linguistic structures, higher formant data (F3 and F4) were lost (if present in the first place). For certain vowel types these formants (F3 in particular) are important perceptually and combine with F2 to create F2' (the *effective second formant*), a key concept in the vowel perception and inventory dispersion literature. Section 3.4 describes two models derived statistically from the raw data, one estimating F3 frequencies based on F1, F2 and vowel type (Section 3.4.2), and the other estimating F2' based on F1, F2 and F3 (Section 3.4.3). These models are applied to the normalized vowel data, making them more suitable for dispersion-oriented analysis. Section 3.5 describes a procedure that merges different entries belonging to the same language, and sharing the same structure, into one data point for statistical analyses, thus reducing the bias towards better studied languages. The result of the entire process is a set of 304 language-specific, structure-specific, normalized acoustic geometries, most of which are further grouped into *cross*-linguistic, structure-specific average acoustic geometries.

Section 3.6 highlights certain properties of the cross-linguistic acoustic geometries in the context of inventory structure typology established in the literature in the past.

3.1 Centroids and the Universal Centroid

3.1.1 Linear vs. logarithmic centroid

The centroid is the set of average frequencies in Hz for each formant, calculated from all the vowels in the inventory, and is a key concept in normalization procedures, as it is supposed to represent a point of constancy in the inventory. Not only does the centroid result from a balance between all vowels, but it is also close to the center of the acoustic space, which is characterized by lower articulatory effort (ten Bosch 1991a,b), and in particular it is often close to the uniform-tube schwa, which is commonly regarded as a neutral and effortless vowel (see e.g. Ladefoged 1996:116, Johnson 2005:103). The correlation between articulatory effort and acoustic peripheralization (or articulatory laxness and centralization) implies that vowels in the center of the acoustic space, and the centroid among them, should be more stable than peripheral vowels across circumstances imposing different constraints on articulatory effort, in particular elicitation methods (de Graaf & Koopmans-van Beinum 1984).

The association of centroid with articulatory and acoustic stability has also led to its use as an anchor in standard vocal tract normalization algorithms. Both Lobanov's (1971) and Nearey's (1978) between-speaker normalization methods use speakers' centroids as anchor points. The major difference between the two methods is the scale: linear centroid in Lobanov (1971) vs. logarithmic centroid in Nearey (1978). However, the centroid is very sensitive to the details of the inventory's acoustic geometry, and can therefore serve for normalization only if geometry constancy can be assumed, i.e. normalization within the same language (Ferrari-Disner 1980). Hence neither Lobanov (1971) nor Nearey (1978) nor any other centroid-based normalization method can be used for normalization across languages, which requires an alternative, geometry-insensitive centroid-like entity as an anchor. Nevertheless, the properties of such an entity are most likely to be found through cross-inventory averaging of inventory-specific centroids, which can also be used in within-language normalization. It is therefore important to determine first which type of centroid should be used, according to some measure of stability.

Since centroids are inventory-dependent, their stability can be assessed only across different instances of the same inventory. A natural test case is therefore stability of the centroid of the same inventory, and preferably based on data elicited from the same speakers, but across different elicitation methods. Stability will be measured based both on the absolute formant frequencies of the centroid and on the position of the centroid relative to the entire spatial geometry of the inventory. A useful simplification of the latter measure, which can be applied to any inventory regardless of number of vowels and structure, is the stability of the relative position of the centroid formant frequencies within the formant spans (maximum value – minimum value). Since more vowel categories provide better sampling of the acoustic space, inventories that had been split to separate corpus entries for their short and long vowel constituents were merged, and centroids and formants spans were calculated from all the vowels in the two quantity constituents combined. At the absence of other common calculations of centroids, the choice of the more stable centroid calculation will be limited to Lobanov's (1971) linear calculation and Nearey's (1978) logarithmic calculation.

In order to compare centroid behavior across elicitation methods under the tightest control, matched-paired t-tests were performed, using pairs of entries belonging to the same language and sharing the same structure but differing in elicitation method (the independent variable). Entry pairs based on studies comparing formant data for the same speakers across elicitation methods were preferred and chosen whenever possible. The dependent variables were the following linear and logarithmic centroid indices: F1 frequency, relative position within F1 span, F2 frequency and relative position within F2 span. Relative position within span was calculated as follows:

(3.1) $F_{C\text{-}REL} = (F_C - F_{MIN})/(F_{MAX} - F_{MIN})$.

Notice that, in these t-tests, significant difference implied centroid *instability*. There were five pairs of elicitation methods with enough same-language pairs to allow meaningful t-tests: isolation vs. wordlist (15 pairs), isolation vs. carrier sentence (8 pairs), wordlist vs. carrier sentence (18 pairs), wordlist vs. meaningful sentence (14 pairs) and wordlist vs. running speech (15 pairs). Thus the total number of t-tests was 40 (5 elicitation method pairs x 4 centroid indices x 2 scale types). Following Bonferroni correction, the significance threshold was set at $p<0.00125$ (=0.05/40). At this low threshold, none of the 40 t-tests yielded a significant centroid difference as a function of elicitation method difference, but the linear centroids were slightly more consistent, in that only three out of the 20 tests were near-significant ($0.02<p<0.05$), whereas six of the 20 tests for logarithmic centroids were near-significant ($p<0.05$), including two at $p<0.01$.

In order to confirm the apparent superiority of the linear centroid, unpaired t-tests were performed, comparing all four centroid indices for all possible ten pairs of elicitation methods, using the centroids of all the inventories in the survey as observations. Comparing centroids grouped from different geometries involves some statistical noise, but the immense variety of structures for each method ensures that the effect of such noise would be random. None of the 80 tests (10 method pairs x 4 indices x 2 scales) reached significance at the Bonferroni-corrected threshold of $p<0.000625$ (=0.05/80), but only three out of the 40 linear centroid tests were near-significant ($p<0.05$), compared to eleven of the 40 logarithmic centroid tests. Although these results are still inconclusive, it was decided to use the linear centroid in the normalization process on the basis of the near significant results.

3.1.2 Universal centroid

One important outcome of the analysis of centroids across elicitation methods is the near-constant nature of the 'centroid of linear centroids', or the average of all the linear centroids from all inventories in the survey. Table 3-1 provides the absolute frequencies and relative positions of centroid averages and standard deviations across elicitation methods, as well as the grand averages for the entire survey.[10]

		F1		**F2**	
elicitation method	**observations**	**frequency**	**relative position**	**frequency**	**relative position**
Isolation	41	452.2±50.9	0.395±0.069	1450.8±98.7	0.460±0.057
Wordlist	234	468.3±52.7	0.395±0.065	1474.2±89.6	0.471±0.047
Carrier sentence	91	452.8±46.9	0.374±0.056	1483.3±101.5	0.463±0.044
Meaningful sentence	41	465.9±43.1	0.404±0.064	1471.4±62.4	0.458±0.039
Running speech	38	457.8±48.9	0.388±0.049	1471.9±84.2	0.455±0.058
All	**445**	**462.5±50.5**	**0.391±0.063**	**1473.3±90.3**	**0.466±0.048**

Table 3-1: Averages and standard deviations of frequencies and relative positions in formant spans for F1 and F2 of linear centroids in the survey, as a function of elicitation method.

The centroid of linear centroids, from all inventories and acoustic geometries, is probably the best approximation of the 'dead center' of the vowel space. Assuming a

[10] The number of observations is 445 and not 447 because, in two inventories, crucial data for calculating F1 and F2 spans are missing.

uniform-tube schwa ($F2=3xF1$) with F1 at 485-490Hz and F2 at 1455-1470Hz, this vowel is a slightly raised schwa, which is in good agreement with an effortless vowel, with neutral tongue and lip position and loose and slightly open yet relatively high jaw position (for a true uniform tube the jaw has to be lowered somewhat). This vowel will be referred to as the *universal centroid (UC)* hereafter.

3.1.3 Universal centroid approximation

The absolute formant frequencies of the UC (F1=463Hz, F2=1473Hz) mean very little with regard to individual inventory data. Although these formant frequency coordinates are located in the interior region of the acoustic space for virtually every adult male speaker, they may characterize a raised and rounded schwa ([ɵ]) for a speaker with a small vocal tract and a vowel between [ɜ] and [ɛ] (lowered and advanced schwa) for a speaker with a very large vocal tract. More important are the relative positions of the UC within the F1 and F2 frequency spans, because they enable us to approximate the inventory-specific reflection of the UC, with reasonable accuracy, based solely on formant minima and maxima. The point located at the 391 thousandth of the F1 span and the 466 thousandth of the F2 span should be very close to the same 'slightly raised schwa' in any inventory, regardless of the language, the number of vowels, phonological structure and elicitation method. The formant frequencies of an inventory's *universal centroid approximation index* (UCA) are:

(3.2) $F1_{UCA}=F1_{MIN}+0.391(F1_{MAX}-F1_{MIN})$

(3.3) $F2_{UCA}=F2_{MIN}+0.466(F2_{MAX}-F2_{MIN})$

The cross-inventory stability of UCA vs. centroid was tested using all 442 inventories, for which both F1 and F2 frequencies of the centroid and UCA could be reliably calculated. For centroids, average F2/F1 ratio was 3.220 and standard deviation was 0.360. For UCAs, average F2/F1 was 3.200 and standard deviation was 0.305. While the difference in average ratios was not statistically significant (paired $t(441)=1.600$, $p>0.11$ two-tailed), the variance of UCA ratios was found to be significantly smaller than the variance of centroid ratios ($F(441,441)=1.398$, $p<0.0003$), implying that UCAs have more consistent acoustic qualities across languages and inventory geometries than centroids do, as expected.

The effectiveness of this UC approximation is easily illustrated by data from studies of Korean. Korean is very diverse in terms of vowel inventory structure across dialects, owing in part to changes in the standard (Seoul) dialect that took place in recent generations. Owing to the rather homogeneous ethnic background of Koreans, substantial differences in average speaker vocal tract size between multiple-speaker studies are unlikely, so the acoustic quality of 'slightly raised schwa' should be relatively consistent across Korean dialects. Table 3-2 summarizes centroid and UCA indices from all seven studies of Korean included in the survey. Although the average centroid is incidentally identical to the UC while the average UCA is slightly different, variance is significantly smaller for the UCAs than for the centroids.

Dialect, source, # speakers and structure	elicitation method	formant spans		centroid		UCA	
		F1	F2	F1	F2	F1	F2
Seoul old, Han (1975), 1, /i e ɛ a ɔ(ʌ) o u y ø ɨ(ɯ)/	wordlist	302 830	988 2229	440	1561	508	1566
Seoul old, Yang (1996), 10 /i e ɛ a ʌ o u y ø ɨ(ɯ)/	wordlist	338 738	945 2219	479	1587	494	1538
Seoul new, Lee (2000), 8 /i e ɛ a ə(ʌ) o u ɯ/	carrier sentence	320 770	890 2245	499	1460	496	1521
Seoul new, Kim (2001), 1 /i ɛ a ʌ o u ɯ/	isolation	330 710	950 1980	473	1424	479	1430
Pyongyang, Kang (1996), 1 /i e ɛ a o u/	carrier sentence	260 765	1007 2090	410	1570	457	1511
Chungnam, Seong (2005), 5 /i ɛ a ʌ o u ɯ/	carrier sentence	341 740	764 2209	493	1319	497	1437
Hamkyong, Kang (1997), 2 /i e ɛ a o u ɨ(ɯ) ʌ(ɤ)/	carrier sentence	307 735	822 2117	448	1406	474	1425
		Average (sd):		**464.7 (31.3)**	**1475.3 (100.6)**	**486.6 (17.3)**	**1489.8 (58.0)**

Table 3-2: Centroids and UCA indices in all studies of Korean inventories in the survey.

The only problematic inventories for universal centroid approximation are those that lack a particular peripheral region altogether, like the inventory of Southern California English, with no true back-rounded vowels (see Hagiwara 1994 for formant frequencies). For such inventories, the UCA is removed quite far from the 'slightly raised schwa', but such inventories are very rare. Much more common are inventories with structural asymmetries and/or crowded acoustic regions (e.g. the high-front region in the inventories of most Germanic, Uralic, Altaic and Chinese languages). Centroids, being calculated from all vowels, gravitate towards crowded acoustic regions. Conversely, UCA indices, which are calculated only from F1 and F2 spans, are impervious to crowded regions or asymmetries.

In summary, to the extent that it is possible to define a point of relative constancy across languages, inventory structures and elicitation methods, this point should be the inventory's universal centroid approximation index (UCA), as defined in relative positions within the inventory's F1 and F2 spans on the linear Hz scale. UCA indices were calculated for all the inventories in the survey, and whenever an inventory was formed by the merger of two entries (short and long vowels), the same UCA index was assigned to both entries.

3.2 **Vocal tract normalization**

3.2.1 Background and rationale

Vocal tract normalization of survey data was necessary for two reasons. First, most studies provided formant data from very few speakers, making language-specific effects and between-language variance strongly confounded with speaker-specific effects, vocal tract size being an important source for such effects. Second, even studies whose data are taken from many speakers might not be comparable with one another if their respective speakers come from very distinct ethnic backgrounds, with characteristic differences in stature, which inevitably lead to differences in vocal tract size (Fitch & Giedd 1999).

Many vocal tract normalization procedures for vowel inventories have been proposed and used in the literature, and it is beyond the scope of the current work to evaluate them, both because this has been done in the past (Ferrari-Disner 1980, Syrdal 1984, Adank et al. 2004), and because none of them is appropriate for the survey data. The reason is that these methods are dedicated to the problem of normalizing data between speakers of the same language, where underlying (linguistic) geometry of the inventory is assumed to be consistent across speakers. As explained in Section 3.1.1, centroid-based vocal tract normalization methods like Lobanov (1971) and Nearey (1978) are inappropriate for cross-linguistic and cross-structural data, due to the sensitivity of the centroid to inventory-specific geometry. Methods like Gerstman's (1968), which anchor inventories at their formant minima and maxima, are even less appealing. Not only do they distort genuine differences between languages, for example by practically reducing cross-linguistic variance of /i/ to zero (/i/ being simultaneously F1 minimum and F2 maximum in nearly all languages), but also immediately annul one of the key dispersion-related analyses, of formant span as a function of phonological structure. Methods that rely on frequency data of F3 and higher formants, which are more consistent across vowels and thus potentially better correlated with speakers' vocal tracts regardless of inventory acoustic geometry, would have been more suitable (e.g. Fant 1959, Halberstam & Raphael 2004). Unfortunately, too many studies included in the survey provide only F1 and F2 data, and in many others F3 frequencies seem inaccurate. Methods using formant ratios or formant differences in perceptual scales (Mel, Bark, ERB) suffer from the same problem, because they rely on the availability of data beyond F1 and F2 (at least f0 or F3). Morrison & Nearey (2006) is probably the only attempt to specifically address the problem of between-language normalization, but their model is applicable only for pairs of languages. It was therefore necessary to devise a novel vocal tract normalization procedure, which is based only on F1 and F2 and yet minimally sensitive to the inventory acoustic geometry so it can be applied to all inventories.

3.2.2 Devising the normalization procedure

The normalization procedure devised here is based on the following principle: the set of universal centroid approximation indices (UCAs) from all inventories presumably represent the same vowel quality, a slightly raised schwa. Most of the variation in UCA frequencies is due to differences in vocal tract size, which is roughly inversely related to formant frequencies. Formant frequency ratios between the universal centroid (UC) and the inventory's UCA can serve as multiplication constants by which the formant frequencies of all the inventory's vowels can be rescaled. This will anchor the inventory's UCA index at the UC, while retaining the acoustic geometry of the inventory intact. Since rescaling by constants is a logarithmic transposition, it retains the acoustic geometry intact in logarithmic scales. As such, it also retains the perceptual geometry intact to a great extent, because perceptual scales (Bark, ERB, Mel) are quasi-logarithmic.

F1 and F2 were treated independently. F1 and F2 frequencies of all the vowels in a given inventory were respectively multiplied by the ratios $F1_{UC}/F1_{UCA}$ and $F2_{UC}/F2_{UCA}$. This is equivalent to transposing the entire inventory geometry on a logarithmic F1xF2 plane. Figure 3-1 illustrates this procedure by plotting, using both linear (a) and logarithmic (b) scales, the raw (grey) and vocal-tract normalized (black) vowels of the /i a u/ inventory of Amis, based on formant data drawn from two speakers in Maddieson & Wright (1995).[11] The UCA index for this inventory is: $F1_{UCA}$ = 517Hz ($F1_{UC}/F1_{UCA}$ = 0.894), $F2_{UCA}$ = 1622Hz ($F2_{UC}/F2_{UCA}$ = 0.908). Notice that normalization lowers the formant frequencies of all vowels, implying that the average vocal tract of the two speakers recorded was relatively short.

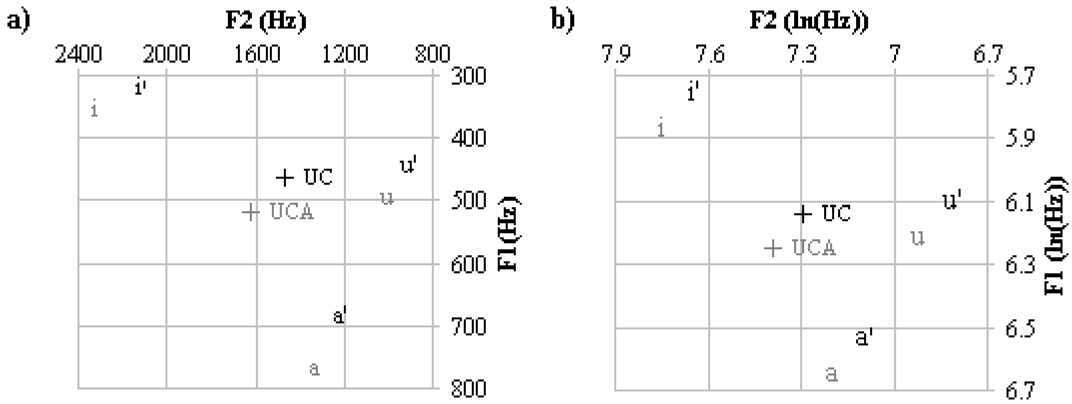

Figure 3-1: Raw (grey) and vocal-tract normalized (black) vowels of the /i a u/ inventory of Amis (Maddieson & Wright 1995), plotted both linearly (a) and logarithmically (b).

[11] All figures were prepared using Microsoft Excel and finalized using Microsoft Paint.

This implementation of vocal-tract normalization accepts any UCA as a ‘slightly raised schwa’, even when the UCA is obviously removed from this vowel quality (i.e. $F2_{UCA}/F1_{UCA}$ ratio very different from 3.2), and has the potential drawbacks of distorting F2/F1 ratios within vowels. A somewhat more complicated alternative would have been to change UCA indices minimally such that all the UCAs would have F2/F1 ratios identical to $F2_{UC}/F1_{UC}$ (=3.2), and then apply the same F_{UC}/F_{UCA} ratio as a rescaling factor for both F1 and F2 frequencies, thus retaining the original within-vowel F2/F1 ratios. However, changing the UCA index to a UC-like F2/F1 ratio has disadvantages of its own: Whenever the non-corrected $F1_{UCA}$ is below $F1_{UC}$ while non-corrected $F2_{UCA}$ is above $F2_{UC}$ or vice-versa, any constant shift that would yield, for all the inventory's vowels, reasonable frequencies for one formant, would yield disturbingly high/low frequencies for the other.

3.2.3 Implementation and validation

Vocal tract normalization was thus performed for all the inventories in the survey, excluding those for which spans could not be calculated (due to absent formant data for a point vowel), by multiplying all F1 frequencies by $F1_{UC}/F1_{UCA}$ and all F2 frequencies by $F2_{UC}/F2_{UCA}$. It was hoped that this normalization procedure would increase the geometrical match between inventories belonging to the same structural configuration. In more statistically meaningful words, reduction of variance was expected in the distribution of F1 and F2 frequencies for individual vowel categories within those structures for which there are enough different entries.

Recall from Section 2.3.2 that in the entire survey there are 17 structural configurations occurring in five languages or more. There were 7 other structures occurring in four languages and/or in seven or more entries. Together, these 24 structures cover 501 entries in total. For these 24 structures, means and standard deviations of F1 and F2 frequencies were calculated for each vowel category, pooled from its instances in all entries. The 171 vowel categories from all 24 structures thus have standard deviations of F1 and F2 frequencies in both the raw and the vocal-tract normalized data. This allows a simple and robust paired t-test comparing standard deviation values between 171 pairs of raw and normalized standard deviations for a specific vowel category within a specific structure. The reduction in average F1 standard deviation from 64.5Hz (±27.6) in raw entries to 51.5Hz (±19.8) in vocal-tract normalized entries was extremely significant ($t(170)=6.899$, $p<0.5\text{x}10^{-11}$, one tailed). The reduction in average F2 standard deviation was more modest, from 150.5Hz (±46.2) in raw entries to 140.7Hz (±50.4) in vocal-tract normalized entries, but was nevertheless highly significant ($t(170)=3.987$, $p<0.5\text{x}10^{-5}$, one tailed). It can thus be inferred that the vocal-tract normalization procedure devised here successfully reduced within-structure acoustic variability significantly.

The effectiveness of the vocal-tract normalization procedure is illustrated in Figure 3-2, juxtaposing raw (a) and vocal-tract normalized (b) F1xF2 geometries for the 6R3 inventories of Shanghai Wu (long vowels, /i e a ɔ o u y ø ɤ/, based on Chen 2008, three speakers, carrier sentence elicitation) and Muhu Estonian (long vowels, /i e æ ɑ o u y ø ɤ/, based on Niit 2007, two speakers, wordlist elicitation). The raw data differences resulting from the larger vocal tracts of the Estonian speakers mask the category correspondences and differences between the two inventories. Vocal-tract normalization anchors the UCAs (small '+' signs on the raw data chart) at the UC (large '+' sign), bringing the centroids ('C' signs) much closer to one another, and all the corresponding vowels as well. The remaining differences between corresponding vowels, like the central /a/ in Wu vs. front /æ/ in Estonian, are for the most part language-dependent.

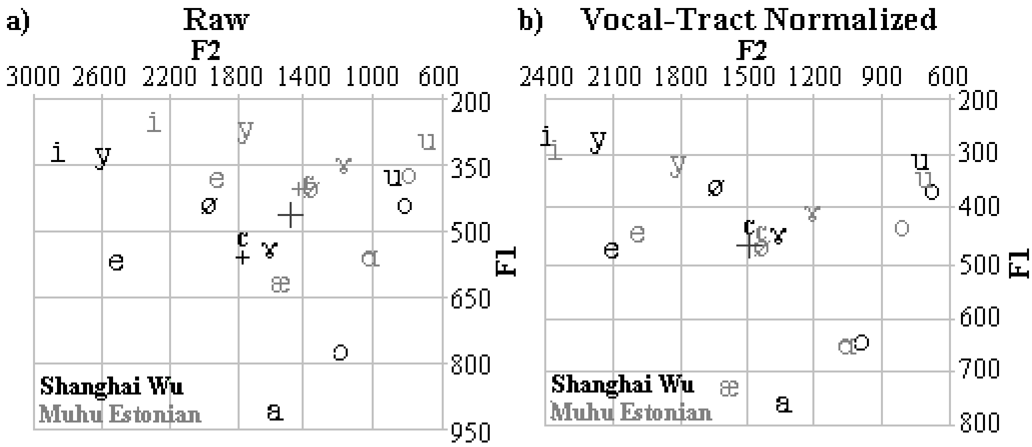

Figure 3-2: Raw (a) and vocal-tract normalized (b) F1xF2 data for Shanghai Wu (raw data based on Chen 2008, black) and Muhu Estonian (raw data based on Niit 2007, grey). The large '+' sign marks the universal centroid, the small '+' signs mark the UCA indices in the raw data, and the 'C' signs mark the centroids.

Of course, as the inventories of Shanghai Wu and Muhu Estonian have very similar structures and acoustic geometries, the relative positions of their respective centroids are very similar (and incidentally very close to their respective UCAs). Centroid-anchored vocal tract normalization would have yielded equally good alignment of these two inventories. The unique merits of UCA-anchored normalization are better appreciated when inventories differ drastically in their acoustic geometries and the relative positions of their centroids, so centroid-anchored normalization results in severe misalignment of the acoustic geometries.

This is easily demonstrated by the high-front crowded /i e a o y ø/ 4L2a inventory of Wari' (based on MacEachern et al. 1996, six speakers, wordlist elicitation) and the mid-back crowded /i ɪ ɑ ɔ ʊ u ə o/ 6R2b inventory of Chakhar Inner Mongolian (based on Svantesson 1995, one speaker, wordlist elicitation).[12] The difference in raw formant spans of the two inventories is not as pronounced as in the case of Shanghai Wu and Muhu Estonian, but nonetheless suggests that the Chakhar Inner Mongolian speaker has a slightly smaller vocal tract than the average Wari' speaker, an impression further corroborated by F3 data, which are available for both inventories. For example, the F1-F3 frequencies of Chakhar Inner Mongolian /i/ (356Hz, 2347Hz, 3016Hz) and /ɑ/ (825Hz, 1329Hz, 2851Hz) seem slightly elevated relative to Wari' /i/ (325Hz, 2170Hz, 2920Hz) and /a/ (745Hz, 1545Hz, 2550Hz). Figure 3-3 shows F1xF2 plots of the inventories. On the raw data plot (a), it is noticeable that the inventories' UCAs (small '+' signs) differ only slightly from each other and from the UC (large '+' sign), while their respective centroids ('C' signs), which are gravitated towards the crowded regions, are far apart. Centroid-anchored normalization (b) has a colossal misalignment effect, retracting the Wari' vowels while advancing and raising the Chakhar Inner Mongolian vowels too much (notice the vowels /i/ and /a~ɑ/ in particular). Conversely, UCA-anchored normalization (c) improves the acoustic compatibility between the two

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[12] The structure of this inventory of Chakhar Inner Mongolian was interpreted as 6R2b, with /ə/ and /o/ as non-peripheral vowels contrasting horizontally with the peripheral /ɪ/ and /ʊ/ and with each other. The interpretation of /o/ as a non-peripheral vowel on the basis of its acoustic contrast with /ʊ/, which seemed to be based more on F2 than on F1, was later found to among the few cases where the structural interpretation had been inconsistent with the criteria described in Section 2.3.2, because the F2 frequency of this /o/ is too low to count as non-peripheral. The inventory of Chakhar Inner Mongolian participates in a robust pharyngealization/ATR vowel harmony system, where /ɪ ɑ ɔ ʊ/ are the [-ATR] counterparts of the [+ATR] /i ə o u/. Similar acoustic patterning of /ʊ/ and /o/ was found in a number of inventories in the corpus, all characterized by robust ATR harmony (and /ɔ ʊ/ correspondence to /o u/). In all these other inventories /o/ was properly interpreted as a back vowel. Such interpretation of this Chakhar Inner Mongolian inventory would have assigned it the structure 7R1. Since both 6R2b and 7R1 are extremely rare, the cross-linguistic acoustic typology is largely unaffected by the erroneous interpretation as 6R2b. However, the interpretation of this inventory as consisting of a 6R periphery and two non-peripheral vowels contrasting horizontally must have had some effect on analyses of the corpus that are sensitive to the configuration of the periphery and of the non-peripheral region, in particular the analyses of peripheral mid vowels reported in Section 4.4.

inventories relative to the raw data, for example by equating the heights of the three unrounded peripheral vowels (Wari' /i e a/, Chakhar Inner Mongolian /i ɪ ɑ/).

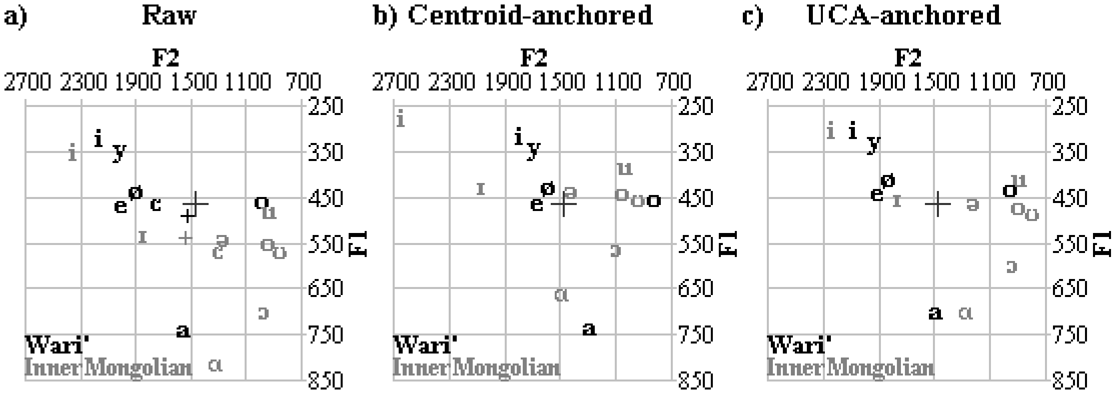

Figure 3-3: Raw (a), centroid-anchored normalized (b) and vocal-tract normalized (c) F1xF2 data for Wari' (raw data based on MacEachern et al. 1996, black) and Chakhar Inner Mongolian (raw data based on Svantesson 1995, grey). The large '+' sign marks the universal centroid, the small '+' signs mark the UCA indices in the raw data, and the 'C' signs mark the centroids.

3.3 Elicitation method normalization

3.3.1 Background and rationale

Vocal-tract differences are not the only non-linguistic source for within-structure acoustic variance. No less influential is the elicitation method. Different elicitation methods position the elicited vowels in different segmental, prosodic and speech rate contexts, and also involve different levels of speaker's awareness and consciousness of pronunciation. Longer duration, higher prosodic prominence and greater awareness all contribute to greater articulatory displacement whenever the articulatory target of the vowel is distant from the effortless position. Conversely, shorter duration, lower prominence and casual speech all contribute to vowel undershoot and contextual coarticulation, which are manifested systemically as acoustic centralization, because the position of least effort is at the center of the acoustic space (Lindblom 1963, de

Graaf & Koopmans-van Beinum 1984, van Bergem 1993, Fourakis et al. 1998, Johnson & Martin 2001, Parker 2001, Calamai & Sorianello 2003, among others).[13]

There is no empirical a priori preferred reference point for between-method normalization. However, the well established effects of elicitation method on formant frequencies and inventory space size suggest that this confound should not remain untreated. The safest approach is to choose the most common elicitation method as the target of normalization, thus leaving as much data as possible untouched. The target of method normalization will therefore be wordlist elicitation, which covers more than one half of the entries in the survey. It should be kept in mind that, to the extent that such normalization can be accurate, the normalized data should still suffer from distortions of acoustic vowel targets characteristic of wordlist elicitation, like coarticulatory effects of adjacent consonants, which do not exist in isolation elicitation.[14]

Formal models of acoustic vowel reduction as a function of speech rate have been proposed in the past (e.g. Lindblom 1963, van Bergem 1993). Unfortunately, as vowel duration and speech rate are usually unavailable in the studies in the survey, such models are of little relevance here. Although the discrete reduction and centralization effect of speech condition, style or utterance type has been addressed in many studies, none of them have proposed a formal acoustic model for this phenomenon. De Graaf & Koopmans-van Beinum (1984) is probably the only study that goes a certain way in this direction. In their study, the effect of three elicitation methods on vowel formants

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[13] Notice that this is not obvious. One could easily imagine a hypothetical language where all consonants are somewhat pharyngealized and a default tongue position with constricted pharynx, but vowel targets are not pharyngealized. In such a language, the acoustic vowel space would still compress under prominence and temporal reduction and casual speech style, but clearly wouldn't centralize, because F1 would rise and F2 would fall for all vowels.
[14] Isolation elicitation has its own shortcomings, like the unnatural nature of the task, and hyperarticulation.

was demonstrated using data from six different languages. Vowel space size was expressed as a function of distances of vowels from a global center point, the logarithmic average of all vowels in all speech conditions. Comparing average distance indices between vowels in isolation, in words and in running speech yielded roughly consistent ratios of space size reduction. The choice of the logarithmic average from all speech conditions implicitly suggests that this spatial point is relatively stable across elicitation methods, and could serve as an anchor for interpolation or extrapolation of formant frequencies as part of normalization. This choice seems rather peculiar given de Graaf & Koopmans-van Beinum’s (1984) own data. Their logarithmic vowel charts clearly show stronger centralization for high than for low vowels and for back than for front vowels, that is, the logarithmic shift is greater for lower F1 and F2 frequencies, which is expected if the shifts are of equal magnitude on a linear scale.[15] The findings in Section 3.1.1 also suggest that the linear centroid is more stable across elicitation methods, hence more suitable as a normalization anchor. In the absence of an adequate between-method normalization procedure, such a procedure had to be devised here.

3.3.2 Devising the normalization procedure

The simplest normalization approach is to find, for each method pair comprising wordlist elicitation and another method, the most representative between-method ratios for F1 and F2 distances between vowels and the linear centroid. Notice that the universal

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[15] In de Graaf & van Beinum's (1984) logarithmic formant charts, the forward shift of back vowels and the downward shift of high vowels look substantially greater than the backward shift of front vowels and upward shift of low vowels. Linear representation would have yielded much more symmetrical inwards shifts, of about 200-250Hz for F2 and 75-100Hz for F1, from isolated vowels to running speech vowels.

centroid approximation (UCA) could in principle be used instead of the centroid, in particular as the UCA seemed to be even more stable than the centroid across elicitation methods. However, the centroid was preferred here because it is a familiar concept established and used elsewhere for within-language inventory normalization.

The normalized frequencies for a given vowel are achieved by extrapolation, from the centroid, of the F1 and F2 distances of the non-normalized vowel, multiplied by the appropriate method-specific ratios, which are yet to be found. Let R_{M1} and R_{M2} be the representative ratios of F1 and F2 distance from centroid for wordlist elicitation vs. method M, then the method-normalized formant frequencies for vowel V in an inventory whose centroid is C elicited by method M are:

(3.4) $F1_{V\text{-MethodNormalized}} = F1_C + (F1_C - F1_V) \times R_{M1}$

(3.5) $F2_{V\text{-MethodNormalized}} = F2_C + (F2_C - F2_V) \times R_{M2}$

Notice that, since both the vocal-tract normalization procedure and this between-method normalization scheme keep intact all the distance ratios in the inventory (within the same formant), the combined result of both procedures is the same no matter which procedure is applied first. However, the specific between-method ratio constants and the analyses meant to establish them need to be performed using the linear Hz scale. Therefore, the less variable the data are on this scale, the more reliable the analyses. In Section 3.2.3 it was shown that vocal-tract normalization significantly reduced variance on the Hz scale. Thus, vocal-tract normalized data, rather than raw formant data, was used in the between-method normalization analyses.

As the relative position of the centroid in the inventory frequency spans is stable across elicitation methods, formant span ratios between elicitation methods are appropriate candidates for the extrapolation ratios necessary for between-method normalization. However, formant spans and span ratios represent only the behavior of the inventory point vowels, while the centroid is a function of all the vowels in the inventory. It is possible that the behavior of point vowels as a function of elicitation method differences differs from the behavior of other vowels, and it is important that other vowels would also be represented in the calculation of the extrapolation ratios. It was therefore decided to devise an additional index of distance from the centroid, derived from all the vowels in the inventory and representing their distribution – the more all the vowels are distributed, the more expanded the inventory. If a given formant's frequencies from all the inventory's vowels are considered a sample and the centroid's frequency for this formant is the sample mean, then the sample standard deviation essentially represents the desired index. Thus, for each inventory, four dispersion indices were calculated: $F1_{SPAN}$, $F1_{SD}$, $F2_{SPAN}$ and $F2_{SD}$.

The next step was to determine, for each of the four method pairs (wordlist elicitation vs. each of the other four), whether the indices are indeed significantly different. A series of 16 matched-pair t-tests was performed, with all four indices ($F1_{SPAN}$, $F1_{SD}$, $F2_{SPAN}$ and $F2_{SD}$) as dependent variables for each of the four method pairs, using the same sets of entries as in the centroid analyses reported in Section 3.1.1. The one-tailed significance threshold was Bonferroni-corrected to 0.0033 (=0.05/16). Table 3-3 summarizes the results. Notice the similarity between average ratios between corresponding span and standard deviation indices, implying that the behavior of point vowels and other vowels as a function of elicitation method differences is rather similar.

		Isolation	carrier sentence	meaningful sentence	running speech
	df	15	17	13	14
$F1_{SPAN}$	*t*	4.878**	1.767	2.904*	5.538**
	average ratio	0.884	1.055	1.171	1.340
$F1_{SD}$	*t*	5.663**	1.492	3.762*	5.280**
	average ratio	0.873	1.047	1.210	1.380
$F2_{SPAN}$	*t*	4.580**	2.159*	5.028**	11.443**
	average ratio	0.903	1.058	1.183	1.258
$F2_{SD}$	*t*	5.261**	2.534*	6.261**	10.367**
	average ratio	0.875	1.079	1.188	1.290

Table 3-3: Matched-pair t-tests results for the differences in indices of distance from centroid between wordlist elicitation and each of the other elicitation methods, and average between-method ratios for each index. "*" denotes near-significance at $p<0.05$ and "**" denotes significance at the Bonferroni-adjusted threshold of $p<0.0033$.

Virtually all the differences between wordlist elicitation and each of isolation, meaningful sentence and running speech elicitations were highly significant. The expanded indices in isolation elicitation are consistent with the longer duration, the absence of coarticulatory effects and the higher phonetic awareness associated with this task, relative to wordlist elicitation. Similarly, the reduced indices in meaningful sentence and running speech elicitations are also consistent with these parameters, because vowels are expected to be shorter, prosodically-weaker and more coarticulated in entire sentences than in isolated words. Although no direct comparison between the latter two elicitation methods was performed, their respective results compared to wordlist elicitation suggest that running speech elicitation involves more centralization than meaningful sentence elicitation. This is expected given that speech rate and segmental context are typically partially controlled in meaningful sentence elicitation but not in running speech elicitation.[16]

[16]The consistency of vowel space contraction and expansion as a function of elicitation method, combined with the consistent position of centroids across elicitation methods as well, imply that the effects of vowel undershoot (and/or overshoot) manifest overall centralization. This effect might be different from vowel space reduction in unstressed syllables, which has been claimed to manifest upward contraction due to constrained jaw movement, leading to substantial raising of the vowel space

In light of these highly significant results, the stronger centralization attested in carrier sentence elicitation relative to wordlist elicitation seems genuine, and it would be unwise to dismiss it solely due to statistical non-significance, given the very restrictive significance threshold. If the differences between wordlist elicitation and each of isolation, meaningful sentence and running speech elicitation had not been put to test based on clear past evidence (e.g. de Graaf & Koopmans-van Beinum 1984), the Bonferroni correction would have been less conservative, and some of the wordlist vs. carrier sentence differences would have become significant. At the same time, expanding carrier sentence-elicited vowel spaces by ratios around 1.06 without clear-cut support seems equally unwise, because, in such studies, segmental context is often controlled and subject awareness might be enhanced due to the unnatural repetitions of the same sentential framework. This may lead to pronunciation of the target word with special, contrastive focus, which is not the case in the more natural, lexicon-oriented task of wordlist elicitation.[17]

It was therefore decided to look into the distribution of these four dispersion indices as a function of elicitation method based on all inventories, without control for language, assuming, as in the case of centroid comparisons, that the great variety within each elicitation method exerts only a random effect on the average indices.

The average index ratios across elicitation methods appeared more conservative than under within-language control. Isolation vs. wordlist elicitation ratios increased

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floor (Flemming 2005, Padgett & Tabain 2005, Herrick 2005). This type of vowel reduction should yield a significant drop in centroid F1 frequencies, which is clearly not attested in the corpus data, as seen in Table 3-2 in Section 3.1.3. It is plausible that vowel undershoot in unstressed vowels is different from undershoot in stressed vowels in faster or more casual speech circumstances. However, much more cross-linguistic acoustic data on phonetic vowel reduction in unstressed syllables are necessary to establish the case for jaw movement constraints and acoustic raising as the source.

[17]Notice that wordlist elicitation using near-minimal sets is common in studies of English vowels (*heed, hid, head* etc.) but is rare elsewhere.

slightly ($F1_{SPAN}$: 0.923, $F1_{SD}$: 0.891, $F2_{SPAN}$:0.899, $F2_{SD}$: 0.898), and meaningful sentence vs. wordlist ratios decreased substantially ($F1_{SPAN}$: 1.123, $F1_{SD}$: 1.109, $F2_{SPAN}$: 1.089, $F2_{SD}$:1.097), as did running speech vs. wordlist ratios ($F1_{SPAN}$: 1.254, $F1_{SD}$: 1.233, $F2_{SPAN}$: 1.170, $F2_{SD}$:1.195). These more conservative ratios remained significant in unpaired t-tests (p<0.0033 for all except for one comparison with p=0.0045). However, the picture changed dramatically for carrier sentence vs. wordlist elicitation ratios: carrier sentence elicitations turned out to have *greater* F1 dispersion than wordlist elicitations ($F1_{SPAN}$ ratio: 0.966, $F1_{SD}$ ratio: 0.968), and the two methods fared virtually equally in their F2 dispersion indices ($F2_{SPAN}$ ratio: 1.011, $F2_{SD}$ ratio: 0.997). None of these ratios was the result of even a near-significant difference.

Overall, the analyses of elicitation method effects suggested a complicated state of affairs. The more tightly-controlled but less comprehensive comparisons suggested rather drastic distance-from-centroid ratios, implying major arithmetical transformations. Conversely, the more loosely-controlled but more comprehensive comparisons suggested more conservative ratios and transformations. It was decided to average them, as well as the span and standard deviation ratios. Thus the final distance-from-centroid ratios, for each formant, for each method pair, was the average of four values (span ratio and standard deviation ratio from both the language-controlled and uncontrolled comparisons), rounded to the nearest 0.01, except for the case of F1 for carrier sentence, where the average of 1.0089 was rounded to 1 (i.e. no transformation), due to the non-significant and somewhat contradictory nature of the comparison results. The final ratios are listed in Table 3-4. The consistency between F1 and F2 ratios in both isolation and meaningful sentence elicitations is intriguing, but is assumed to be coincidental.

	Isolation	carrier sentence	meaningful sentence	running speech
F1	0.89	1	1.15	1.30
F2	0.89	1.04	1.14	1.23

Table 3-4: Average ratios of vowel distance from centroid between each of the four elicitation methods listed and wordlist elicitation, pooled from all indices.

Before applying these ratios and normalizing the inventories for elicitation method, it was necessary to ensure that expanded inventory geometries (from meaningful sentence and running speech elicitations) would never reach formant spans that are highly improbable in wordlist elicitation. The rationale is as follows: it is quite plausible that a particular running speech study would yield an inventory with large formant spans (for example, if all vowels analyzed were preselected according to a criterion of minimal duration). If such formant spans are scaled by large factors, they might reach unnatural magnitudes. While examining the F1 and F2 spans of the 234 word-list elicited, vocal-tract normalized inventories in the survey, two inventories stood out for their extremely large F1 spans and one inventory stood out for its large F2 span. Given the large corpus, it is plausible that these three extreme formant spans are due to errors. Thresholds were set below these three extreme spans, in the nearest 0.05 unit of the ln(Hz) representation ($\ln(F_{MAX}) - \ln(F_{MIN})$) immediately above the next largest formant spans. Logarithmic representation of span threshold was used so that they could be applied without change if elicitation method normalization is applied prior to vocal tract normalization and/or if the estimate of the universal centroid changes (due to addition of many more studies). The span thresholds are as follows:

(3.6) $F1_{SPAN}$=605Hz ($F1_{MIN}$=226Hz, $F1_{MAX}$=831Hz, $\ln(F1_{MAX})=\ln(F1_{MIN})+1.3$)

(3.7) $F2_{SPAN}$=1806Hz ($F2_{MIN}$=632Hz, $F2_{MAX}$=2438Hz, $\ln(F2_{MAX})=\ln(F2_{MIN})+1.35$).

Any inventory whose extrapolated formant span(s) exceeded these thresholds by the elicitation method normalization was corrected by applying the extrapolation constant(s) that reach these thresholds instead. Such corrections were needed (for either formant span) in eight inventories: four with meaningful sentence elicitation and four with running speech elicitation.

3.3.3 Implementation and validation

The elicitation method normalization procedure was also evaluated by paired t-test comparison of formant standard deviations for all vowel categories in all common structures. First, comparison between vocal-tract normalized formant standard deviations to vocal-tract-and-elicitation-method formant standard deviations was performed, using the same 171 standard deviation pairs as in the evaluation of vocal-tract normalization in Section 3.2.3. This comparison yielded only fractional, questionably statistically significant reduction of 0.44Hz on average, in F1 standard deviations ($t(170)=1.719$, $p=0.044$, one-tailed), and a non-significant reduction of 0.04Hz in F2 standard deviations ($t(170)=0.053$, $p=0.48$, one-tailed). This was somewhat expected, because three quarters of the formant data from which the standard deviations were calculated were essentially the same – wordlist elicitation data and carrier sentence F1 data remained unchanged while carrier sentence F2 data were changed only marginally.

Excluding entries based on wordlist elicitation reduced the number of sufficiently populated structures from 24 to 18 (covering 233 entries, rather than 501), with 123 vowel categories in total. This time standard deviation reduction for F1, from 51.2Hz to 49.6Hz on average, was clearly significant ($t(122)=2.471$, $p<0.008$, one-tailed). F2 standard deviations also decreased, from 139.0Hz to 136.7Hz on average, but this reduction was not significant ($t(122)=1.323$, $p=0.093$, one-tailed).

In order to see to what extent the elicitation method normalization procedure was effective at the within language level, the following procedure was performed. Multiple entries sharing the same language and the same inventory structure but differing in elicitation method were grouped, and those entry groups containing wordlist elicitation entries were excluded, leaving only 11 entry groups, which, at the absence of wordlist entry among them, could not have been used when the normalization procedure was devised. These 11 language-specific, structure-specific entry groups comprised 97 vowel categories together. For every pair of entries in each group, formant differences were calculated for each vowel category, and the absolute values of all differences were summed, yielding a variability index for every language-structure-vowel-formant combination (97 indices for each of F1 and F2). These scores were calculated on the vocal-tract normalized data, both before and after elicitation method normalization. Paired t-tests were performed, comparing corresponding variability indices before and after normalization. The elicitation method normalization procedure reduced F1 variability indices by 13% on average, which was significant ($t(96)=2.554$, $p<0.007$, one tailed), while the 1% reduction in F2 variability indices was not ($t(96)=0.209$, $p>0.41$, one tailed).

The between-method normalization procedure thus successfully reduced variance in F1 data, and F2 variance did not increase. It was therefore decided to apply this normalization procedure, keeping in mind that a much better procedure might be found, in particular for F2, for example, by allowing different normalization calculations for vowels from different acoustic and/or articulatory regions.[18]

The entire normalization process (vocal tract and method normalization) is illustrated in Figure 3-4, showing data pooled together from the 11 different entries of the /i e ɛ a ɔ o u/ inventory of Italian in the survey, based on formant data from Ferrero (1972), Trumper et al. (1989), Esposito & Stevens (1995), Calamai (2001, 2002a, 2002b) and Calamai & Sorianello (2003), with all five elicitation methods included (in some of these sources, vowels were elicited in more than one method). Some of the variance within vowel categories is due to dialectal differences. Notice the gradual within-category consolidation as normalization proceeds.

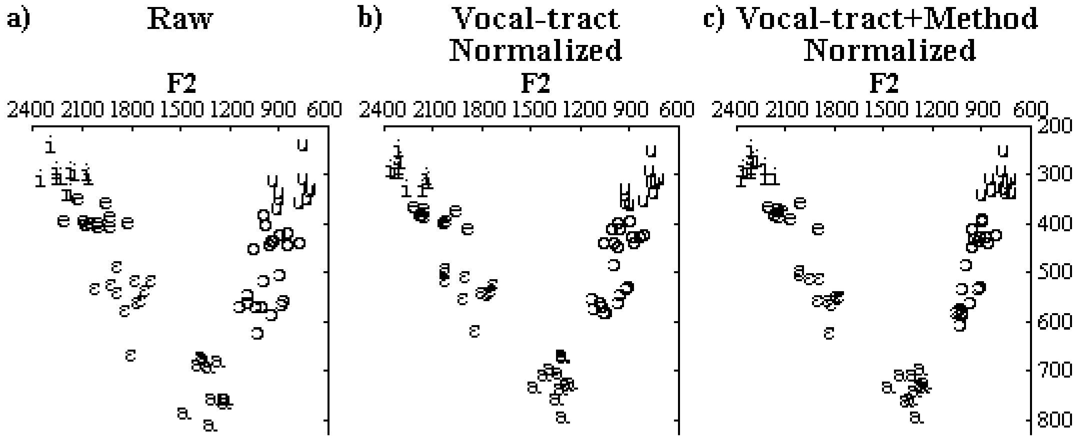

Figure 3-4: Raw (a), vocal-tract normalized (b) and vocal-tract+method normalized (c) F1xF2 data pooled from the 11 /i e ɛ a ɔ o u/ entries of varieties of Italian in the survey.

[18] One reasonable explanation for the failure to significantly reduce F2 variance is the variability of the segmental context adjacent to vowels in all the studies, across all elicitation methods other than isolation. Consonantal coarticulation predominantly affects the F2 frequency of vowels, and when such effects are not controlled for, they introduce statistical noise that the between-method normalization is unable (and not meant) to reduce.

3.4 Estimating F3 and F2' for fronter vowels after normalization

3.4.1 Background and rationale

In most vowel inventories, the phonemic role of F3 is very limited, which is why F3 data are often not reported (or not measured in the first place) in acoustic descriptions of inventories. Out of the 447 inventories in the survey, F3 data are reported only for 275, many of which lack F3 data for some vowels and/or have apparently unreliable F3 data for others.[19] The existing F3 data in the survey are thus partial and noisy, and were discarded during the normalization process.

Absence or loss of F3 data is problematic for the estimation of perceptual dispersion. F3 contributes to the perception of frontness in fronter vowels (front unrounded, front rounded and high to mid central unrounded vowels), and enhances perceptual dispersion. For example, for speakers of languages that distinguish /i/ from /y/, a vowel with F2 frequency characteristic of [i], but with F3 only slightly above it (a property of [y]) is often perceived as /y/ and not as /i/ (see e.g. Schwartz & Escudier 1989). This means that chromaticity of fronter vowels is an integrated percept of F2 and F3. This integrated percept is best manifested in experimental studies where listeners adjust the frequency of the second formant in two-formant synthesized vowels so that they match targets, which are either multi-formant stimuli or the listeners' internal notion of the prototypical auditory qualities of vowel phonemes in their language. The frequency of this formant, known as F2' or the

[19]Given the general stability of F3 across the acoustic space, it was clear during the review process that, in many studies, F3 data were far less accurate and reliable, and probably more prone to analysis errors, than F1 and F2. In some studies, although F3 data were in acceptable ranges and behaved in an expected fashion across vowels, they also seemed systematically too high or too low (which is often the case if parameters of automatic formant analysis are not properly adjusted), which would have created serious inadequacies had F3 data been used for vocal-tract normalization.

effective second formant, matches the F2 frequency of the target if the target is a back vowel. If the vowel is fronter, typically with F2 frequency above 1400Hz for adult males, then F2' is consistently higher (Delattre et al. 1952, Bladon & Fant 1978, among others). Regardless of whether F2' is a real psychoacoustic phenomenon or an artifact of a forced attempt to approximate a complex spectral topography by a simple one, using F2' is probably the only means to keep calculations of perceptual vowel distance sufficiently faithful and yet two-dimensional. Therefore, F2' appears consistently in the vowel perception and inventory dispersion literature, especially in simulation studies (Liljencrants & Lindblom 1972, Schwartz et al. 1997b, de Boer 2000). From a perceptual dispersion point of view, a typology of acoustic geometries of inventory structures without F2' data is incomplete.

For vowel qualities outside the high front region, the systematic effect of F3 on F2' is limited and F2' is within the lower third of the interval between F2 and F3. This means that F2' can be reasonably estimated based on F2 even if F3 is only coarsely approximated. An error of 150Hz in F3 is translated to an error smaller than 50Hz in F2' for most fronter vowels. Such an error in F2' estimation is about the just noticeable difference for formants in these frequencies (Flanagan 1955, Mermelstein 1978). Estimating F3 based on F1 and F2 is possible, at least for some vowel types, and Nearey (1989) gives a simple model of this sort for front unrounded vowels. Nearey's (1989) model was tested against F3 data in the survey, but its performance for vowels other than front unrounded was far from satisfactory, and even its reasonable performance for front unrounded vowels ($r^2 = 0.541$, residual standard error: 172Hz) suggested that there was much room for improvement. It was therefore decided to devise a new model for F3 estimation based on F1 and F2, using the F3 data available in the survey. Notice that, while the existing F3 data in the survey might not always be accurate and cannot be used for *within-inventory* processing, it is most likely that F3 inaccuracies *across* inventories go in both directions, so the average behavior of F3 as a function of F1 and F2 across all inventories should be rather typical, even if its distribution is greater than desired.

3.4.2 F3 estimation models

In the 275 survey inventories whose raw data include F3 frequencies, there are about 1200 individual vowels for which F3 might participate in F2' (F2>1350). The models are derived using regression analysis of F3 as a function not only of F1 and F2, but also an extrinsic index of vocal-tract size, in the form of UCA index of the inventory, and last but not least, information about the state of the lips as implied by the transcription symbol of the vowel. In order to ensure the validity of the model, a certain amount of data is kept out of the sample used for modeling, and serves as a sample for independent validation. Thus, the model is justified not because it is elegant and/or theoretically sound, but because it works well, in the sense that it can be generalized to a sample that did not participate in its construction. Once the model has been independently validated, it can be applied to the normalized data.

The vowels in which F3 plays a role in determining F2' are primarily divided into front (unrounded) vs. non-peripheral vowels. In front vowels, F3 behaves differently from other vowel types, and increases, rather than decreases, with decrements in F1. Also, in these vowels, the effect of F3 on F2' is greatest, so F3 estimation should be as accurate as possible. Fortunately, in front unrounded vowels, chances for accurate estimation are high, because there is very little freedom for the state of the lips, and more importantly, these vowels are very common, allowing large samples for both modeling and validation. In the case of non-peripheral vowels, a further division into rounded (front to central) vs. unrounded (central to back) vowels is needed, because these two vowel types overlap in F1xF2 but differ in F3, with the rounded (and fronter) vowels having significantly lower F3 than the unrounded (and backer) vowels. Coarse observation of raw vowel data accumulated according to transcription symbols from all survey entries, showed overlap in F1 and F2 frequencies but systematic differences in F3 frequencies in each of the pairs /ʏ ɨ/, /ø ɘ/, /œ ə/ and /ʉ ɯ/, implying that the two vowel types should be modeled separately.

Finally, all three data sets (front unrounded, non-peripheral rounded, non-peripheral unrounded) had to be further downsized, because the ultimate goal of the models was to estimate F3 frequencies for vowels that are method-normalized towards wordlist elicitation. Variation in elicitation method might exert its own effects on F3, which is an unnecessary confound if the models are to be used on method-normalized data. It was therefore decided to use, for both modeling and validation, only wordlist and carrier sentence elicitation data (we have seen in Section 3.3.2 that these two methods are nearly equivalent), and treat the data elicited by all other methods as an additional, optional validation sample. Dividing wordlist and carrier sentence data between modeling and validation sample was done at random. Table 3-5 summarizes the distribution of data used in modeling.

	Front unrounded	**rounded non-peripheral**	**unrounded non-peripheral**
valid for use (F3 available, UCA calculated, F2>1350)	860	207	85
wordlist or carrier sentence elicitation only	620	138	62
used in modeling sample	400	96	40
used in validation sample	220	42	22
other elicitation methods (additional validation)	240	69	23

Table 3-5: Numbers of fronter vowels with specified F3 frequencies as a function of vowel type and elicitation method, and their utilization in the construction and validation of the F3 estimation models.

For each of the three modeling samples, regression analyses were performed using F3 as the dependent variable and F1, F2, $F1_{UCA}$ and $F2_{UCA}$ and some functions derived from them (e.g. $F1^2$) and interactions (e.g. $F2_{UCA}xF2$) as the independent variables. The exhaustive list of variables and the trial-and-error process of arriving at the best models are of little interest. The best models were those with the highest r^2 values among models based only on variables with statistically significant contribution ($p<0.05$). While it is possible that even better models can be found, it is unlikely that further improvements would be more than marginal without significantly expanding the modeling samples. The models and their respective r^2 values and residual standard errors are presented in Table 3-6. Notice that, since the normalization process anchors the UCA index of every inventory at the UC ($F1_{UC}$=462.5Hz, $F2_{UC}$ =1473.3Hz), the inventory-specific contribution of $F1_{UCA}$ and $F2_{UCA}$ are translated into constants in the normalized versions of the models.

Model	**modeling sample**		**validation sample**		**additional sample**	
	r²	RSE	r²	RSE	r²	RSE
front unrounded: $F3 = 3699 + 0.6013 \times F1_{UCA} - 1.86 \times F1 - 1.391 \times F2 + \ldots$ $(15.95 \times F1^2 + 4.911 \times F2^2) \times 10^{-4}$ normalized: $F3 = 3977 - 1.86 \times F1 - 1.391 \times F2 + \ldots$ $(15.95 \times F1^2 + 4.911 \times F2^2) \times 10^{-4}$	.630	135.4	.603	144.3	.644	138.8
rounded non-peripheral: $F3 = 625.6 + 0.5677 \times F2_{UCA} + \ldots$ $(17.74 \times F1_{UCA} \times F1 + 2.489 \times F2_{UCA} \times F2) \times 10^{-4}$ normalized: $F3 = 1456 + 0.8205 \times F1 + 0.3642 \times F2$	.558	107.0	.497	112.7	.450	138.4
unrounded non-peripheral: $F3 = 1496 + (11 \times F1_{UCA} \times F1 + 3.086 \times F2_{UCA} \times F2) \times 10^{-4}$ normalized: $F3 = 1496 + 0.5088 \times F1 + 0.4516 \times F2$	.403	120.1	.447	144.1	.116	171.6

Table 3-6: F3 estimation models derived by regression analyses and their r² and residual standard errors for the modeling sample, validation sample and the additional (optional) validation sample.

The F3 predictions of all models are significantly more accurate than Nearey's (1989) model, and are well within the 150Hz range of residual standard error, for both the modeling sample and the independent validation sample. In terms of r^2, the model for front unrounded vowels is particularly stable, and the residual standard error is at about 5% of the formant frequency (average F3 = 2707Hz, sd = 227Hz). Its very high r^2 value for the data elicited in the 'other' methods is particularly encouraging. This model can therefore be generalized with confidence. In terms of raw standard error, the model for rounded non-peripheral vowels performed even better, but this can be attributed to the lower frequency range (average F3 = 2336Hz) and the much narrower overall distribution of F3 frequencies for such vowels (sd = 166Hz). Its r^2 values clearly decrease from the model sample to the validation sample and further to the additional validation sample, but remain sufficiently high nevertheless. Least impressive was the model for unrounded non-peripheral vowels (average F3 = 2477Hz, sd = 169Hz), whose standard error increased substantially from the modeling sample to the validation sample. Its performance in the additional validation condition was particularly poor. However, its performance in the more relevant validation sample was sufficient, especially since the contribution of F3 to F2' in these vowels is marginal. It was therefore decided to apply all three models and estimate F3 for all normalized vowels with F2 frequency higher than 1350Hz.

3.4.3 F2' estimation model

With F3 frequencies for fronter vowels now estimated, F2' can be estimated as well. Although there are many models of F2' to choose from (Fant 1959, Carlson et al. 1975, Bladon & Fant 1978, Paliwal et al. 1983, Mantakas et al. 1986), none of them is appropriate here, either because they require F4 data (Bladon & Fant 1978, Mantakas et al. 1986), or because they are highly inaccurate (Fant 1959, Paliwal et al. 1983, see criticism respectively in Carlson et al. 1970, Bladon 1983), or both (Carlson et al. 1975, see criticism in Bladon & Fant 1978).

One problem of these models is that they are each based on a different empirical study, and there are contradictory behaviors of listeners in different studies. For example, in Carlson et al.'s (1970) study of F2' for Swedish vowels, the absolute F2'-F2 shift and the relative (F2'-F2)/(F3-F2) shift are greater for [e] (310Hz, 62%) than for [y] (80Hz, 16%), whereas in Bladon & Fant's (1978) study of F2' for cardinal vowels the opposite is true ([e]:181Hz, 33%, [y]: 211Hz, 58%). Another problem is that the F2' frequency modeled for [i] is often extremely high, between F3 and F4 (Carlson et al. 1975, Bladon & Fant 1978, Mantakas et al. 1986). The empirical motivation for this F2' modeling for [i], supported independently also by Bladon & Lindblom (1981) and Eek & Meister (1994), is usually confounded by the presence of an /i y/ contrast in the inventories of the languages spoken by the participants in these studies (Swedish, French and Estonian, although Bladon & Lindblom's 1981 data are based on judgments of Swedish-like vowels by English speakers). In most F2' studies of English (Miller 1953, Paliwal et al. 1983, Blamey et al. 1996) and in Grigorjevs' (2008) F2' study of Latvian, F2' for [i] is below F3. Finally, if experienced phoneticians are the listeners most likely to transcend native language top-down effects of contrast enhancement, then Delattre et al.'s (1952) data of two-formant approximations of cardinal vowels are probably the most reliable source for a 'baseline' F2' frequency for [i] and other front vowels. In their study, the F2' frequency for [i] was found at 2900Hz (slightly below F3 for very close [i]). It is desirable that F2' frequencies above F3 would be a possible output of the model, but at the same time their scope should be more limited than suggested by existing models, restricted to a small region of extreme [i] qualities (e.g. F1<275, F2>2300, F3>3100 for normalized [i] in the survey data). Delattre et al.'s (1952) F2' data for [e] (2400Hz) and [y] (1900Hz) also suggest greater absolute and relative shifts for the former vowel.

Observing F2' data from various sources and keeping in mind their paucity and sometimes contradictory results, the following, tentative hierarchy of relative upward F2' shift ((F2'-F2)/(F3-F2)) seems appropriate:

(3.8) [i]>[i̽]>[e ɪ]>[y ɛ] > [ɨ ø æ]>[ʉ ɘ œ a].

F2' is thus closer to F3 in correlation with frontness, height and F2-F3 proximity. For the purpose of the survey, an ad-hoc F2' formula manifesting these tendencies was devised using F1, F2 and F3 only, as follows:

$$(3.9) \quad F2' = F2 + (F3 - F2) x \left\{ \left(\frac{F2 + F3 - F1 - 3000}{2450} \right)^2 x \frac{F2 - F1}{1890} + 1.8 x \left(\frac{F2}{F3} \right)^8 \right\}$$

Table 3-7 lists F2' frequencies calculated by this function, for selected vowels with formant frequencies close to the averages of raw data in the survey. The shifts of F2' relative to the F2-F3 interval (the "%" columns) are in agreement with the tentative hierarchy suggested above.

	F1	F2	F3	F2'	%		F1	F2	F3	F2'	%		F1	F2	F3	F2'	%
i	250	2300	3200	**3239**	**104**	**y**	290	1820	2330	**1998**	**35**	**ɨ**	360	1650	2430	**1759**	**14**
i̽	310	2180	2880	**2669**	**70**	**ʏ**	370	1620	2360	**1716**	**13**	**ɘ**	420	1590	2440	**1672**	**10**
e,ɪ	390	2030	2690	**2324**	**45**	**ø**	420	1590	2320	**1672**	**11**	**ə**	490	1470	2450	**1515**	**5**
e̞	470	1910	2600	**2110**	**29**	**œ**	480	1500	2310	**1554**	**7**	**ɜ**	540	1450	2460	**1488**	**4**
ɛ	540	1850	2580	**2009**	**22**	**ɶ**	540	1470	2350	**1513**	**5**	**ɐ̞**	700	1380	2500	**1400**	**2**
æ	650	1660	2490	**1737**	**9**	**ʉ**	330	1350	2350	**1384**	**3**	**ɯ**	390	1310	2420	**1335**	**2**
a̟	740	1530	2510	**1570**	**4**												

Table 3-7: F2' frequencies calculated by the ad-hoc function for selected vowels, from F1,F2 and F3 frequencies that are close to the averages of all raw data vowels transcribed by the particular IPA symbol.

Notice that the estimated F2’ for vowels with the same F1 and F2 and different F3, e.g. [ø] and [ɘ], are similar. Since the available sources provide no empirical F2’ data for such pairs, it was decided to tune the function such that, within typical formant ranges, larger relative F2’ shifts within smaller absolute F3-F2 ranges (as in [ø]) and smaller relative F2’ shifts within larger absolute F3-F2 ranges (as in [ɘ]), would be translated onto similar absolute F2’ shifts.

The behavior of the formula was not tested on vowels with F2 frequencies below 1200Hz, but at F2 frequencies between 1200Hz and 1400Hz the difference between the calculated F2’ and F2 is below 20Hz. In the survey, the formula is applied only on normalized vowels. Since normalized vowels with F2 frequency lower than 1350Hz are not assigned F3 frequencies, the behavior of the formula for lower F2 frequencies is of no concern. In vowels with F2 frequency lower than 1350Hz, F2’ is assigned the frequency of F2.

3.5 Correcting for language, dialect and speaker distribution

3.5.1 Background and rationale

The last major shortcoming of the corpus data in their raw form is the abundance of data from certain languages compared to others. While the vast majority of languages covered in the survey are represented by one entry (or two entries, if their inventory has a quantity contrast) based on a single study, some languages (mostly European) are represented by multiple entries based on many different studies. Such languages played a key role in devising the normalization procedures, but their multiple entries might dominate the set of entries belonging to a specific structural configuration. Unless such entries are grouped into one, the cross-linguistic acoustic geometry for the structure would be strongly biased towards very few languages and not typologically representative, especially if these languages are related or in contact.

Pooling data from different entries is not trivial, because the different entries are not equally reliable. Reliability is a function of many variables, including but not limited to the number of speakers, number of tokens recorded, methodology, researcher's experience and expertise etc. It is impossible to weight all of these factors, and it is impossible to weight any of them objectively, except for the number of speakers. In order to keep weighting objective and simple, it was decided to use the number of speakers as the only weighting factor.

3.5.2 Devising the weighting factor

In meta-analysis, if different studies of the same question are weighted according to the number of subjects, weighting is often linear. This would make sense here too, whenever different studies describe the same language variety, e.g. the vowels of RP British English. However, in most cases where a language is represented by multiple entries in the survey, it is also represented by multiple dialects. Dialects sharing the same inventory structure are nevertheless likely to differ in their precise realizations, so the average of studies of different dialects cannot be merely the average of speakers in these studies. To take a concrete example, there are 12 corpus entries for different varieties of Spanish, with a total of 141 speakers, of which 91 are from Martinez-Melgar's (1994) study of Eastern Andalusian. If linear weights were used, the averaged formant data for Spanish would be extremely biased towards Eastern Andalusian. While the entry based on Martinez-Melgar's (1994) study should weight much more than any of the other entries, it should not wipe them out, especially when cross-dialectal data from 50 speakers in eleven studies would otherwise be regarded as highly reliable and representative, when most languages are represented by one study and one or two speakers only.

It is thus clear that the weight of the number of speakers should be balanced against sufficient weighting of the availability of multiple studies, with preference for the latter. A log-based weighting therefore seems most appropriate. In the absence of any other established standard for weighting pooled data, it was decided to devise a log-based weighting function, as follows: the weight of a given entry equals the natural log of the number of speakers plus one ($W=1+\ln(N)$). Thus all entries based on only one speaker (or unknown number of speakers), have the default weight of 1, whereas an entry based on four speakers has the weight of 2.386, and the entry based on Martinez-Melgar’s (1994) 91 speakers has the maximal weight of 5.511.

Within-language weighted averaging was performed over all entries representing the same language (same ISO 639-3 code) and the same phonological structure, for raw, vocal-tract normalized and vocal-tract+method normalized data. Separate entries representing short vs. long constituents of the same phonological structure within the same language were nevertheless pooled together, even in cases where there are large acoustic differences between corresponding vowels (as in e.g. seven-vowel representation of Standard Hungarian, where long /a/ corresponds to short /ɒ/), because there is no objective a priori threshold for small vs. large acoustic difference. For simplicity, different entries based on the same study, with the same speakers but different elicitation methods, contributed to the pooled average as independent entries with equal weights.[20] Whenever the value of a particular formant of a given vowel was

[20] This independent treatment unnecessarily boosts the contribution of certain individual speakers, but it stands to reason that such studies are more comprehensive in their coverage of the acoustic patterns

missing, the weight of the entry was properly subtracted from the denominator of the weighted average for that formant of that vowel. As a result of the weighted averaging procedure, the number of entries decreased from 555 to 304, and for each structure, a given language had only one entry, with the number of speakers being the sum of speakers in all the original entries together. The F1xF2 plot in Figure 3-5 shows the merged 5S0 entry for Spanish (black '+' signs) resulting from weighted averaging of the twelve Spanish entries in the corpus (grey circles), based on data from Godinez (1978), Alvarez –Gonzalez (1981), Morimoto (1988), Almeida (1990), Martinez-Melgar (1994), Bradlow (1995), Sanders (1998), Iribar & Turrez (2001) and Guíon (2003 and p.c.).

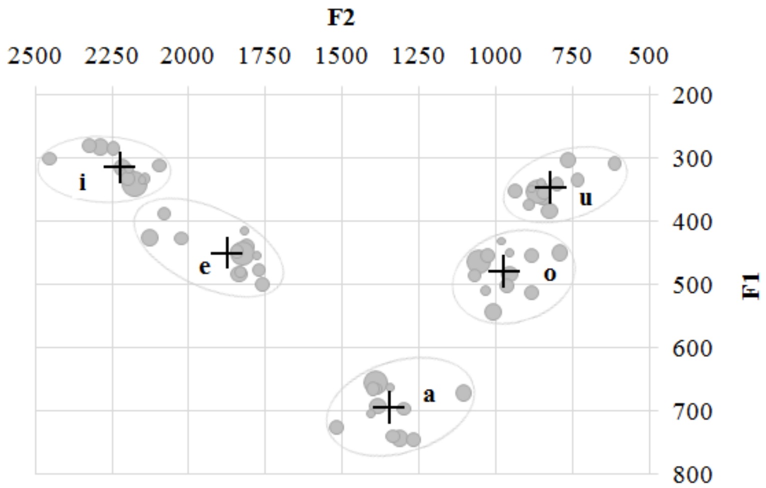

Figure 3-5: Merger of the twelve 5S0 entries of Spanish in the corpus into one using weighted average. The individual entries are represented by grey circles. Circle sizes roughly represent entry weights (1+ln(N), where N is the number of speakers). The merged Spanish entry is represented by '+' signs.

In theory, it is possible and even desirable, to use this weighting procedure between languages as well, and obtain weighted average acoustic geometries for each structure. For example, when coming to establish the cross-linguistically representative acoustic geometry for the 7S0 structure (/i e ɛ a ɔ o u/), it makes very little sense to assign

of the inventory. While it might have been useful to take only wordlist elicitation data from such studies and ignore data of other elicitation methods, this solution would be inappropriate if wordlist elicitation was not among the methods used in the study.

Eastern Dinka, whose inventory was described in one study with one speaker, the same weight as Italian, for which the survey contains 11 entries, from multiple dialects and more than 40 speakers. In practice, however, this would have enhanced the already strong European bias resulting from over-representation of European languages discussed in Section 2.2.2. In addition, assigning weights to different entries within the same structure would have complicated between-structure analysis, because in standard statistical analyses individual observations in a sample are not weighted. It was therefore decided not to apply weighting beyond within-language entry merger.

3.6 **Acoustic geometries and inventory typology**

The output of the entire data transformation process described in Sections 3-3.5 is a corpus of 304 vocal-tract normalized, elicitation-method normalized, language-specific and structure-specific inventory entries. All these entries participate in the analyses in Chapter 4. Before turning to the analyses, it is worthwhile to highlight some of the typological characteristics of corpus data. Section 3.6.1 discusses the distribution of the corpus vowels in the acoustic space and suggests characteristic formant frequencies for standard IPA vowel symbols. Section 3.6.2 is dedicated to the distribution of common inventory structures in the corpus. Section 3.6.3 examines the acoustic geometries of several structural configurations that were split to two or more structures in Schwartz et al. (1997a), and Section 3.6.4 suggests possible splits of certain well-represented structural configurations into separate acoustic geometries. Section 3.6.5 discusses the distribution of inventories with robust vowel harmony in the corpus and highlights unique characteristics of those structural configurations where vowel harmony inventories are dominant.

3.6.1 Distribution of the corpus vowels in the acoustic space

The corpus of 304 vocal-tract normalized, elicitation-method normalized, language-specific and structure-specific inventory entries comprises 2086 vowels in total. In two entries F2 frequencies could not be normalized due to absent data for a point vowel, and in four other entries formant data were missing for one vowel, leaving a total of 2065 vowels with normalized F1 and F2 frequencies (and also F3 and F2' frequencies in fronter vowels). Table 3-8 shows the proportional distribution of these vowels between the four coarse regions of the vowel space (front, low, back and non-peripheral), together with the corresponding proportions of the 1928 vowels in the 317 inventories in UPSID according to Schwartz et al. (1997a). The proportions are similar, except for the slightly higher proportion of non-peripheral vowels in the current corpus.

	Corpus		**UPSID**	
	vowels	%	vowels	%
front	743	36	715	37
low	302	15	327	17
back	730	35	681	35
non-peripheral	290	14	205	11
All	**2065**	**100**	**1928**	**100**

Table 3-8: Distribution of vowels between the four regions of the vowel space (front, low, back and non-peripheral) in the corpus and in UPSID according to Schwartz et al. (1997a).

F1 and F2 frequencies for the 2065 corpus vowels are plotted in Figure 3-6. A thin grey line demarcates an area contiguously populated by about 2000 vowels (~97%), and is assumed to represent the characteristic range of vowels pronounced without excessive effort in wordlist elicitation. Also plotted, in thick grey, are one quadratic function (curve) and two linear functions (straight lines). The curve distinguishes low from non-low vowels and the straight lines distinguish non-peripheral vowels from front and back vowels. These functions, which form a compromise between maximal discrimination and arithmetical simplicity, divide the acoustic spacesuch that 91.5% of each of the front, low and back vowels and 88.5% of the non-peripheral vowels are contained within their respective regions. These functions are as follows:

(3.10) Low vs. non-low: $F1 = (17 / 18000) \times F2^2 - (187 / 72) \times F2 + (343525 / 144)$

(3.11) Front vs. non-peripheral: $F1 = 1650 - (2 / 3) \times F2$

(3.12) Back vs. non-peripheral: $F1 = 3 \times F2 - 2835$

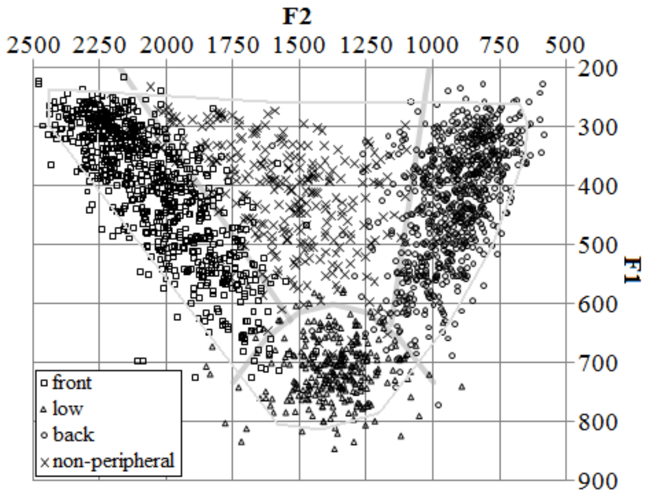

Figure 3-6: F1xF2 plot of the 2065 vowels with fully calculated formant frequencies in all the language-specific, structure-specific entries in the corpus (squares: front vowels; triangles: low vowels; circles: back vowels; 'x' marks: non-peripheral vowels. The thin grey line demarcates the area assumed to represent the characteristic range of vowels pronounced without excessive effort in wordlist elicitation. The thick grey curve and lines divide the space to the front, low, back and non-peripheral regions.

The most noticeable trends in the distribution of the vowels in the acoustic space are as follows: The front and back regions are densely populated from the high to the lower-mid levels (260Hz<F1<580Hz). The low region is densely populated in the ranges 640Hz<F1<760Hz, 1200Hz<F2<1550Hz. Despite the apparent concentration of the corpus vowels along the periphery, the periphery is not a narrow strap along the edges of the space, but rather a thick 'belt', about 350Hz wide in the front and back regions and 100Hz high in the low region. Various analyses in Chapter 4 examine whether the positions of peripheral vowels within this thick belt are regulated by

Dispersion Theory principles. The fronter two thirds of the non-peripheral region (F2>1325Hz) are moderately populated, while the backer third of the non-peripheral region (F2<1325Hz) and the near-low part front and back regions (600Hz<F1<700Hz) are somewhat more sparsely populated. A large region around maximally high [ʉ] (F1<320Hz, 1100Hz<F2<1500Hz) is unpopulated altogether, although there is no articulatory obstacle for producing a vowel with F1 frequency similar to [y] and [ɯ] and F2 frequency between them. The distributional patterns of non-peripheral vowels are also analyzed in Chapter 4.

Figure 3-7 tentatively suggests characteristic F1 and F2 frequencies for the 28 vowel symbols on the standard IPA vowel chart, within the range of vowels pronounced without excessive effort in wordlist elicitation. . The IPA symbols in Figure 3-7 are used, often with diacritics, in narrow transcriptions of vowel qualities throughout the rest of Section 3.6, Chapter 4 and Appendix B.

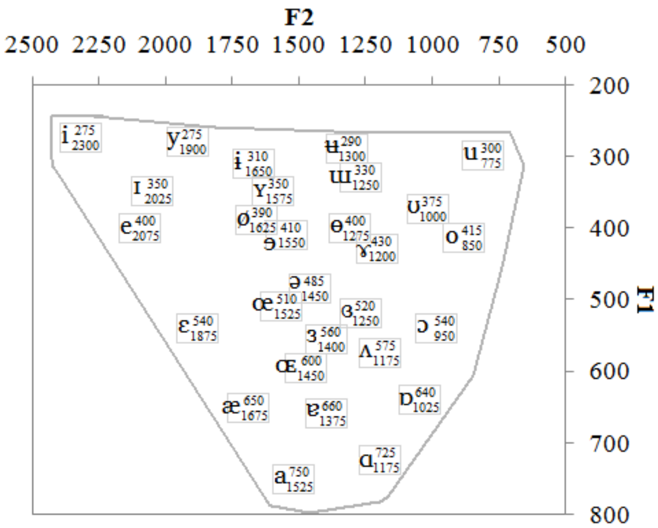

Figure 3-7: F1xF2 plot of representative formant frequencies of the 28 standard IPA vowels, used in narrow transcriptions of vowels throughout the rest of the dissertation.

3.6.2 *Coverage of inventory typology*

Out of the 304 language-specific, structure-specific entries in the corpus, 237 belong to the 17 structural configurations whose averaged acoustic geometries are likely to be sufficiently representative, as they are represented in five different entries or more. Table 3-9 lists these structures, each with the number of entries in which it appears in the corpus and in UPSID (based on Roark 2001 and, in the case of ten-vowel structures, on Schwartz et al. 1997a).

structure	entries	UPSID	structure	entries	UPSID	structure	entries	UPSID
3S0	20	19	5S2a	14	12	7S1	6	8
3S1	7	7	6L0	8	12	7S2	12	11
4L0	7	14	6L1	8	8	7S3a	5	(1)
4L1	7	5	6L2	9	2	9S0	12	7
5S0	42	97	6R0	12	4	9S1	8	(3)
5S1	26	41	7S0	34	27			

Table 3-9: Structural configurations appearing in five or more language-specific, structure-specific entries in the corpus, and their corresponding number of instances in UPSID according to Roark (2001) and Schwartz et al. (1997a).

Appendix B describes, for each of these 17 structural configurations, the fully transformed acoustic geometries, in terms of averages and standard deviations of formant frequencies (F1, F2, F3 and F2') of all the vowels, and of formant spans (F1 and F2) and F1xF2 area function of the polygon encircled by the lines connecting adjacent peripheral vowels. In each structure, the average standard deviation magnitudes, calculated from all vowel categories, is between 7.5% and 12.6% of the formant frequencies, and the grand average of standard deviation magnitudes from all structures together is 9.96% of the formant frequencies. It can therefore be assumed that the acoustic geometries in Appendix B sufficiently represent their respective structural configurations.

There are 12 structures appearing seven times or more in UPSID: 3S0, 3S1, 4L0, 5S0, 5S1, 5S2a, 6L0, 6L1, 7S0, 7S1, 7S2, 9S0. All these structures appear in six entries or more in the corpus, and their acoustic geometries appear in Appendix B. Among the remaining structures whose acoustic geometries are established, two (4L1, 6R0) appear in UPSID four or five times. These 14 common structures cover 84% of UPSID (and 70% of the entries in the current corpus). Owing to the rigorous language sampling applied towards the construction of UPSID, it is likely that the same 14 structures together account for a similar proportion of the world's languages. Together with the remaining structures that are rare in UPSID but well represented here (6L2, 7S3a, 9S1), it is likely that the corpus provides representative acoustic geometries for structures covering more than 85% of the world's languages. There are only three other structures appearing in UPSID four or five times (4R0, 4R1, 5S3), which are rare in the corpus. At the end of Appendix B, five other structural configurations, appearing in four languages each**,** are listed with their average formant frequencies, and all other structures are listed only with the languages in which they appear.

3.6.3 Merger of structures split elsewhere

Schwartz et al. (1997a) is the only typological study of inventories that combines rigorous classification of inventories into structural configurations with attention to phonetic detail (as much as can be learned from inventory transcriptions without acoustic data). It is therefore worthwhile to review the properties of acoustic geometries of certain structural configurations where there seems to be a difference between their treatments in Schwartz et al. (1997a) and in the current corpus, specifically where Schwartz et al. (1997a) list more than one structure where the current corpus (and also Crothers 1978 and Roark 2001) recognize only one. The following discussion is by no means systematic and comprehensive, and is intended only to highlight the potential typological insights from the current corpus.

For small structures with one back vowel (3S0, 3S1, 4L0, 4L1), Schwartz et al.'s (1997a) typology suggests vertical high-to-mid variability in the back vowel, corresponding to a consistently high front vowel. For example, 3S0 varies between /i a u/ and /i a o/, and 4L0 similarly varies between /i ẹ a u/ and /i ẹ a ọ/. Similar variability is presumably attested in the non-peripheral vowel in 3S1 and 4L1. Due to these two variable categories, one finds 3S1 inventories labeled as /i a u ə/, /i a u ɨ/ and /i a o ɨ/. Such variability should be manifested in greater variance of F1 frequencies for the back and non-peripheral vowels in these structures, both in comparison with the corresponding front vowel and with most vowels in all other structures.

The acoustic data in the current survey suggest otherwise. Figure 3-8 shows F1xF2 plots for these four structures (repeated from Appendix B) with vowel categories represented by averages and one standard deviation ranges of their formant frequencies (back and non-peripheral vowels are in black, other vowels in grey). F1 standard deviations of the back and non-peripheral vowels in these structures are not always greater than those of the (higher) front vowel. Given that the cross-structure, cross-category average standard deviation of F1 frequencies is 51Hz, only the back vowel in 3S1 has an exceptionally large F1 standard deviation of 86Hz, which is nevertheless mirrored by a large F1 standard deviation of 68Hz in the front vowel in the same structure.

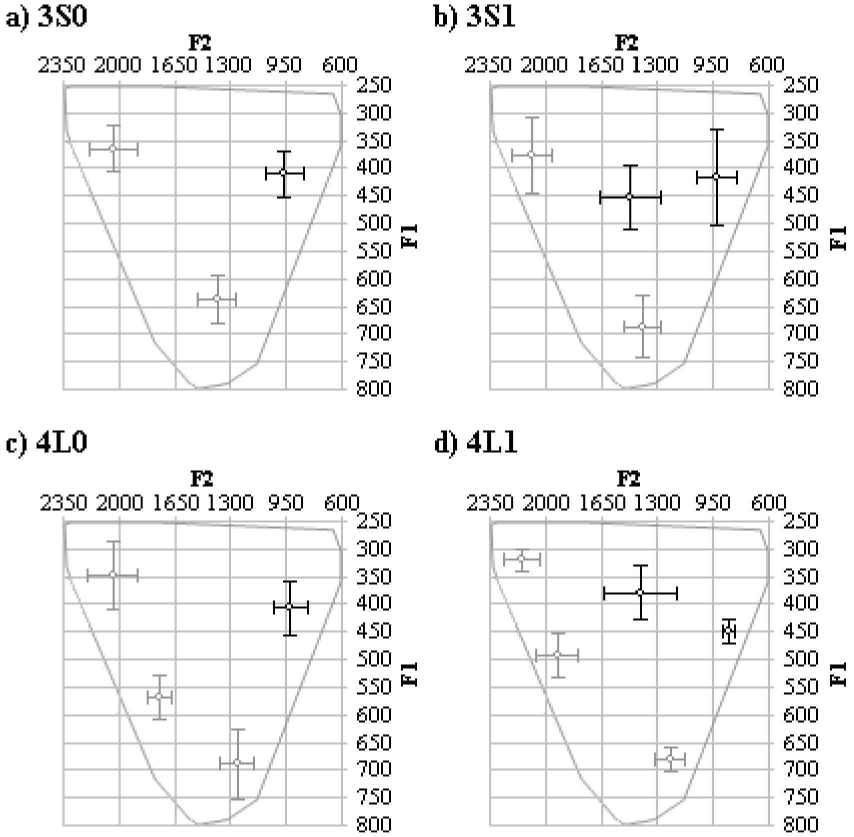

Figure 3-8: F1xF2 plots of the acoustic geometries of the structures (a) 3S0, (b) 3S1, (c) 4L0 and (d) 4L1, repeated from Appendix B. Each vowel category is represented by its one standard deviation ranges for F1 and F2. The back vowel in all structures and the non-peripheral vowel in 3S1 and 4L1 are in black, all other vowels are in grey.

There is no evidence for a split between structures with a high vowel and structures with a mid vowel in the back and non-peripheral regions. Instead, there is a continuum of vertical (F1) differences between the front vowel and the back and/or non-peripheral vowel, with the front vowel being anywhere between negligibly lower (F1 higher by up to 25Hz) to markedly higher (F1 lower by up to 140Hz) than the other vowels. However, given the rather similar F1 standard deviations, F1 variability of the front vowel is just as accountable for these differences as F1 variability of the back and/or non-peripheral vowel. Moreover, there seems to be no correlation between an explicit transcription of height contrast between the front vowel and the back/non-peripheral vowel and F1 difference. For example, among the twenty 3S0 entries, in the three entries with the largest F1 difference between the front and the back vowel (a difference larger than 95Hz in the normalized data), these vowels are transcribed as having the same height (/i u/ in Amis, Maddieson & Wright 1995; /ɪ ʊ/ in Quichua, Guíon 2003, and in Punjabi, Singh 2005). Conversely, in Chickasaw (Gordon et al. 1997) these two vowels are transcribed as /i o/ although the F1 difference between them is as small as 45Hz. At least in the case of the back vowel, the high-mid split in the back vowel attested in typological studies seems to be an artifact of inconsistent transcriptions, which probably result from the fact that the characteristic (normalized) F1 frequency range for this vowel is 400-425Hz, which is ambiguous between high and mid. The F1 frequency of the front vowel, on the other hand, is typically 50Hz lower and seldom reaches 400Hz, which makes it far more likely to be consistently transcribed as a high vowel.

The alleged variability of the back vowel in 4L0 between high and mid led some scholars to interpret this structure as a 'defective' form of 5S0, where the back vowel corresponds to one of the front vowels, and the other front vowel has no back counterpart. In her commentary on vowel inventories in UPSID, Ferrari-Disner (1984) distinguishes such structures (/i ẹ a u/ and /i ẹ a ọ/) from a small minority of 4L0 structures that repair the imbalance by shifting the vowels to cover the vowel space more evenly, creating the structure /i ɛ ɑ ʊ/. The acoustic geometry of 4L0 established here suggests that the latter structure (or its somewhat centralized version) is the rule. The independence of this structure from 5S0 is apparent in Figure 3-9, where the two geometries are plotted together (4L0 in black, 5S0 in grey). Each of the 4L0 vowels is distinct from the 5S0 vowel(s) closest to it, a fact manifested in the narrow transcriptions of the prototypical vowels in each structure in Appendix B ([ɪ ɛ̝ a̽ o̟] for 4L0, [ɪ̽ e̽ e̞ o̽ u̽] for 5S0).[21] The position of the back vowel [o̟] in 4L0 halfway between the high back [u̽] and mid back [o̽] in 5S0, hence a position ambiguous between typical high and mid, is also apparent.

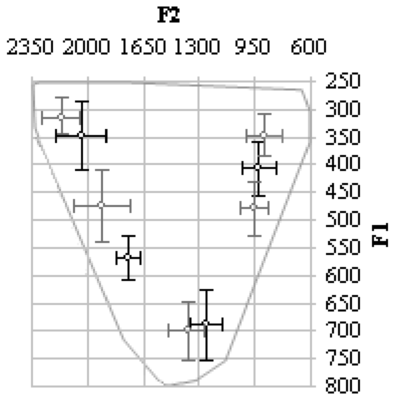

Figure 3-9: F1xF2 plot of the acoustic geometries of 4L0 (black) and 5S0 (grey) together.

Another striking case of merger of a category split elsewhere is the homogeneous vertical quality of the non-peripheral vowel in 5S1, as expressed by its relatively narrow distribution of F1 frequencies (standard deviation: 46Hz). While the peripheries of such inventories are nearly always transcribed as /i e a o u/, the transcription of the non-peripheral vowel, in descriptive studies as well as in acoustic studies included in the survey, varies from high (/y ɨ ʉ ɯ/) through near-high (/ɪ ʏ/), higher-mid (/ø ɘ ɤ/) to mid (/ə/). Schwartz et al. (1997a) accordingly treat 5S1 structures with /ɨ/ vs. /ə/ as two distinct structures that are both common cross-linguistically. Yet the acoustic geometry of 5S1, shown in Figure 3-10, suggests that

[21]Standard IPA diacritics are used here in narrow transcriptions, denoting mostly raising, lowering, fronting, retraction and mid-centralization (e.g. [ʊ̝ ʊ̞ ʊ̟ ʊ̠ ʊ̽] respectively). These diacritics usually indicate F1 deviations of 30-50Hz and F2 deviations of 100-150Hz relative to the characteristic formant frequencies of IPA vowels. For example, assuming that [ʊ] has the characteristic formant frequencies: F1 = 375Hz, F2 = 1000Hz, then [ʊ̞] denotes a vowel around F1 = 410Hz, F2 = 1000Hz, [ʊ̟] denotes a vowel around F1 = 375Hz, F2 = 1125Hz, and [ʊ̽] denotes a vowel around F1 = 410Hz, F2 = 1125Hz.

the F1 frequency of the non-peripheral vowel category (in black) is more tightly grouped than some of the peripheral vowels (in grey) in the structure.

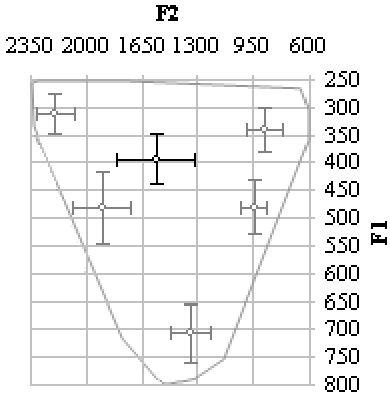

Figure 3-10: F1xF2 plot of the acoustic geometry of structure 5S1, repeated from Appendix B. The non-peripheral vowel appears in black, all other vowels are in grey.

The average F1 frequency of the 5S1 non-peripheral vowel at 394Hz suggests a distinct height level, which is slightly closer to the high vowels (combined F1 average: 326Hz) than to the mid vowels (combined F1 average: 481Hz). However, logarithmic-like perceptual scales (log(Hz), ERB) would render this vowel even closer to the position halfway between high and mid, as the Hz formant ratios are virtually identical (326/394=0.827; 394/481=0.819).

There have been a few cases where a vertical split (two structures distinguished by a higher vs. lower vowel) in Schwartz et al. (1997a) are merged into one in the current survey, but the merged vowel category is indeed characterized by an exceptionally wide F1 frequency distribution. Such is the case in the lower front vowel in 6L0 (F1 standard deviation: 86Hz), where Schwartz et al. (1997a) distinguish between an asymmetrical (left-crowded) structure with one low vowel and a symmetrical structure with two low vowels. The non-peripheral vowel in 6L1 also has a wide vertical distribution (F1 standard deviation: 106Hz), corresponding to a distinction between two 6L1 structures, with high vs. mid non-peripheral vowels, in

Schwartz et al. (1997a). The acoustic geometries of both structures are plotted in Figure 3-11, with the widely distributed vowel categories in black and all others in grey. In both cases, the merged structure is represented in the survey by eight languages only and cannot be split into two structures with coherent acoustic geometries, for which at least five languages are required.

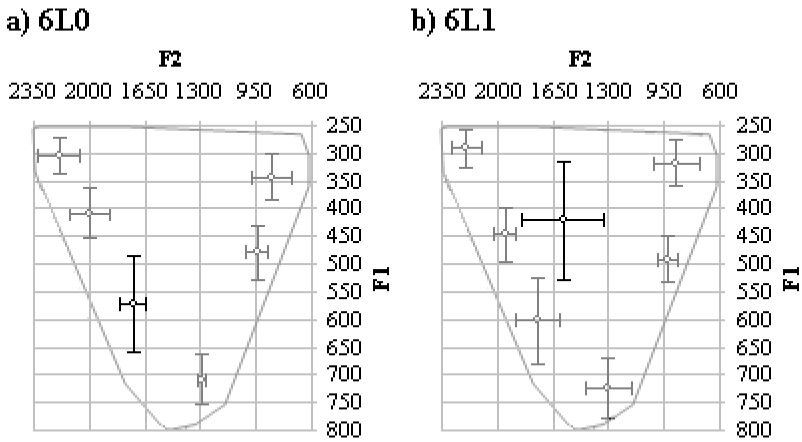

Figure 3-11: F1xF2 plots of the acoustic geometries of the structures (a) 6L0 and (b) 6L1, repeated from Appendix B. The lower front vowel in 6L0 and non-peripheral vowel in 6L1, with their wide F1 ranges, are in black, all other vowels are in grey.

3.6.4 Split of structures merged elsewhere

The structures 5S0, 5S1 and 7S0 are all very frequent in the survey (respectively 42, 26 and 34 languages), making it possible to search for sub-geometries, using the vowel categories with the widest data distribution as natural candidates for geometry splits.

In 5S0, the mid front vowel had the widest distribution. The data distribution of this vowel category suggested three distinct trends: a major variant resembling the global average of the category, a high and tense minor variant and a low and lax minor variant. The former co-occurred with a fronted low vowel and overall tenseness (peripheralization and raising) in the non-low vowels, and the latter with a raised low vowel and overall laxness (centralization and lowering) in non-low vowels. The entire

5S0 dataset was partitioned manually, in a manner that maximizes these tendencies, into three sub-geometries: a major sub-geometry [i̽ e̽ ɐ̞ o̽ u̽] (23 languages) almost identical to the global 5S0 geometry, a 'lax' minor sub-geometry [ɪ̝ ɛ̠ ɐ ɔ̟ ʊ] (11 languages) and a 'tense' minor sub-geometry [i̞ e̞ a̝ o̞ u̞] (8 languages). Figure 3-12 plots F1 and F2 averages and standard deviations for the 5S0 geometries (global geometry in (a) and the sub-geometries in (b): major in black; 'lax' minor in dark grey; 'tense' minor in light grey).

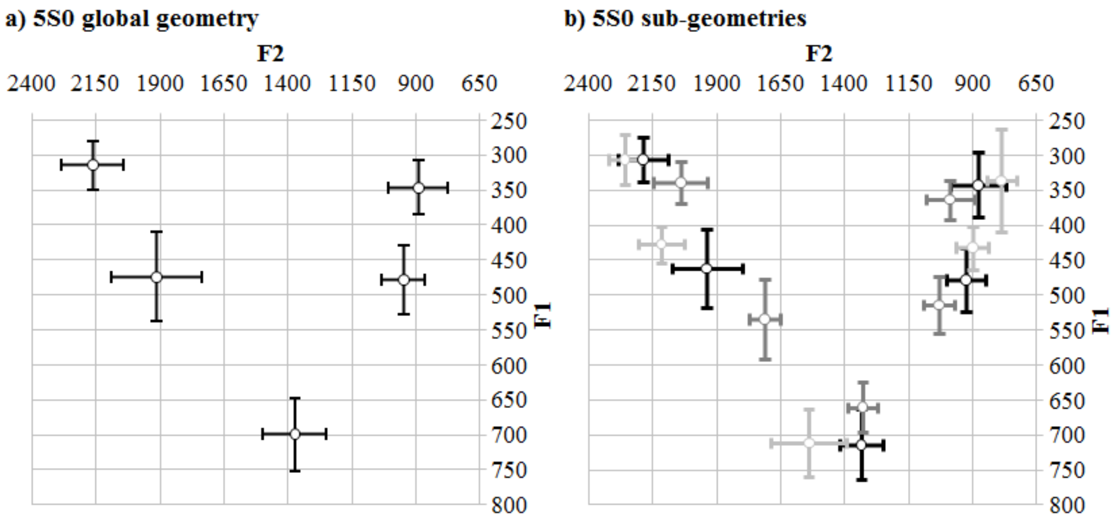

Figure 3-12: F1xF2 plot of means and standard deviations of the vowels in the global 5S0 geometry based on 42 languages (panel a) and its three sub-geometries (panel b): the major sub-geometry (black, 23 languages), the 'lax' minor sub-geometry (dark grey, 11 languages) and the 'tense' minor sub-geometry (light grey, 8 languages).

As seen in Figure 3-12, this partition results in complete separation (no overlap) between the one standard deviation ranges of the corresponding categories in the two minor strategies, and in overall reduction of standard deviations of F1 and F2. Among the new 30 standard deviations (2 formants x 5 vowels x 3 sub-geometries), 26 are smaller than their correspondents in the global 5S0 geometry.

There is no apparent principle that explains the differences between the three sub-geometries, but they are not an artifact of the normalization process. A split between a peripheralized sub-geometry and a centralized sub-geometry could have been an artifact of the concentric anchoring of inventories as part of vocal-tract normalization. However, there is no reason why such a split should be correlated with vertical separation in mid vowels, where the only relevant dimension for peripheralization vs. centralization is horizontal, and with horizontal separation in the low vowel, where only the vertical dimension is relevant. Elicitation method normalization cannot be held accountable either because the distribution of methods is similar across the three datasets. Finally, the datasets did not differ in the distribution of quantity constituents (long, short, uniform etc.) either.

In 5S1, the most widely distributed vowel is the non-peripheral, due to its wide range of F2 frequencies (2032≥F2≥1105). Gaps in the distribution of this category's formant data suggested a three-way split between fronted (F2≥1540Hz, 14 languages), higher-central (F1≤412Hz, 1422≤F2≤1471Hz, 6 languages) and lower-retracted (F1≥419Hz, F2≤1380Hz, 6 languages). This partition resulted in rather distinct sub-geometries. The first sub-geometry, with the fronted non-peripheral vowel, had a periphery almost identical to the global 5S1 geometry ([i̝ e̽ ɐ̝ o̽ u̽ ɪ̠-ʏ̟]).[22] The second, with the higher-central non-peripheral vowel, was tenser overall ([i e̝ a̠ o̽ u ɘ̝-ʏ̠]), its mid-front vowel being higher and tenser (average F1: 453Hz, average F2: 1994Hz) and its low vowel fronter (average F2: 1411Hz). The third, with the lower-retracted non-peripheral vowel, was more centralized overall ([ɪ̽ ɛ̽ ɑ̽ o̽ u̽ ɤ-ɵ̝]), its mid-front vowel was lower (average F1: 514Hz, average F2: 1752) and its low vowel was

[22]Non-peripheral vowels in the acoustic geometries are usually ambiguous between a more advanced rounded vowel and more retracted unrounded vowel. In the narrow transcriptions here, these ambiguities are reflected by a hyphenated pair of symbols, the first denoting the unrounded option and the second denoting the rounded option, e.g. [ɪ̠-ʏ̟].

retracted (average F2: 1252Hz). However, these splits failed to reduce formant standard deviations except in the non-peripheral vowel category, and for each pair of sub-geometries, all corresponding peripheral categories remained partly overlapping. These splits are therefore considered tentative and are not discussed further.

In 7S0, the most widely distributed category was the lower-mid front vowel. With the exception of two languages where this vowel was extremely high ([e], F1<425Hz), its data suggested a dichotomous split between mid to lower-mid realization ([ě̈-ɛ] 460Hz<F1<580Hz, 23 languages) and near-low realization ([æ], F1>615Hz, 9 languages). The latter, minor sub-geometry ([i e æ ɑ ɒ̣ o u]) had a distinctly retracted low vowel and more peripheralized realization overall, while the former, major sub-geometry ([i̠ e ɛ̝ a̠ ɔ̟ o̟ u̟]) had a slightly fronted low vowel and negligible centralization elsewhere relative to the global 7S0 geometry. In order to maximize the geometry split, two languages were moved from the majority to the minority sub-geometry due to their general F1xF2 shapes.[23] Though this split failed to reduce within-category distribution and there is overlap between the realizations of most categories, it is probably genuine. It is clearly attested in UPSID (Madison 1984), where three 7S0 languages (out of 23) are transcribed with /æ/ rather than /ɛ/, and is also known as an isogloss in Tuscan Italian dialectology (Calamai 2001, 2002a, 2002b).[24] Figure 3-13 plots F1 and F2 averages and standard deviations for the 7S0 geometries (global: thin black, major: dark grey, minor: light grey).

[23] The inventory of Bengali, one of these two languages, is consistently transcribed as containing /æ/ rather than /ɛ/, both in the two studies included in the survey and in UPSID and many other sources.

[24] In the survey, the /ɛ/ vs. /æ/ split in the Italian data was removed due to within-language data merger. It can nonetheless be seen in the cross-entry Italian data plotted in Figure 3-4 in Section 3.3.3, where one token of /ɛ/ appears consistently with distinctively high F1 frequency.

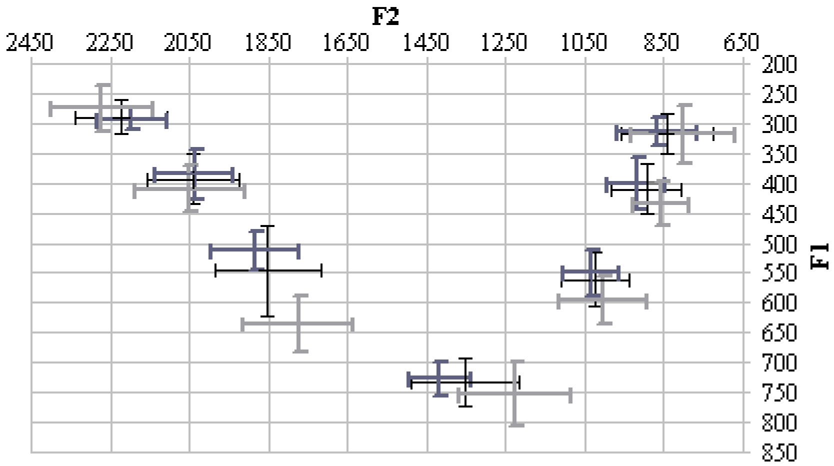

Figure 3-13: F1xF2 plot of means and standard deviations of the vowels in the global 7S0 geometry (thin black lines, 34 languages) and its two sub-geometries, major (dark grey, 21 languages), and minor (light grey, 11 languages).

In the analyses in Chapter 4, the sub-geometries of structures 5S0, 5S1 and 7S0 suggested here will be ignored. However, it is worthwhile to recognize them, as they might be useful if acoustic geometries established here are to serve in the future in the evaluation of simulated formal models predicting vowel inventories.

3.6.5 Cross-structure distribution of inventories with robust vowel harmony

Out of the 304 inventory entries, 27 are specified as participating in robust vowel harmony patterns, i.e. inventories that comprise two sub-systems. The harmonizing feature may be frontness, pharyngealization, register or ATR, respectively exemplified by Võru, Khalkha, Somali and Degema. The sets of entries of most structural configurations include very few inventories with vowel harmony, if any, so whatever effect vowel harmony may have on the acoustic geometry of a particular entry becomes negligible at the cross-linguistic level. However, in the structures 9S0 and 9S1 vowel harmony inventories are the majority. All these inventories manifest ATR harmony and belong to the Niger-Congo or Nilo-Saharan families. This generalization holds for all of the instances of these structures in UPSID as well. One distinctive property immediately observable in the acoustic geometries of these structures is the close proximity and the overlap between certain vowels, in particular the second and third highest vowels in both the front and the back region. This is shown in Figure 3-14, with the overlapping vowels in black and all other vowels in grey.

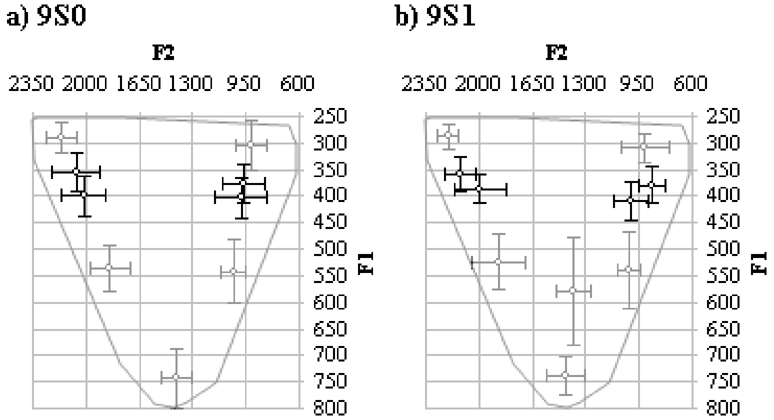

Figure 3-14: F1xF2 plots of the acoustic geometries of the structures (a) 9S0 and (b) 9S1, repeated from Appendix B. The second- and third-highest vowels, which overlap in both the front and back regions in both structures, are in black, all other vowels are in grey.

Such proximity between vowels is not attested in any of the other acoustic geometries established here. This and several other properties of the acoustic geometries of 9S0 and 9S1 (and also 10L0 and 10R0) set these structures apart from others, and will be discussed in greater detail in the context of various analyses in Chapter 4. From a typological point of view it is important to notice that these generalized phonogical structures appear very rarely in languages without vowel harmony, and their viability seems to depend on the presence of vowel harmony in the language.

4. Analyses

In this chapter, the corpus data are used to test various predictions of Dispersion Theory. General predictions are set forth in Section 4. Section 4.2 analyzes the relationship between entire inventory complexity and acoustic space size. Sections 4.3-4.5 are dedicated to the effects of local structural differences on individual vowels: point vowels in Section 4.3, peripheral mid vowels in Section 4.4 and non-peripheral vowels in Section 4.5. Section 4.6 is dedicated to even spacing between vowels. Section 4.7 summarizes the insights gathered from all the analyses, proposes modifications necessary for improving existing formal dispersion models, and outlines directions for future research.

4.1 Dispersion Theory and its predictions

In order to test the validity of Dispersion Theory, it is necessary to set forth its predictions explicitly. As mentioned in Section 1.3.2 the term 'Dispersion Theory' does not refer specifically to any one formal model, but to the general concept of dispersion as a common denominator in studies of different kinds: theoretical, computational, experimental or descriptive.

As can be seen from the acoustic geometries appearing in Appendix B, vowels seldom reach the edges of the acoustic space, which implies that the classical approach of maximization of dispersion as a single factor cannot be assumed. Instead, the approach assumed here is that of 'sufficient dispersion' (Lindblom 1986), or alternatively, a balance between maximization of dispersion and minimization of articulatory effort (ten Bosch 1991a,b). Such an approach has been assumed in most studies that test Dispersion Theory empirically, in particular studies comparing acoustic space size and vowel variability as a function of the number of vowels in the inventory (Ferrari-Disner 1983, Jongman et al. 1989, Bradlow 1995, Guion 2003, Recasens & Espinosa 2006, 2009).

The first and most basic prediction of Dispersion Theory according to this approach is that acoustic space area and structural complexity should be correlated. This prediction holds both for entire inventories and for inventory components, like series (e.g. the front unrounded vowels) or any set of adjacent vowels (e.g. the set of peripheral, non-high, non-back vowels). Dispersion Theory predicts that the acoustic area and/or formant frequency spans that such inventory components cover should be correlated with the number of vowels comprising them. Any structural change in such components should be reflected in a change in the acoustic area they cover, which should further affect the acoustic geometry of the entire inventory. For example, adding a new vowel between two existing vowels significantly shortens the perceptual distances associated with these two vowels and should lead to their repulsion away from the new vowel. Consequently, they might fall closer to other vowels, which are repelled further, albeit by a smaller magnitude, and this process propagates as a push chain shift with gradual decay through other vowels until the entire system finds a new balance.

In order to simplify the testing and discussion of the adaptive behavior of vowels, predictions will be made along one acoustic dimension at a time (F1 or F2/F2'). Furthermore, in order to simplify the statistical analyses and make them more robust, structural components not directly related to the hypothesis tested are assumed to be constant even when they are not. For example, in tests of the effect of the presence or absence of one peripheral vowel on the quality of another, the entire non-peripheral region is assumed to exert no effect regardless of the number of non-peripheral vowels. Similarly, in tests of the behavior of a certain vowel as a function of peripheral symmetry or skewedness, inventories may be grouped into categories like symmetrical, left-crowded or right-crowded regardless of the number of vowels in the entire periphery or elsewhere (so, for example, 5S0, 5S2, 7S1 and 9S3 all count as 'symmetrical').

The predictions of Dispersion Theory are assumed to be as follows:

a) Inventories with more vowels should have wider formant frequency spans and cover larger space sizes than inventories with fewer vowels.

b) Similarly, more crowded regions should cover greater formant spans than less crowded regions. For example, the F1 span from highest to lowest front vowel should be greater than the span for back vowels in a left-crowded periphery.

c) A crowded region repels other vowels. For example, in left-crowded periphery inventories, the low vowel should be relatively more retracted.

d) Vowels should be evenly spaced. Given the correct representation of the perceptual space, distances between adjacent vowels should be similar across vowel pairs.

In each of the following analysis sections, the general predictive principles described here will be translated into more explicit and concrete predictions.

4.2 Entire vowel space effects

According to the view of Dispersion Theory assumed here, inventories with more vowels should cover larger proportions of the available acoustic space. This prediction is strongly supported by the survey data, as described in Section 4.2.1 and analyzed in Section 4.2.2. As the available acoustic space is finite, the correlations between structural complexity and formant spans are modeled as asymptotic curves, which are described and discussed in Section 4.2.3.

4.2.1 Structure and space size – descriptive statistics

In the survey, entries have three structural indices: the total number of vowels (V), the number of peripheral vowels (P) and the number of non-peripheral vowels (NP). Entries also have three space size indices: area of the peripheral polygon[25] (in 10000Hz² units), $F1_{SPAN}$ and $F2_{SPAN}$. Table 4-1 summarizes the averages and standard deviations of the space size indices as a function of the structural indices.[26] Parenthesized indices represent only inventories without vowel harmony, whenever inventories with vowel harmony constitute a significant proportion of the sample.

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[25] The area of the peripheral polygon was calculated as the sum of areas of triangles between whose corners are adjacent peripheral vowels and the inventory centroid. Polygons were extended to include high non-peripheral vowels if they were outside the polygon (above the line connecting the high back rounded and high front unrounded vowels), which was often the case in 4L1 inventories but rarely elsewhere.

[26] On the right, the structural indices are grouped in a manner that emphasizes trends in the data and is also structurally meaningful. Grouping of V is based on the likelihood of non-peripheral vowels (3-4: rare; 5-6: possible, but rarely more than one, i.e. not as a series; 7-9: likely, including as a series; 10-14: rarely absent, and in addition, such 'extra-large' inventories are typologically very rare, see Schwartz et al. 1997a). Grouping of P is based on the number of members in the shortest peripheral vertical series (3-4: one vowel; 5-6: two vowels; 7-8: three vowels; 9-10: four vowels). Grouping of NP is based on the likelihood of non-peripheral vowel series (0-1: impossible, 2-6: rarely absent).

V	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**	**V**	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**
3	20	13.52±5.52	275±64	1075±234	**3-4**	35	15.88±7.16	296±85	1109±239
4	15	19.03±8.04	323±103	1154±245					
5	55	27.83±10.00	389±80	1318±223	**5-6**	105	28.26±9.14	395±77	1330±209
6	50	28.73±8.16	401±74	1343±194					
7	62	34.11±9.95	434±71	1395±213	**7-9**	126	34.46±9.39	431±72	1408±204
8	28	34.62±7.55	418±64	1449±174					
9	36	34.92±9.92	435±81	1397±213					
	(25)	(36.49±9.72)	(434±85)	(1443±209)					
10	24	34.60±8.60	450±71	1385±168	**10-14**	38	36.28±9.62	446±67	1429±189
	(16)	(35.96±9.50)	(452±78)	(1425±151)					
11	7	34.47±8.74	414±59	1431±226					
12-14	7	43.65±11.36	464±57	1573±174					
P	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**	**P**	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**
3	31	16.55±8.25	305±89	1159±278	**3-4**	52	19.63±9.96	326±86	1196±253
4	21	24.16±10.73	357±74	1251±205					
5	87	28.82±9.53	398±81	1328±212	**5-6**	144	30.26±9.30	401±79	1358±221
6	57	32.46±8.55	406±78	1404±228					
7	61	35.63±9.26	446±65	1420±185	**7-8**	79	36.18±9.14	443±65	1432±187
8	18	38.00±8.74	435±63	1472±193					
9	23	34.76±10.48	460±75	1366±172	**9-10**	29	34.78±10.24	458±68	1353±190
	(8)	(41.47±10.79)	(503±65)	(1448±136)		(11)	(41.02±11.48)	(490±60)	(1450±157)
10	6	34.90±10.21	451±39	1302±262					
	(3)	(39.82)	(458)	(1456)					
NP	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**	**NP**	**entries**	**area**	**$F1_{SPAN}$**	**$F2_{SPAN}$**
0	144	28.23±11.42	394±97	1288±246	**0-1**	216	28.61±10.92	396±90	1307±227
1	72	29.36±9.87	401±76	1346±180					
2	53	33.97±9.07	428±72	1443±184	**2-6**	88	34.73±9.69	425±73	1450±198
3	27	35.04±8.78	421±68	1454±212					
4-6	8	38.73±15.59	420±103	1486±267					

Table 4-1: Averages and standard deviations of space size indices – area (in 10000Hz²), $F1_{SPAN}$ (in Hz) and $F2_{SPAN}$ (in Hz) – as a function of number of vowels (V), peripheral vowels (P) and non-peripheral vowels (NP). The structural index values on the left are grouped on the right. For V,P = 9~10, where vowel harmony inventories form at least a significant minority, parenthesized space size indices are based only on inventories without vowel harmony.

Local inconsistencies aside, space size indices clearly expand with increments in structural indices, as predicted. The most convincing cases are: area as a function of V and NP, $F1_{SPAN}$ as a function of V and P, and $F2_{SPAN}$ as a function of NP. These trends are more consistent when adjacent values of the structural indices are grouped. The only major deviants are the behaviors of the $F2_{SPAN}$ and area indices as a function of P, which expand up to P=8, and then shrink back. However, the parenthesized $F2_{SPAN}$ and area indices for P>8 are larger and consistent with predictions, indicating that these deviations are due to the narrower F2 span in inventories with vowel harmony, which comprise two smaller sub-systems. Figure 4-1 displays the averages and standard deviations of (a) the area, (b) $F1_{SPAN}$ and (c) $F2_{SPAN}$ indices as a function of grouped values of V (darker grey bars), P (lighter grey bars) and NP (white bars). The indices for P=9-10 are based on data of inventories without vowel harmony.

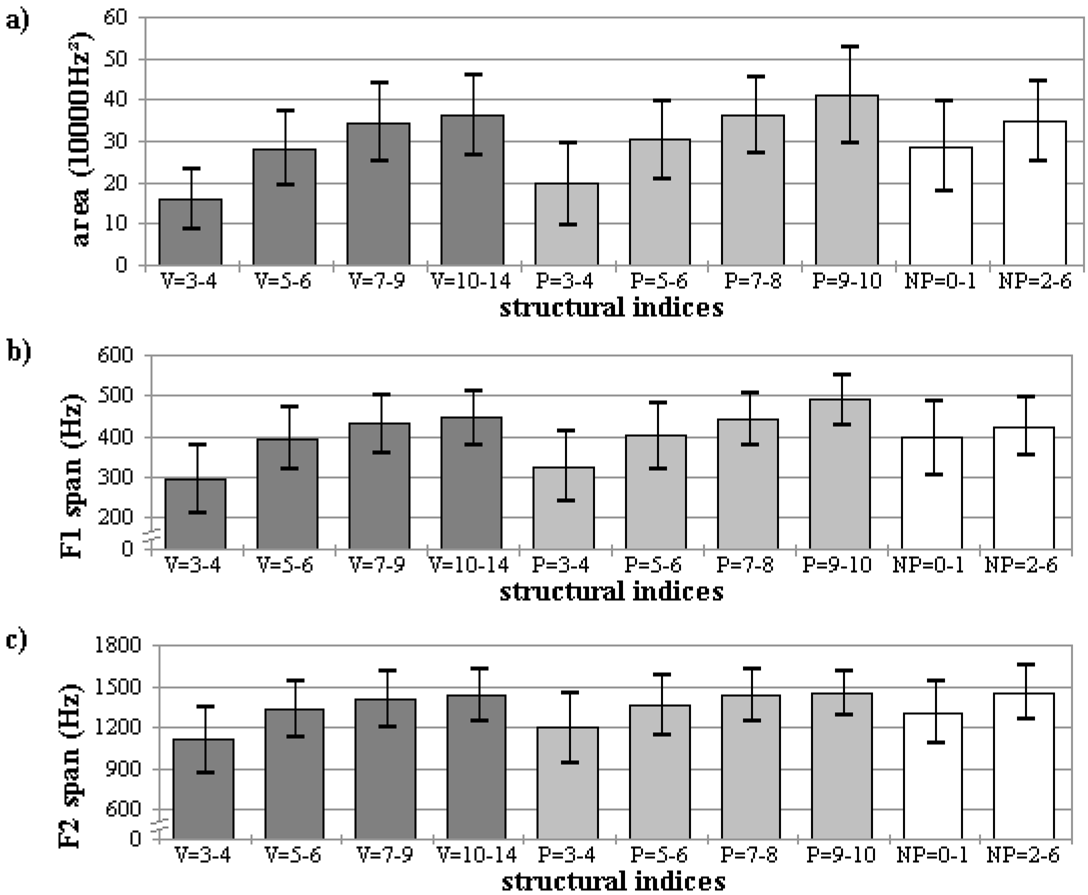

Figure 4-1: Averages and standard deviations of area (a), $F1_{SPAN}$ (b) and $F2_{SPAN}$ (c) as a function of grouped indices of total number of vowels (V, darker grey), number of peripheral vowels (P, lighter grey) and number of non-peripheral vowels (NP, white). The indices for P=9-10 are based only on inventories without vowel harmony.

4.2.2 Structure and space size – analyses

Pearson coefficients were calculated between structural indices and space size indices based on all 304 inventory entries. As the acoustic space is limited, dependency of space size on structural complexity is expected to be asymptotic rather than linear, i.e. the greater the structural index, the smaller the increment in space size should be for further increment of the structural index. Accordingly the structural indices were converted into asymptotic indices: 1/(1+1/V), 1/(1+1/P) and 1/(1+1/(NP+1)), and Pearson coefficients were calculated between these asymptotic structural indices and the space size indices as well. Notice that, for each of these indices, the asymptote equals 1, and that the index for non-peripheral vowels is adjusted to allow the value NP=0. Table 4-2 summarizes the r^2 values for the various correlations. Correlations based only on the 277 entries of inventories without vowel harmony are in parentheses.

	V	**P**	**NP**	**1/(1+1/V)**	**1/(1+1/P)**	**1/(1+1/(NP+1))**
area	0.257 (0.306)	0.232 (0.306)	0.068 (0.091)	0.313 (0.356)	0.285 (0.325)	0.057 (0.072)
$F1_{SPAN}$	0.180 (0.202)	0.201 (0.243)	0.020 (0.035)	0.246 (0.269)	0.240 (0.260)	0.020 (0.033)
$F2_{SPAN}$	0.135 (0.181)	0.075 (0.132)	0.090 (0.100)	0.171 (0.214)	0.107 (0.148)	0.087 (0.090)

Table 4-2: r^2 values for the correlation between structural indices and space size indices of all the inventories in the survey. The structural indices appear both in regular and asymptotic form, where the asymptote is always 1. In parentheses: r^2 values for correlations based only on inventories without vowel harmony.

Each of the space size indices is clearly correlated with V and P, and these correlations are stronger with the asymptotic representations of V and P. Also, all correlations are stronger once inventories with robust vowel harmony are excluded. Notice that while the correlation between $F2_{SPAN}$ and P (and its asymptotic representation) are weak, as a result of the behavior of $F2_{SPAN}$ for P>8, the correlation between $F2_{SPAN}$ and V is stronger. Since V is the sum of P and NP, this must be the result of the contribution of the genuine, albeit weak correlation of $F2_{SPAN}$ with NP. The overall weak correlations of NP with space size indices are primarily the result of the distribution of NP values. While all other indices are roughly normally distributed, NP is distributed exponentially, with many tokens at the bottom of the scale (NP=0) and very few at the top.

The fact that P is mostly correlated with $F1_{SPAN}$ while NP is mostly correlated with $F2_{SPAN}$ is in agreement with Dispersion Theory principles. Within the periphery, where F1 is the dominant acoustic correlate of contrast, accommodating an additional vowel requires expansion of the F1 span in order to allow sufficient F1 differences. The F1 span is less important in the accommodation of non-peripheral vowels, because, across inventory structures, the number of vowels in any non-peripheral vertical series is never greater than in the peripheral vertical series (a universal generalization mentioned in Crothers 1978). Hence very little vertical adjustment is needed to accommodate a non-peripheral vowel series. Conversely, non-peripheral vowels are stuck between the front and back peripheries, so adding non-peripheral vowels results in horizontal pressure, leading to F2 span increase. It is worth noticing that the F2 span increase from one non-peripheral vowel to two is greater than the increase from zero to one. Accommodating the first non-peripheral vowel requires relatively little horizontal adjustment because this vowel is vertically free and tends to form its own height degree, as seen in the inventory geometries in Appendix B (see also Section 3.6.3). The contrast between this vowel and neighboring peripheral vowels is partly vertical, alleviating some of the horizontal pressure. Once the second non-peripheral vowel appears there is less vertical freedom, and non-peripheral vowels are forced into F1 frequency ranges similar to those of peripheral vowels, leaving the acoustic contrast between a non-peripheral vowel and its closest peripheral neighbors entirely to F2, and the F2 span expands substantially as a result.

In addition to correlation analyses, space size indices of adjacent structural index groups were directly compared in 21 unpaired t-tests (3 space size indices x 7 pairs of adjacent groups: three for V and P, one for NP). Significance threshold was

Bonferroni-adjusted to 0.0024 (0.05/21). The results are listed in Table 4-3. Details of tests involving inventories with P=9-10 and no vowel harmony are in parentheses.

		Area		**F1$_{SPAN}$**		**F2$_{SPAN}$**	
		df	*t*	*df*	*t*	*df*	*t*
V	3-4 vs. 5-6	138	-7.298**	138	-6.420**	138	-5.234**
	5-6 vs. 7-9	228	-5.044**	229	-3.665**	228	-2.854**
	7-9 vs. 10-14	160	-1.034	162	-1.145	160	-0.575
P	3-4 vs. 5-6	194	-6.935**	194	-5.731**	194	-4.353**
	5-6 vs. 7-8	219	-4.538**	190^{u}	-4.300**	219	-2.484*
	7-8 vs. 9-10	104 (86)	0.680 (-1.609)	106 (88)	-1.027 (-2.285*)	104 (86)	1.926* (-0.306)
NP	0-1 vs. 2-6	300	-4.553**	198^{u}	-2.919**	300	-5.123**

Table 4-3: Summary of 21 unpaired t-tests (degrees of freedom, t-score and probability) comparing space size indices (area, F1$_{SPAN}$ and F2$_{SPAN}$) for grouped values of structural indices (V – total number of vowels, P – number of peripheral vowels, NP – number of non-peripheral vowels). In the df columns, "^{u}" denotes that the number of degrees of freedom is appropriate for unequal-variance unpaired t-test, as determined by a preliminary F-test for variance (with $p<0.05$ as significance threshold). "*" denotes near-significance at $p<0.05$ and "**" denotes significance at the Bonferroni-adjusted threshold of $p<0.0024$. In parentheses are the details of t-tests for P=7-8 vs. P=9-10 where the latter sample consists only of inventories without vowel harmony.

All 15 tests other than the tests comparing indices of the 'extra-large' inventories (V=10-14 or P=9-10) were significant (14 tests) or almost significant (one test) in the direction predicted by Dispersion Theory. Conversely, all the six tests comparing extra-large inventories to the 'large' group below them were non-significant: four in the direction predicted by Dispersion Theory and two in the reverse direction (which nevertheless get corrected once the set of inventories with 9-10 peripheral vowels is limited to inventories without vowel harmony). The fact that extra-large inventories do not occupy significantly larger spaces than large inventories implies that the large inventories already tend to reach close to the maximal size. This space size might be too small for the extra-large inventories, which are typologically rare. In this regard, we are reminded that in the more typologically representative survey of UPSID (Maddieson 1984), inventories with 10 vowels or more are rare (less than 6%), and that Schwartz et al. (1997a:242) consequently suggest that "… the highest limit [of number of vowels] for a viable primary system [= inventory of plain oral monophthongs] is 9". This fact, together with the tendency of extra-large inventories without vowel harmony to nevertheless span the largest acoustic dimensions, imply that the non-significant results cannot be interpreted as counter-evidence to Dispersion Theory. In summary, Dispersion Theory accounts for the relationship between structural complexity and acoustic space size in a satisfactory manner.

4.2.3 Asymptotic behavior of formant spans

Recall that in Table 4-2 in Section 4.2.2, the highest r^2 values for F1 and F2 spans were achieved when these indices were correlated with 1/(1+1/V), the asymptotic representation of V, and vowel harmony inventories were ignored. Regression analyses of F1 and F2 spans as the dependent variables and 1/(1+1/V) as the independent variable yielded the following models:

(4.1) $F1_{SPAN} = 1080.9 / (1 + 1 / V) - 524.23$

(4.2) $F2_{SPAN} = 2543.7 / (1 + 1 / V) - 831.8$

These models represent the average formant spans as a function of (1+1/V), and they respectively reach the asymptotes 567Hz and 1712Hz when V is infinite. If average formant spans represent the point of equilibrium between maximization of dispersion and minimization of articulatory effort for a given value of V, then any span beyond these asymptotes is on the more effortful side of the equilibrium for any value of V, in wordlist elicitation.

Recall that, in Table 3-4 in Section 3.3.2, the most representative formant span interpolation ratio from isolation to word-list elicitation was found to be 0.89 for both F1 and F2, implying that the reverse (extrapolation) ratio is 1.124. Multiplying the F1 and F2 span asymptotes by this ratio gives respectively 637Hz and 1924Hz as the span asymptotes for isolation elicitation (213Hz≤F1≤850Hz, 576Hz≤F2≤2500Hz). Since isolation elicitation posits no articulatory constraints and all humanly possible vowels are reachable, it stands to reason under Dispersion Theory that these span asymptotes and formant extrema represent the absolute edges of the vowel space for the average male speaker in the studies included in the corpus. This implies that, under vocal-tract normalization only, no inventory in the corpus should exceed these span asymptotes. In the entire corpus of 447 inventories normalized only for vocal tract, there are two inventories with F1 span greater than 637Hz and one inventory with F2 span greater than 1924Hz. 99% of the inventories have formant spans smaller than 600Hz for F1 and 1800Hz for F2. It is thus plausible that these three odd cases are due to errors, and that the isolation elicitation asymptotes are indeed reasonable estimates of the possible vowel space.

4.3 **Vowel-specific effects I: point vowels**

Every inventory in the survey has at least one front vowel, a low vowel and at least one back vowel. The highest front vowel, the low vowel and the highest back vowel constitute the three point vowels, which will be referred to as *I*, *A* and *U* henceforth. Section 4.3.1 briefly discusses the behavior of point vowels as a function of structural complexity. Sections 4.3.2 and 4.3.3 discuss the effect of peripheral configuration respectively on the behavior of *A* along the F2 dimension and on the behavior of *I* and *U* relative to each other along the F1 dimension.

4.3.1 Point vowels and structural complexity

With very few exceptions, *I* is always at both the F1 minimum and F2 maximum of the inventory, while *A* is always at the F1 maximum by definition, and *U* shows an overwhelming tendency, albeit not as universal as those of *I* and *A*, to be at the F2 minimum and close to the F1 minimum. Dispersion Theory therefore predicts that F1 of *I* and *U* and F2 of *U* should decrease, while F2 of *I* and F1 of *A* should increase, as a function of any increase in structural complexity. Unfortunately, the combination of concentric inventory anchoring as part of vocal-tract normalization described in Section 3.2 and the consistent correlations between structural complexity and formant spans shown in Section 4.2 render these predictions trivially valid. Any correlation between structural indices and inventory formant spans is paralleled by a correlation between the same structural indices and formant extrema. Suffice it to say that such significant correlations, albeit much weaker, are present already in the raw data. For example, in the raw data, the correlations between the total number of vowels and F1 frequencies of *A* and *I* have the respective r^2 values 0.088 and 0.079 ($p<10^{-6}$ for both). The normalization process greatly improves these correlations, but it is impossible to disentangle the complementary contributions of vowel-specific behavior and of the methodological artifact due to the normalization procedure.

4.3.2 F2 of the low vowel as a function of peripheral configuration

While the F1 frequency of *A* is directly correlated with the inventory F1 span and hence with structural complexity, its F2 frequency, which is always somewhere in the middle of the F2 span, cannot be apriori assumed to correlate with any structural property. However, Dispersion Theory makes clear predictions regarding the F2 of *A* as a function of peripheral configuration. As the prominence of the front periphery increases from right-crowded inventories through symmetrical to left-crowded inventories, the front periphery should extend up and down. As a consequence, *A* should be pushed back, i.e. its F2 should decrease.

In order to examine the effect of peripheral arrangement on the F2 frequency of *A*, the set of 302 entries (two entries, for which normalized F2 frequencies could not be calculated, were excluded) was divided into the three groups according to periphery configuration: Symmetrical (S, 198 inventories), Left-crowded (L, 60 inventories) and Right-crowded (R, 44 inventories). For simplicity and robustness, the specific number of vowels in any region was ignored. Descriptive statistics of F2 frequencies of the *A* show tendencies consistent with Dispersion Theory predictions, with average values rising from F2=1274Hz (sd = 126Hz) in L inventories, through F2=1372Hz (sd = 128Hz) in S inventories, to F2=1489Hz (sd = 141Hz) in R inventories. Preliminary F-tests showed that the variances of the three groups were not significantly different, and consequently equal-variance unpaired t-tests were used for comparing the three groups. The effect of periphery configuration was highly significant in all cases (S vs. L: $t(256) = 5.224$, $p<1\times10^{-6}$; S vs. R: $t(240) = 5.398$, $p<1\times10^{-7}$; L vs. R: $t(102) = 8.173$, $p<1\times10^{-12}$).

These results imply that the F2 frequency of *A* is regulated by dispersion principles, but it was suspected that a major confound was involved, the insistence on only one low vowel per inventory. In inventories that are better described as having symmetrical peripheries with two low vowels, this interpretation forced the classification of the inventory as asymmetrical, with a single low vowel closer to the less crowded periphery. It was suspected that a distinctly front or back quality of the lowest vowel appeared almost exclusively in such inventories, and that, if there was truly only one low vowel, this vowel would be central even if the inventory is left-crowded or right-crowded.

In order to eliminate this confound, a very restrictive criterion was imposed on inventories previously analyzed as asymmetrical: only those inventories, where *A* had

F1 frequency more than 100Hz above the lowest among the vowels of the more crowded periphery, were treated as 'truly left-/right-crowded'. This reduced the number of left-crowded inventories from 60 to 34, excluding 26 inventories where the lowest vowel (typically rather back) contrasted with a very low front vowel. The number of right-crowded inventories also decreased from 44 to 26, excluding 18 inventories where the lowest vowel (typically rather front) contrasted with a very low back vowel. In the two restricted asymmetrical groups pooled together (60 inventories), the average F1 frequencies of *A* and the second lowest vowel were respectively 720Hz (sd = 44Hz) and 534Hz (sd = 64Hz). As a result of the removal of inventories suspected as having two low vowels, the average F2 frequency of *A* rose to 1302Hz (sd=99Hz) in the restricted L inventory group, and dropped to 1448Hz (sd=149Hz) in the restricted R inventory group, implying that the low vowels indeed got somewhat centralized.

Variances were significantly different for the L and R inventories ($F(33,25) = 0.436$, $p<0.02$) and for the S and L inventories ($F(197,33) = 1.677$, $p<0.04$), but not for S and R inventories ($F(197,25) = 0.732$, $p>0.12$). Subsequent unpaired t-tests show a reduced, yet still highly significant, effect of periphery configuration on the F2 frequency of *A* (S vs. L: $t(54) = 3.646$, $p<0.0003$; S vs. R: $t(222) = 2.795$, $p<0.003$; L vs. R: $t(41) = 4.317$, $p<0.00005$). Thus, even when there is clearly only one low vowel, the geometry is sensitive to dispersion pressures. It compensates for a slightly shorter vertical contrast and/or greater vertical crowdedness by slightly increasing horizontal contrast and attracting *A* to the less crowded periphery.

The relatively small acoustic magnitude of this effect, typically well within 100Hz from 'perfect central', is probably why this effect often goes unnoticed in impressionistic descriptions of vowel inventories with asymmetrical peripheries, as *A* is overwhelmingly transcribed as (central) /a/. More often than not, *A* is within the (normalized) range of 1275Hz<F2<1475Hz, i.e. an acceptable central low vowel. Given speaker and context variability, it makes little sense to indicate its deviation from central in summaries that aim at language properties other than phonetic precision. It is only by examining data from hundreds of languages that the subtle effects of dispersion become apparent. Along the same line, it is worth noticing that, when the inventory seems to contain two low vowels, impressionistic descriptions are often sensitive to the horizontal quality of the vowels, transcribing them as e.g. /æ/ vs. /ɑ/. According to the survey data, this is far from surprising. Recall that restricting front-crowded and back-crowded inventories only to those inventories, where the F1 frequency of *A* is at least more than 100Hz above that of second lowest vowel, yielded reduced sensitivity of the low vowel to peripheral asymmetries. The 44 inventories that were excluded by this criterion (26 left-crowded, 18 right-crowded) may be suspected of having two low vowels. These inventories are characterized by a lowest vowel with average F1 frequency of 693Hz (sd = 47Hz), compared to average F1 frequency of 652Hz (sd = 52Hz) of the lower vowel in the more crowded periphery, a marginal F1 contrast. In these inventories, the lowest vowel is clearly back (average F2 = 1238Hz, sd = 149Hz) or clearly front (average F2 = 1549Hz, sd = 106Hz) if the inventory is respectively left-crowded or right-crowded. Regardless of whether or not these inventories have two low vowels, it is clear that the marginal F1 contrast between the two vowels is compensated for by a significantly greater F2 contrast, as Dispersion Theory predicts.

In summary, the behavior of *A* along the F2 dimension strongly supports Dispersion Theory: it is in the middle when the periphery is symmetrical, but in case of asymmetry, the more crowded side pushes *A* away towards the less crowded side, and the lower the more crowded side gets, the farther *A* is pushed to the other side. Figure 4-2 displays the one standard deviation distribution ranges of *A* on the F1xF2 plane as a function of peripheral configuration (S = symmetrical, L = strictly left-crowded, R = strictly right-crowded, L?S2 = left-crowded but suspected as symmetrical with low vowels, R?S2 = right-crowded but suspected as symmetrical with two low vowels).

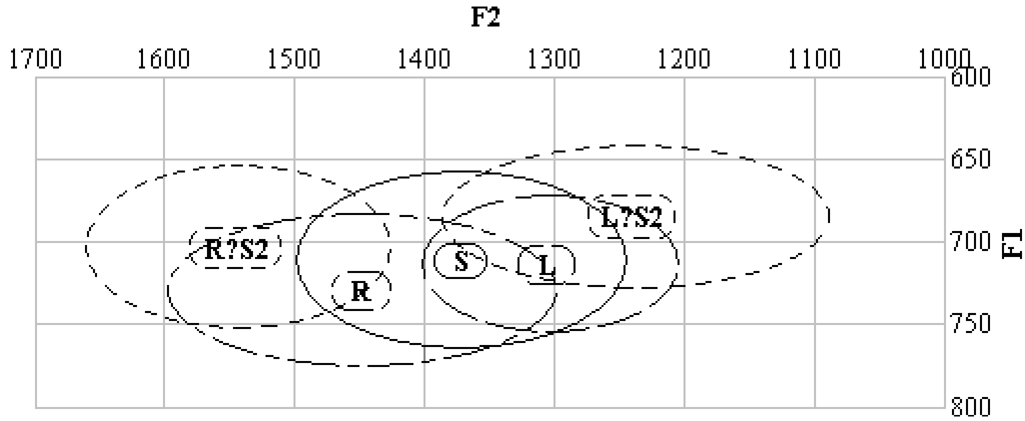

Figure 4-2: Average and standard deviation of the F2 frequency of the low vowel in inventories with the following peripheral configurations: symmetrical ("S", solid line, 198 inventories), strictly left-crowded ("L", dashed line, 34 inventories), strictly right-crowded ("R", dashed-dotted line, 26 inventories), left-crowded but suspected as symmetrical with two low vowels ("L?S2", dotted line, 26 inventories) and right-crowded but suspected as symmetrical with twi low vowels ("R?S2", dotted line, 18 inventories).

In addition to supporting Dispersion Theory, the F2 behavior of *A* constitutes strong evidence against Quantal Theory (Stevens 1972, 1989). According to Quantal Theory, the cross-linguistic omnipresence of a low vowel in inventories is not a result of relative distance from other vowels, but of an absolute property of this vowel: acoustic stability and proximity of F1 and F2 at a point where F2 is at its lowest (and F1 allegedly at its highest frequency). Thus, *A* should be fixed as a back [ɑ] regardless of inventory structure. In addition, certain versions of Quantal Theory predict the dominance of [ɑ] not only on the basis of articulatory-to-acoustic stability, but also of acoustic-to-perceptual stability, because [ɑ] is the only low vowel where F1 and F2 are closer than the Center of Gravity Effect threshold of 3-3.5Bark (Chistovich &

Lublinskaya 1979). The horizontal variability of *A* itself, and the rather limited presence of back [ɑ] quality in inventories, are contradictory to the predictions of Quantal Theory, as is the fact that the preferred quality of *A* is low central [ɐ̞], which is characterized neither by a stable distance between F1 and F2 nor by F1-F2 distance smaller than 3.5Bark (for the most typical *A*, with F1=700Hz and F2=1375Hz, this distance is 3.9Bark). Finally, Figure 4-2 shows that *A* is not lowest at the back region, as Quantal Theory suggests, nor is it at the central region. The lowest qualities (highest F1 frequencies) are decidedly at the half-front region around F2=1450Hz, although this might be due the fact that the fronter-than-central region is used more frequently in inventories with more vowels (and consequently larger F1 spans).

4.3.3 F1 difference between high vowels as a function of peripheral configuration

While the behavior of *I* and *U* along the F1 frequency dimension is correlated with the F1 span and hence with structural complexity, the difference between their respective F1 frequencies, henceforth $F1_U - F1_I$, is not. It is well known that F1 tends to be slightly lower in *I* than in *U* in inventories. Indeed, in 256 of the 304 inventories in the corpus, the $F1_U - F1_I$ index is positive, whereas it is negative in 36 inventories and equals 0 in twelve. This tendency is valid across all structures. Even so, it is interesting to see whether the peripheral configuration has correlates in the behavior of $F1_U$-$F1_I$. Assuming that the $F1_U$-$F1_I$ is positive, Dispersion Theory predicts that, relatively to $F1_U$-$F1_I$ in inventories with a symmetrical periphery, a front-crowded periphery should push *I* up more, lowering its F1 frequency and increasing $F1_U$-$F1_I$, whereas a back-crowded periphery should push *U* up more, thus reducing $F1_U$-$F1_I$.

Before testing these predictions using the survey data, some complications and pitfalls should be considered. First, in some inventories, the identities of *I* and *U* are the consequences of subjective interpretation. For example, the Standard Japanese /i e a o ɯ/ inventory is classified as a 4L1 inventory (left-crowded four vowel periphery and one non-peripheral vowel). This disputable interpretation both forces the inventory into the left-crowded group and assigns the *U* status to /o/, whose F1 frequency is obviously much higher than that of /i/, thus biasing the data in the direction of Dispersion Theory predictions. Second, some of the smaller inventories whose peripheral structures are not disputable, nevertheless have a pronounced height asymmetry between *I* and *U*, which is manifested already in the transcription, as in the 3S0 inventory of Creek (/i a o/) or the 4L0 inventory of Navajo (/i ɛ a o/), but there are no reverse cases where *I* is /e/ and *U* is /u/ (such structures do not appear in UPSID either, see Ferrari-Disner 1984 for discussion). Recall that, as mentioned in Section 3.6.3, such instances of /o/-labeled *U* are not necessarily lower than instances of /u/-labeled *U* in other inventories. It is nevertheless plausible that, in some inventories, the decision to label a vowel as /o/ rather than /u/ is based on phonological considerations (e.g. participating in regular patterns together with the lower front vowel but not with the higher front vowel in 4L0). It can therefore be argued that the true test for Dispersion Theory here is when such height asymmetries are neutralized, that is, when the test is based only on those inventories whose *I* and *U* denote vowels transcribed as sharing the same height. Finally, again as a result of subjective interpretation, symmetrical inventories with two low vowels may have been artificially treated as left- or right-crowded, as seen already in the analysis of F2 of the low vowel in Section 4.3.2.

Having taken these possible confounds into account, separate analyses were performed according to looser and stricter criteria. Table 4-4 lists the various exclusion criteria, the number of inventories observed in each case and average and standard deviation of $F1_U$-$F1_I$. Qualitative observation suggests that $F1_U$-$F1_I$ averages behave exactly according to the predictions of Dispersion Theory, i.e. the difference is always greatest for left-crowded periphery inventories and always smallest for right-crowded periphery inventories. However, standard deviations indicate that the behavior of $F1_U$-$F1_I$ substantially overlaps between all three types. Table 4-5 summarizes the results of 15 unpaired t-tests (3 periphery type pairs x 5 exclusion criteria). The one-tailed significance threshold was Bonferroni-corrected to 0.0033 (=0.05/15).

Exclusion criteria	**left-crowded**		**symmetrical**		**right-crowded**	
	obs.	Av. F1*u*-F1*I*	obs.	Av. F1*u*-F1*I*	obs.	Av. F1*u*-F1*I*
none	60	52.0 (±48.8)	199	30.8 (±34.8)	45	23.4 (±23.5)
disputable interpretation of *I/U*	55	45.3 (±45.0)	197	30.2 (±34.2)	45	23.4 (±23.5)
pronounced height asymmetry	48	33.2 (±31.1)	194	29.5 (±34.0)	45	23.4 (±23.5)
disputable interpretation of periphery asymmetry	29	59.9 (±52.9)	197	30.2 (±34.2)	27	23.0 (±22.6)
pronounced height asym. And disputable interpretation of periphery asymmetry	22	38.1 (±35.5)	194	29.5 (±34.0)	27	23.0 (±22.6)

Table 4-4: Number of inventories, and average and standards deviations for $F1_U$-$F1_I$ as a function of peripheral configuration (left-crowded, symmetrical, right-crowded), according to different criteria for excluding inventories whose peripheral configuration is suspected to have been improperly assigned.

Exclusion criteria	**L vs. R**		**S vs. L**		**S vs. R**	
	df	*t*	*df*	*t*	*df*	*t*
none	90^u	3.964**	78^u	3.126**	94^u	1.731*
I/U interpretation	84^u	3.122**	72^u	2.306*	92^u	1.591
pronounced height asymmetry	87^u	1.711*	240	0.669	92^u	1.435
peripheral asymmetry interpretation	38^u	3.440**	32^u	2.935**	44^u	1.452
height asymmetry + peripheral asymmetry interpretation	34^u	1.732*	214	1.111	44^u	1.319

Table 4-5: Summary of unpaired t-tests for mean difference of $F1_U$-$F1_I$ between different peripheral configurations ("S" = symmetrical, "L" = left-crowded, "R" = right-crowded) according to different criteria for excluding inventories whose peripheral configuration is suspected to have been improperly assigned. In the df columns, "^{u}" denotes that the number of degrees of freedom is appropriate for unequal-variance unpaired t-test, as determined by a preliminary F-test for variance (with $p<0.05$ as significance threshold). "*" and "**" respectively indicate near-significant ($p<0.05$) and significant ($p<0.0033$) results.

Evidently, not all differences are significant, in particular between the symmetrical and each of the asymmetrical types. Significance is least attested in the strictest exclusion criteria condition, which compares only inventories whose *I* and *U* are transcribed as having the same height. However, in the case of left- vs. right-crowded peripheries, the average $F1_U$-$F1_I$ indices are always significantly or near-significantly different, implying that the vertical positions of *I* and *U* are genuinely sensitive to the configuration of the inventory periphery as predicted by Dispersion Theory, even if this sensitivity is subtle. In addition, in the comparisons between inventories with symmetrical vs. right-crowded peripheries, where results were least conclusive, the differences were in the direction predicted by Dispersion Theory ($p<0.10$ in all five conditions), which adds to the apparent consistency of this subtle sensitivity.

4.4 Vowel-specific effects II: peripheral mid vowels

Peripheral mid vowels are never at the F1 extrema of inventories, and with very few exceptions, they are never at the F2 extrema either. As such, their formant frequencies are not necessarily correlated with formant spans, and constitute an independent test-case for Dispersion Theory. Section 4.4.1 examines the behavior of individual peripheral mid vowels along the F1 dimension as a function of peripheral configuration, and Section 4.4.2 looks at F2 of peripheral mid vowels as a function of the number of non-peripheral vowels.

4.4.1 F1 of peripheral mid vowels as a function of peripheral configuration

In each entry in the corpus, all peripheral vowels other than the three point vowels are mid vowels. As all entries have the three point vowels, any structural difference between the peripheral configurations of any two entries is a difference in the distribution of mid vowels. The principal prediction of Dispersion Theory is that any such difference should be manifested in acoustic rearrangement of the entire periphery and consequently in systematic F1 differences between corresponding vowels in the different configurations. The effect of structural differences on the F1 frequency will be tested for each peripheral mid vowel separately.

The corpus contains sufficient data (at least 8 entries) for each of the following peripheral structures: 4L, 5S, 6L, 6R, 7S, 8L, 8R, 9S. For simplicity and robustness, data are pooled together from similar peripheries, across all non-peripheral configurations accompanying them.[27] In the analyses, peripheral mid vowels will be labeled as follows: the peripheral structure, followed by F/B for ‘front/back’, followed by H/M/L (higher mid – the highest among more than one mid vowels in the periphery; mid – the only mid vowel in the periphery or the middle one among three mid vowels; lower mid – the lowest among more than one mid vowels). For example, 6L:F:L refers to the lower-mid front vowel in a left-crowded six-vowel periphery. Figure 4-3 illustrates this nomenclature with the peripheral mid vowels in 5S, 6L and 8R peripheral configurations.

[27]This is a simplification, because the number of non-peripheral vowels has been shown in Section 4.2.2 to exert some effect (albeit small) on the F1 span of the inventory, which would be most pronounced in the F1 frequencies of the point vowels, but might carry onto mid vowels as well. Not less importantly, it follows from Dispersion Theory itself that any change in the number of vowels would be reflected in reorganization of the entire inventory, differences in the number of non-peripheral vowels included. However, due to the great spatial variability of non-peripheral vowels and the small number of inventories pertaining to many of the specific (peripheral + non-peripheral) structures, this simplification is worthwhile, because it not only bases each of the analyses on many more inventories, but also allows us to extend the analysis into peripheral structures that are rather rare (e.g. 8 peripheral vowels).

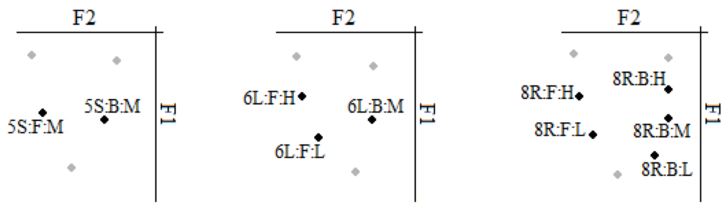

Figure 4-3: Illustration of the peripheral mid vowel nomenclature in 5S (left), 6L (center) and 8R (right) periphery configurations. Mid vowels (labeled) are in black, point vowels (unlabeled) are in grey.

Since the number of mid vowels in a given region (front or back) varies between one, two and three, correspondence between vowels belonging to the same region in different structures is not always one-to-one. For example, when the mid front vowels of a five-vowel periphery and of a left-crowded six-vowel periphery are compared, 5S:F:M (the only mid front vowel in 5S) corresponds to both 6L:F:H and 6L:F:L (the higher and lower mid front vowels in 6L). On the other hand, correspondence is not all-to-all either: H and L vowels do not correspond to each other across structures. In fact, as the average F1 frequencies of the H vowel sets are all outside the single standard-deviation range of the L vowel sets and vice-versa, it can be safely assumed that H vowels are always higher (having lower F1 frequencies) than L vowels.

Three distinct effects of peripheral configuration on the F1 frequency of peripheral mid vowels will be tested, defined as extension of a smaller peripheral component to a larger one:

(a) Adding a vowel to the examined side (6R:F:M vs. 7S:F:H, 6R:F:M vs. 7S:F:L etc.).

(b) Adding one/two vowel(s) to the opposite side (4L:F:M vs. 5S:F:M/6R:F:M etc.).

(c) Adding one vowel to each side (5S:F:M vs. 7S:F:H, 5S:F:M vs. 7S:F:L etc.).

According to Dispersion Theory, expansion of the examined periphery, which is the case in both (a) and (c), should result in vowels in the larger structure with F1 frequencies extrapolated above and below the vowel(s) in the smaller structure.

However, the asymmetrical expansion in (a) should extend further into the low vowel region, hence the extrapolated F1 frequencies of the more complex structure should be higher in (a) than in (c). In (b), it is the opposite periphery that expands, with the effect of pushing the low vowel closer to the examined periphery, and consequently, Dispersion Theory predicts that the examined periphery would be pushed up and its F1 frequencies decrease. Notice that (b) balances (a) to yield (c).

Table 4-6 lists the sets of peripheral mid vowels analyzed, each with the number of observations and the average and standard deviation of its F1 frequency.

Vowel	**obs.**	**Average±sd**	**vowel**	**obs.**	**Average±sd**
4L:F:M	18	510±63			
5S:F:M	85	480±58	5S:B:M	86	484±52
6:F:HL 6L:F:L	31 31	426±52 587±81	5L:B:M	31	481±48
6R:F:M	26	440±72	6R:B:H 6R:B:L	26 26	447±57 598±66
7S:F:H 7S:F:L	59 59	393±40 546±73	7S:B:H 7S:B:M	59 58	417±45 568±56
8L:F:H 8L:F:M 8L:F:L	8 8 8	395±36 494±92 616±75	8L:B:H 8L:B:L	8 8	431±49 530±67
8R:F:H 8R:F:L	10 10	402±37 526±81	8R:B:H 8R:B:M 8R:B:L	10 10 10	390±44 484±61 617±89
9S:F:H 9S:F:M 9S:F:M	22 (7) 21 (7) 22 (7)	358±34 (349±46) 396±32 (405±33) 535±45 (542±61)	9S:B:H 9S:B:M 9S:B:L	22 (7) 22 (7) 22 (7)	381±37 (381±50) 413±42 (425±54) 550±66 (591±80)

Table 4-6: The individual peripheral mid vowels in peripheral configurations appearing in eight or more inventories in the survey, each with the number of inventories, and the average and standard deviation of the F1 frequency. In some cases, the number of inventories is not the same for vowels belonging to the same peripheral configuration, because of inventories where the data for a particular peripheral mid vowel is missing. Data for peripheral mid vowels in 9S inventories without vowel harmony are in parentheses.

Figure 4-4 depicts the F1 averages and standard deviations listed in Table 4-6, ordered from left to right according to front vs. back, then according to the number of mid vowels in the periphery, and finally according to the order that should yield F1 lowering. The F1 lowering effect is apparent, in particular in the M and L vowels.

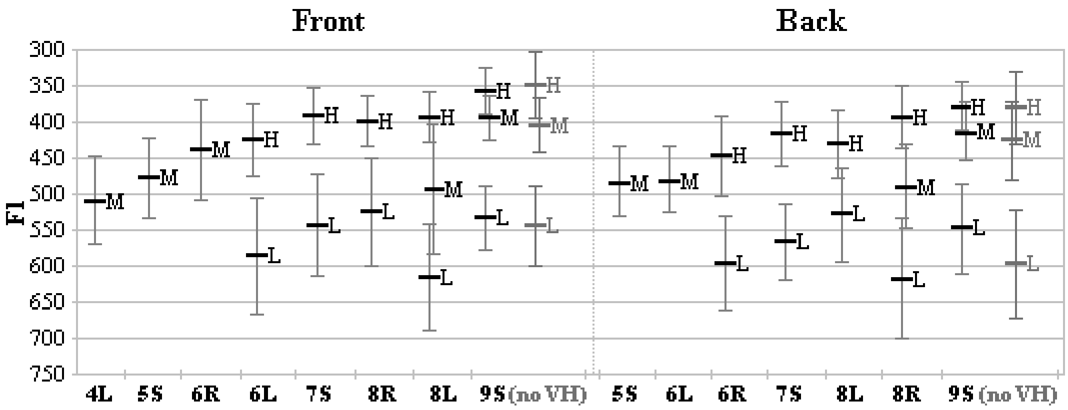

Figure 4-4: Averages and standard deviations of the F1 frequencies for the peripheral mid vowels in each of the peripheral configurations appearing in eight or more inventories in the survey. Peripheral configurations with the same number of mid vowels in a given region are juxtaposed in the order for which Dispersion theory predicts decrements in F1 frequencies from left to right. Data for the peripheral configuration 9S from inventories without vowel harmony are in grey.

Given the 29 sets of peripheral mid vowels listed in Table 4-6 and the three types of configurational differences, 72 comparisons of F1 frequencies of two corresponding sets were performed. In each comparison, depending on a preliminary F-test for variance, equal- or unequal-variance unpaired t-test was performed (one tailed, given the directional prediction of Dispersion Theory). The Bonferroni-corrected significance threshold was set at p=0.0007 (=0.05/72). Table 4-7 summarizes the t-tests for all 72 comparisons.

Adding one vowel to the examined side			adding one/two vowel(s) to the opposite side			adding one vowel to each side		
comparison	*df*	*t*	*comparison*	*df*	*t*	*comparison*	*df*	*t*
5S:F:M, 6L:F:H	114	4.580**	4L:F:M, 5S:F:M	101	2.017*	4LF:M, 6L:F:H	47	5.075**
5S:F:M, 6L:F:L	42^{u}	-6.759**	5S:F:M, 6R:F:M	109	2.898*	4L:F:M, 6L:F:L	47	-3.435**
6R:F:M, 7S:F:H	32^{u}	3.141*	4L:F:M, 6R:F:M	42	3.358*	5S:F:M, 7S:F:H	142^{u}	10.660**
6R:F:M, 7S:F:L	83	-6.212**	6L:F:H, 7S:F:H	49^{u}	3.387*	5S:F:M, 7S:F:L	106^{u}	-5.825**
7S:F:H, 8L:F:H	65	-0.183☹	7S:F:H, 8R:F:H	67	-0.652☹	6R:F:M, 8R:F:H	31^{u}	2.100*
7S:F:H, 8L:F:M	7^{u}	-3.083*	6L:F:H, 8R:F:H	39	1.354	6R:F:M, 8R:F:L	34	-3.120*
7S:F:L, 8L:F:M	65	1.823*	6L:F:L, 7S:F:L	88	2.461*	6L:F:H, 8L:F:H	37	1.542
7S:F:L, 8L:F:L	65	-2.572*	7S:F:L, 8R:F:L	67	0.773	6L:F:H, 8L:F:M	8^{u}	-2.029*
8R:F:H, 9S:F:H	30	3.343*	6L:F:L, 8R:F:L	39	2.058*	6L:F:L, 8L:F:M	37	2.806*
8R:F:H, 9S:F:M	29	0.445☹	8L:F:H, 9S:F:H	28	2.681*	6L:F:L, 8L:F:L	37	-0.921
8R:F:L, 9S:F:M	10^{u}	4.885**	8L:F:M, 9S:F:M	8^{u}	2.959*	7S:F:H, 9S:F:H	79	3.659**
8R:F:L, 9S:F:L	12^{u}	-0.308	8L:F:L, 9S:F:L	9^{u}	2.895*	7S:F:H, 9S:F:M	78	-0.320
5S:B:M, 6R:B:H	110	3.080*	5S:B:M, 6L:B:M	115	0.225	7S:F:L, 9S:F:M	74^{u}	12.729**
5S:B:M, 6R:B:L	110	-9.240**	6R:B:H, 7S:B:H	83	2.585*	7S:F:L, 9S:F:L	60^{u}	0.819☹
6L:B:M, 7S:B:H	88	6.241**	7S:B:H, 8L:B:H	65	-0.809☹	5S:B:M, 7S:B:H	143	7.988**
6L:B:M, 7S:B:L	87	-7.499**	6R:B:H, 8L:B:H	32	0.712	5S:B:M, 7S:B:L	142	-9.472**
7S:B:H, 8R:B:H	67	1.731*	6R:B:L, 7S:B:L	82	2.212*	6L:B:M, 8L:B:H	37	2.615*
7S:B:H, 8R:B:M	67	-4.135**	7S:B:L, 8L:B:L	64	1.821*	6L:B:M, 8L:B:L	37	-2.371*
7S:B:L, 8R:B:M	66	4.440**	6R:B:L, 8L:B:L	32	2.531*	6R:B:H, 8R:B:H	34	2.814*
7S:B:L, 8R:B:L	10^{u}	-1.655	8R:B:H, 9S:B:H	30	0.573	6R:B:H, 8R:B:M	34	-1.731*
8L:B:H, 9S:B:H	28	3.030*	8R:B:M, 9S:B:M	30	3.914**	6R:B:L, 8R:B:M	34	4.724**
8L:B:H, 9S:B:M	28	0.989☹	8R:B:L, 9S:B:L	30	2.395*	6R:B:L, 8R:B:L	34	-0.692
8L:B:L, 9S:B:M	9^{u}	4.642**				7S:B:H, 9S:B:H	79	3.369**
8L:B:L, 9S:B:L	28	-0.706				7S:B:H, 9S:B:M	79	0.362☹
						7S:B:L, 9S:B:M	78	12.069**
						7S:B:L, 9S:B:L	78	1.327☹

Table 4-7: Summary of unpaired t-tests for difference of average F1 frequencies between corresponding peripheral mid vowel categories in different peripheral configurations. In the df columns, "u" denotes that the number of degrees of freedom is appropriate for unequal-variance unpaired t-test, as determined by a preliminary F-test for variance (with $p<0.05$ as significance threshold). "*" denotes near-significance at $p<0.05$ and "**" denotes significance at the Bonferroni-adjusted threshold of $p<0.0007$. "☹" denotes that the difference (always non-significant) is in a direction opposite to the prediction of Dispersion Theory.

Out of the 72 comparisons, 22 resulted in significant difference in the direction predicted by Dispersion Theory, and 30 more comparisons resulted in near-significant difference ($p<0.05$, one-tailed) in the predicted direction, and twelve other comparisons resulted in non-significant differences in the predicted direction. Only eight comparisons resulted in differences in the opposite direction, all non-significant. These results can only be interpreted as strongly corroborating Dispersion Theory. In fact, in the smaller and more common peripheral structures (4L, 5S, 6L, 6R, 7S), mid vowels follow Dispersion Theory predictions with extreme consistency. All 22 comparisons involving these structures had results in the predicted direction, 12 significant and nine more near-significant. If these were the only comparisons performed and the Bonferroni-corrected significance threshold was accordingly set at p=0.0023 (=0.05/22), then four of the nine near-significant results would have become significant as well.

Patterns are not as consistent in the mid vowels of 8L and 8R peripheries. Only three out of the 28 comparisons between mid vowels in any of these peripheries and any of 6L, 6R or 7S turned out significant. However, this is most likely a result of the very low significance threshold, combined with the scarcity of 8L and 8R peripheries (respectively in 8 and 10 inventories in total, none belonging to a structure with more than four inventories). The consequent greater standard deviations and fewer degrees of freedom in t-tests make it very hard to reach significance, especially given the stringent probability threshold. Yet the fact that out of the 25 non-significant results, 15 were near-significant, while only three were non-significant in direction opposite to Dispersion Theory predictions, suggests that 8L and 8R peripheries do adhere to dispersion constraints, and that the major obstacle for showing this is paucity of data.

The results for the peripheral mid vowels of 9S are least consistent with Dispersion Theory predictions. Only 13 out of the 22 comparisons were significant (seven) or near-significant (six), while five were in the opposite direction (all non-significant). As shown in Table 4-6 and Figure 8, the H and M vowels in these inventories are very close together (less than 40Hz apart). This is explained in part by the fact that 15 of the 22 inventories have robust ATR vowel harmony. In these inventories, the H and M vowels in each periphery are virtually indistinguishable by F1 (or by F2), as one of them is the high [–ATR] vowel (/ɪ/ or /ʊ/) and the other is the mid [+ATR] vowel (/e/ or /o/), with no systematic cross-linguistic pattern of which vowel is higher than which (in the corpus, the H vowel is always the vowel with the lower F1 frequency, disregarding its ATR value). It appears that ATR-harmony is the only guarantee for the retention of phonemic contrast between these two height degrees, because inventories of related languages that lost the harmony system very often lose one of these two height degrees and have seven-vowel peripheries. One of the two height degrees is retained, and thus one finds a majority of Niger-Congo and Nilo-Saharan /i e ɛ a ɔ o u/ inventories, a minority of /i ɪ ɛ a ɔ ʊ u/ inventories, but /ɪ e ɛ a ɔ o ʊ/ or /i ɪ e a o ʊ u/ inventories are never attested (Casali 1995, Anderson-Starwalt 2008). ATR-harmony inventories thus look as if they have a 7S periphery, with no true M vowels, but locally split H vowels instead. The H-like nature of the M vowels implies that further lowering of L vowels is not necessary. This explains why so many comparisons yielded non-significant results, including five in the direction opposite to predictions. In addition, the consistently significant results in the comparisons between L vowels in 7S, 8L or 8R and M vowels in 9S are rather trivial if the latter vowels are in fact variants of H. Once again, vowel harmony inventories appear to challenge Dispersion Theory, but they are also the exception that proves the rule.

As seen in Table 4-6 and Figure 4-4, when 9S data are limited to the seven inventories without vowel harmony, the vertical gaps between H and M vowels increase slightly, and the L vowels are further lowered, enough to reverse three of the five comparisons that contradicted Dispersion Theory predictions, but not enough to increase significance in the other comparisons. In a parallel set of 22 comparisons using only 9S data from these seven inventories, only three returned significant and nine more near-significant. This is largely due to lack of power, but also due to the fact that the M vowels in these seven inventories are still too high, which is correlated with ambiguities in the phonological interpretation of some of these inventories.[28]

Finally, it is noticeable that dispersion-related effects are much more pronounced at the immediate vicinity of structural changes, and more subtle in more remote regions. Ten out of the 24 t-tests were significant at $p<0.0007$ (and eight more near-significant at $p<0.05$) upon adding a vowel to the current periphery, whereas adding a vowel to the opposite periphery yielded only one significant result (and 14 near-significant) in 22 tests. This is in accordance with the gradual decay of repulsion mechanisms predicted by Dispersion Theory, as explained in Section 4.

4.4.2 F2 of peripheral mid vowels as a function of non-peripheral configuration

According to Table 4-1 in Section 4.2.1, the F2 span and total area index of inventories tend to increase with increments in the number of non-peripheral vowels, although these tendencies turned out to be correlated more with the total number of vowels, as shown in Table 4-2 in Section 4.2.2. Since the peripheral mid vowels are very rarely at the extrema of the F2 span, those weak correlations imply very little about the F2 frequencies of such vowels. Nevertheless, Dispersion Theory predicts that increments in the number of non-peripheral vowels should increase the horizontal pressure on the peripheral vowels, causing the F2 frequencies of mid front and mid back vowels to increase and decrease respectively.

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[28]It is worth noting that four of these seven inventories belong to Niger-Congo or Nilo-Saharan languages that probably had robust ATR harmony and still bear some of its relics (e.g. Sotho). Moreover, two others belong to Dutch and American English and represent those studies that do not make quantity distinctions and also treat secondary diphthongs as monophthongs, which results, for both languages, in mixed-quantity inventories containing nine peripheral vowels (American English /i ɪ e^{ɪ} ɛ æ ɑ o^{ʊ} ʊ u/, Dutch /i ɪ e^{ɪ} ɛ a ɑ ɔ o^{ʊ} u/). HM and M vowels are covered by the pairs /e^{ɪ} ɪ/, /o^{ʊ} ʊ/ in English and /e^{ɪ} ɪ/, /o^{ʊ} ɔ/ in Dutch. In both languages, both pairs are characterized by a small F1 frequency difference, which is complemented by duration and diphthogization contrast.

The F2 frequency of both front and back vowels is strongly correlated with their F1 frequency, which means that when the behavior along the F2 frequency dimension is examined for either vowel type as a group, the contribution of F1 to F2 has to be controlled. For this purpose, simple regression models for F2 as a function of F1 were calculated separately for mid front and mid back vowels, using all the peripheral mid vowels in the corpus. These models are:

(4.3) $F2_{FRONT} = 2581.1 - 1.347 \times F1$ ($r^2 = 0.474$)

(4.4) $F2_{BACK} = 581.8 + 0.778 \times F1$ ($r^2 = 0.292$)

In order to determine the effect of non-peripheral configuration on F2 of the peripheral mid vowels, each peripheral mid vowel in the corpus was assigned a 'horizontal deviation index' (HDI) relative to the model by subtracting, from the F2 frequency of the vowel, the F2 prediction of the model given the F1 frequency of the vowel.

(4.5) $HDI_{V\text{-}FRONT} = F2_v - 2581.1 + 1.347 \times F1_v$

(4.6) $HDI_{V\text{-}BACK} = F2_v - 581.8 - 0.778 \times F1_v$

Rather than treating non-peripheral configuration simply as the number of non-peripheral vowels, it was decided to take into account the geometry within the non-peripheral region: in case there were multiple non-peripheral vowels, arrangement in one vertical series was distinguished from arrangements with horizontal contrasts within the set of non-peripheral vowels. This was mostly relevant for inventories with three non-peripheral vowels or more, but even among the inventories with only two non-peripheral vowels, there was a small minority (five inventories out of 53) where the two vowels differed clearly in F2 but not in F1. Each peripheral mid vowel was assigned a structural index according to four possible non-peripheral configurations: no vowels (NP=0), one vowel (NP=1), multiple vowels in one vertical series

($NP \geq 2^{VER}$), and multiple vowels with horizontal contrasts ($NP \geq 2^{HOR}$). Table 4-8 summarizes the averages and standard deviations of HDIs of peripheral mid vowels as a function of the non-peripheral configuration.

Non-peripheral configuration		**front**		**back**
	obs.	*Average HDI*	*obs.*	*Average HDI*
NP=0	200	-21.9 ± 130.7	199	+18.3 ± 103.6
NP=1	100	-23.1 ± 128.9	91	-4.8 ± 106.0
$NP \geq 2^{VER}$	96	+38.0 ± 110.7	93	-14.4 ± 96.5
$NP \geq 2^{HOR}$	45	+67.4 ± 134.3	45	-41.4 ± 117.1
NP≤1	300	-22.3 ± 129.9	290	11.0 ± 104.7
NP≥2	141	+47.4 ± 119.1	138	-23.2 ± 104.0

Table 4-8: Averages and standard deviations of 'horizontal deviation indices' for front and back mid vowels as a function of configuration of the non-peripheral vowels in the inventory.

It is apparent that mid front vowels get more advanced (HDI increases) and mid back vowels get more retracted (HDI decreases) as a function of complexity in the non-peripheral region, but the HDI indices greatly overlap between all configuration types. Unpaired t-tests were performed comparing all 14 possible pairs of non-peripheral configuration types (including comparisons between the joined types). The significance threshold was set at $p<0.0036$ (=0.05/14) according to Bonferroni correction. Table 4-9 summarizes the results.

Pairs of non-peripheral configuration	**front**		**back**	
	df	*t*	*df*	*t*
NP=0 vs. NP=1	298	0.077	288	1.745*(p=0.041)
NP=0 vs. $NP \geq 2^{VER}$	218^{u}	-4.096**	290	2.568*(p<0.006)
NP=0 vs. $NP \geq 2^{HOR}$	243	-4.120**	242	3.402**
NP=1 vs. $NP \geq 2^{VER}$	194	-3.549**	182	0.647
NP=1 vs. $NP \geq 2^{HOR}$	143	-3.862**	134	1.829* (p=0.035)
$NP \geq 2^{VER}$ vs. $NP \geq 2^{HOR}$	139	-1.375	136	1.431
NP≤1 vs. NP≥2	439	-5.388**	426	3.170**

Table 4-9: Summary of unpaired t-tests comparing average 'horizontal deviation indices' for peripheral mid vowels between different non-peripheral configurations. In the df columns, "u" denotes that the number of degrees of freedom is appropriate for unequal-variance unpaired t-test, as determined by a preliminary F-test for variance (with $p<0.05$ as significance threshold). "*" denotes near-significance at $p<0.05$ and "**" denotes significance at the Bonferroni-adjusted threshold of $p<0.0036$.

The results for the front vowels are straightforward: there is a categorical split between configurations with zero or one non-peripheral vowel and configurations with more than one non-peripheral vowel. All comparisons between configurations across these two categories are significant, whereas all comparisons between configurations within these categories are not. For the back vowels, the results suggest a more gradual effect, as the only significant comparisons are between the two extreme configurations (zero non-peripheral vowels vs. multiple non-peripheral vowels with horizontal contrasts) and between the two major categories (up to one non-peripheral vowels vs. multiple non-peripheral vowels). The effect is nevertheless reinforced by a few other near-significant results. In order to examine the effect further, regression models of F2 of front and back vowels as a function of F1 were calculated separately for each of the four inventory types. Table 4-10 lists the models and their r² values, and the models are plotted in Figure 4-5.

Non-peripheral configuration		model (F2=…)	r^2
NP=0	front	2526 – 1.276 x F1	0.443
	back	656 + 0.661 x F1	0.219
NP=1	front	2483 – 1.190 x F1	0.410
	back	614 + 0.702 x F1	0.217
$NP \geq 2^{VER}$	front	2723 – 1.565 x F1	0.628
	back	471 + 0.968 x F1	0.456
$NP \geq 2^{HOR}$	front	2771 – 1.602 x F1	0.577
	back	364 + 1.132 x F1	0.496

Table 4-10: regression models of F2 as a function of F1 for peripheral mid vowels in inventories with different non-peripheral configurations.

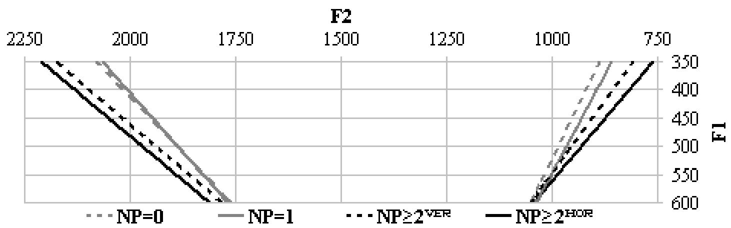


Figure 4-5: regression models of F2 as a function of F1 for peripheral mid vowels in inventories with different non-peripheral configurations.

Figure 4-5 demonstrates the categorical nature of the effect in front vowels as opposed to its gradual nature in back vowels. As already explained in Section 4.2.2, the partly categorical shift from a configuration with one non-peripheral vowel to a configuration with a vertical non-peripheral series seems to relate to the nature of the contrasts with peripheral vowels. As long as a non-peripheral vowel is on its own, it is free to assume its own distinct height and contrast with peripheral vowels both horizontally and vertically, thus requiring very little horizontal adjustment from the peripheral vowels. Once there are two or more non-peripheral vowels, they are no longer free in the F1 dimension, and are more likely to share the same F1 frequencies with peripheral vowels and base the contrast with them only on F2 (or F2'), which pushes the peripheral vowels horizontally into more extreme qualities.

Another interesting fact apparent in Figure 4-5 is the tendency of the peripheralization effect of non-peripheral configuration to correlate, or interact, with vowel height. The effect is greatest in the highest mid vowels (higher-mid to lower high, 350Hz<F1<400Hz), and it decreases gradually until it fades away in the lowest mid vowels (lower-mid to higher-low, 550Hz<F1<600Hz). This apparent interaction was tested using multiple regression analysis of F2 as a function of F1, non-peripheral configuration (simplified to a NP≤1 vs. NP≥2, each represented by a dummy number) and the interaction between the two variables. In front vowels, the analysis suggested effects of F1 and non-peripheral configuration (respectively $p<10^{-5}$ and $p<0.001$) and of the interaction between them ($p=0.02$). In back vowels, effects were found for non-peripheral configuration ($p<0.001$) and for the interaction ($p<0.003$), but the effect of F1 alone is questionable ($p=0.09$). In either case, this analysis both reinforces the effect of non-peripheral configuration on F2 of peripheral mid vowels and suggests that the magnitude of this effect is indeed correlated with vowel height.

This correlation between vowel height and further peripheralization of peripheral mid vowels as a function of more complex non-peripheral configuration is not surprising, and lends further support to Dispersion Theory principles. In Section 4.5.1, which discusses F1 frequency of non-peripheral vowels, it is shown that non-peripheral vowels are concentrated in the higher half of the vowel space, and rarely reach the lower part of the interior region (F1>550Hz, see in particular Figure 4-6, Figure 4-7 and Figure 4-10). Therefore, peripheral lower-mid/higher-low vowels ([ɛ~æ], [ɔ~ɒ]) hardly ever contrast horizontally with a non-peripheral vowel at the same height degree, and require little or no adjustment even if the inventory as a whole has the most complex non-peripheral configuration. This is a local manifestation of the same situation as in inventories with only one non-peripheral vowel with a distinct height degree, where only limited horizontal adjustment of peripheral vowels is necessary to accommodate the non-peripheral vowel.

The horizontal relationship between peripheral mid vowels and non-peripheral vowels is thus regulated by dispersion constraints in three different ways. First, peripheral mid vowels are sensitive to pressure exerted by non-peripheral vowels and get further peripheralized to accommodate them, in particular when horizontal pressure is strong in the presence of non-peripheral vowels at the same height. Second, non-peripheral vowels are avoided in the lowest part of the interior region of the vowel space, because, at these height levels, the entire space is too narrow to allow a three-way horizontal contrast. Third, in the absence of a three-way horizontal contrast in these height levels, the non-peripheral vowels are rather insensitive to peripheral configuration higher in the vowel space. Thus, taken together, the behavior of F2 frequencies of peripheral mid vowels as a function of non-peripheral configuration lends strong support to Dispersion Theory.

4.5 Vowel-specific effects III: non-peripheral vowels

Non-peripheral vowels are the least frequent vowel type in the corpus and at the same time cover the largest acoustic region. As such, they are the least acoustically uniform, allowing fewer and less robust generalizations. Nevertheless, several analyses were performed to test Dispersion Theory predictions. Section 4.5.1 examines the F1 frequency of some non-peripheral vowels as a function of non-peripheral configuration, and Section 4.5.2 examines the effect of peripheral configuration on the relative F2 position of non-peripheral vowels.

4.5.1 F1 of non-peripheral vowels as a function of non-peripheral configuration

Dispersion Theory makes the following predictions regarding the F1 frequencies of non-peripheral vowels. First, in configurations with multiple non-peripheral vowels, the highest and lowest vowels should be respectively above and below the non-peripheral vowel in configurations with one non-peripheral vowel. Second, multiple non-peripheral vowels organized in one vertical series ($NP \geq 2^{VER}$) should cover a larger F1 span than multiple non-peripheral vowels with horizontal contrasts ($NP \geq 2^{HOR}$). Third, in multiple non-peripheral vowels organized in one vertical series, as in the case of peripheral vertical series, the addition of a vowel to the series should result in both vertical expansion and vertical rearrangement of the series, that is, not only should the vertical span be wider, but the individual vowels should shift up and down to accommodate the added vowel.

Averages and standard deviations of F1 frequencies of non-peripheral vowels are presented in Table 4-11 and Figure 4-6. The $F1_{MIN}$ and $F1_{MAX}$ indices respectively refer to the highest and lowest non-peripheral vowel in each configuration (merged for NP=1). F1 frequencies of other non-peripheral vowels are provided only for vertical series configurations with three and four vowels. In the latter configuration, which appears in only three inventories, only averages are reported. For NP=1, the values in parentheses are the result of the exclusion of five 9S1 inventories with robust ATR harmony, where the non-peripheral vowel serves as the low vowel of the [+ATR] subsystem. The superscript letter indices serve as references in the text below.

		Observations	**$F1_{MIN}$**	**$F1_{MAX}$**	**higher mid**	**lower mid**
NP=1		76 (71)	$445^a \pm 98$ ($431^a \pm 85$)			
$NP \geq 2^{VER}$	**NP=2**	48	$328^b \pm 43$	$465^c \pm 66$		
	NP=3	9	$319^d \pm 35$	$483^e \pm 66$	$403^f \pm 64$	
	NP=4	3	298^g	598^h	394^i	481^j
	all	60	$325^k \pm 42$	$474^l \pm 71$		
$NP \geq 2^{HOR}$		28	$330^m \pm 54$	$471^n \pm 61$		

Table 4-11: averages and standard deviations of F1 frequencies of non-peripheral vowels as a function of non-peripheral configuration. For NP=1, parenthesized values represent only inventories without robust ATR vowel harmony. For NP≥2 in a vertical series ($NP \geq 2^{VER}$), F1 data are provided for each vowel for each value of NP. Superscript letters serve as indices for the individual average frequencies and are referred to in the text.

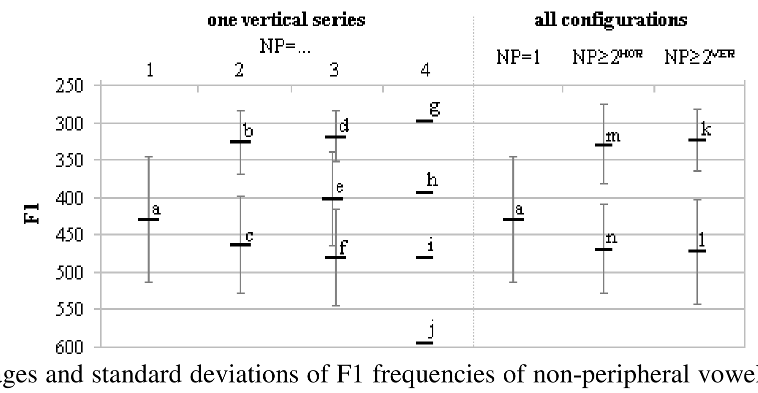


Figure 4-6: Averages and standard deviations of F1 frequencies of non-peripheral vowels. On the left, data points represent all vowel categories in single vertical series configuration of different lengths. On the right, data points represent F1 minima and maxima for different non-peripheral configurations. Superscript letters serve as indices for the individual average frequencies and are referred to in the text.

If standard deviations are ignored, the average F1 frequencies are consistent with predictions of Dispersion Theory. The general predictions of Dispersion Theory can be translated into 18 qualitative predictions regarding pairs of averages in Table 4-11, which, using the superscript letter indices attached to the average values, are: a>k, a<l, a>m, a<n, k<m, l>n, a>b, a<c, b>d, b<f, c>f, c<e, d>g, d<i, f>i, f<j, e>j, e<h. All 18 predictions are borne out without exception, which has a random probability smaller than $4\text{x}10^{-6}$ (or even smaller given that all predictions concerning the average F1 frequency of a single non-peripheral vowel were borne out regardless whether or not inventories with ATR harmony were included).[29]

However, as most of the predicted qualitative differences are manifested in quantitative frequency differences smaller than 20Hz, while most standard deviations are larger than 40Hz, it is clear that very few individual comparisons would come out significant in unpaired *t*-tests. Indeed, only the predictions a>k, a<l, a>m, a<n, a>b, a<c and b<f were significant at $p<0.00278$ (=0.05/18), and the comparisons c>f, d<i, f<j and e<h were near-significant at $p<0.05$ (in some of these, the comparison lacks power because the indices i, j and h represent sets with only three tokens).

Disregarding the difference between predictions that are evidently true from those that are likely to be due to mere chance, a tentative conclusion can be made that F1 frequencies of non-peripheral vowels behave according to the predictions of Dispersion Theory, but more data are needed in order to fully establish these conclusions.

Another aspect of the vertical behavior of non-peripheral vowels is whether or not they share the same F1 frequency range with peripheral vowels, in particular in

[29] Notice that, with the exception of the predictions a>k and a<l, which are inevitably true if a>b>d>g and a<c<e<h are true, any pair of predictions are independent from one another, at least in case one of them is true.

the case of the highest non-peripheral vowel and the point vowels *I* and *U*. It has been claimed in Sections 4.2.2 and 4.4.2 that a single non-peripheral vowel tends to have a unique F1 level distinct from the rest of the inventory, but two or more non-peripheral vowels are not as vertically free, and are forced into F1 levels similar to those of peripheral vowels. Since the F2 and F2' spans are widest at the lowest F1 frequencies, it stands to reason, according to Dispersion Theory, that the highest non-peripheral vowel would be at the F1 frequency range of *I* and *U*, thus allowing more vertical variability in lower non-peripheral vowels, where the F2 and F2' spans are narrower.

In order to test this, each of the 159 inventories with non-peripheral vowels was assigned an index of vertical displacement of its highest non-peripheral vowel relative to the highest vowel in the inventory $F1_{minNP}$-$F1_{min}$. Table 4-12 describes the distribution of these indices for the different non-peripheral configurations. Since the distributions are skewed due to the lower limit of 0Hz, medians and quartile rages are more representative than averages and standard deviations. Again, in the case of non-peripheral vowel inventories, indices were also calculated for the subset of inventories without ATR vowel harmony (in parentheses in the table).

Non-peripheral configuration	**$F1_{minNP}$-$F1_{min}$ (in Hz)**				
	obs.	*Average ± sd*	*median*	*first quartile*	*third quartile*
NP=1 (NP=1, no vowel harmony)	71 (65)	137.4±110.1 (120.1±96.8)	105.4 (100.0)	51.6 (48.2)	216.4 (164.2)
$NP \geq 2^{VER}$	57	29.4±34.1	20.3	5.4	43.4
$NP \geq 2^{HOR}$	31	31.7±41.8	14.83	0	50.7

Table 4-12: average, standard deviation and quartiles of indices of F1 difference between the highest non-peripheral vowel and the highest vowel in the inventory, as a function of non-peripheral configuration.

It is immediately apparent that inventories with single and multiple non-peripheral vowels follow distinct trends. Single non-peripheral vowels tend to be vertically distinct from the highest vowel in the inventory, with F1 difference larger than 50Hz in 75% of the cases. Conversely, the highest among multiple non-peripheral vowels indeed tends to share the F1 level of the highest vowels in the inventory, with F1 difference smaller than 50Hz in 75% of the cases. These data thus validate Crothers' (1978:121) well phrased generalization that "languages with two or more interior vowels always have a high one".

Figure 4-7 plots the highest front, back and non-peripheral vowels in the three inventory types (from all 158 inventories with non-peripheral vowels in the survey for which normalized frequencies of both F1 and F2 are available). Notice the vertical spread of the single non-peripheral vowels (black triangles) and the concentration at the top of the space of the highest among multiple non-peripheral vowels (white- and grey-filled triangles).

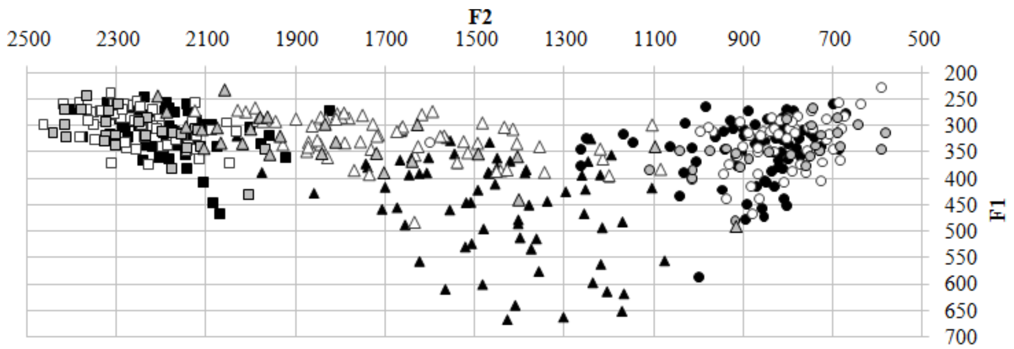


Figure 4-7: F1xF2 plot of the highest non-peripheral (triangles), highest front (squares) and highest back (circles) vowels in all the inventories with non-peripheral vowels in the survey. Black, grey and white mark fillings respectively refer to inventories with one non-peripheral vowel, with multiple non-peripheral vowels in one vertical series and with multiple non-peripheral vowels with horizontal contrasts.

The different trends in single and multiple non-peripheral vowel inventories were highly significant in unpaired t-tests (NP=1 vs. NP≥2^{VER}: $t(86)=7.809$, $p<1\text{x}10^{-11}$ (no vowel harmony: $t(82)=7.070$, $p<1\text{x}10^{-9}$); NP=1 vs. NP≥2^{HOR}: $t(99)=7.028$, $p<1\text{x}10^{-9}$ (no vowel harmony: $t(93)=6.259$, $p<1\text{x}10^{-8}$), all tests assume unequal variance). There was no significant difference between the two different configurations with multiple non-peripheral vowels ($t(86)= 0.245$, $p>0.40$, equal variance assumed).

These results constitute evidence against Carré's Distinctive Region Model (DRM, Mrayati et al. 1988, Carré 2009). As described in Section 1.3.4 this theory maintains that vowel inventories are arranged along very few articulatory trajectories (e.g. low to high-front-unrounded, low to high-back-rounded). Carré (2009) uses Crothers' (1978) generalization that [ɨ] is the first non-peripheral vowel to appear in inventories as evidence for a trajectory along the ceiling of the vowel space, from high-front-spread [i] through high-mid-neutral [ɨ] to high-back-rounded [u]. If the non-peripheral vowel that appears first in inventories is not high, then it is not on the [i]-[u] trajectory. Moreover, as this vowel has its own distinct height, it is not on *any* horizontal trajectory between a front and a back vowel.

Although the results do support Dispersion Theory, they form strong evidence against its common formulation in simulation studies. Most models formalize systemic dispersion as a penalty score based on all between-vowel distances in the *n*-vowel inventory, as follows:

(4.7) $$\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{1}{{d_{i,j}}^{2}}$$

This 'aggregate approach' favors vowels along the edges of the acoustic and perceptual space, including its ceiling (minimal F1 frequency), so that the distances between each vowel and all non-adjacent vowels would span as much as the vowel space allows. Consequently, in model simulations, the first non-peripheral vowel to emerge in the predicted inventories always, inconsistent with the survey data, has minimal F1 frequency at the very top of the vowel space (Liljencrants & Lindblom

1972, Lindblom 1986, Schwartz et al. 1997b, de Boer 2000, Sanders & Padgett 2008a,b). Sanders & Padgett's (2008b) model is able to predict inventories with a lower single non-peripheral vowel, essentially schwa, using an effort minimization component. This is unlikely to be the source of the non-high nature of single non-peripheral vowels, for two reasons. First, a high non-peripheral vowel is clearly favored once there is another non-peripheral vowel in the inventory. If the bias against a high non-peripheral vowel were articulatory, it should have had some manifestation in inventories with multiple non-peripheral vowels as well. Second, and more importantly, as seen in the acoustic geometries in Appendix B, the single non-peripheral vowel tends to be near-high or higher-mid, at a level distinctly lower than the highest vowel but higher than any other level, hence this non-perheral vowel involves some articulatory effort.

Since effort minimization is necessary anyway in order to explain the correlation between the number of vowels and acoustic space size (Section 4.2), it might be possible to explain the higher-mid level of a single non-peripheral vowel by some compromise between aggregate dispersion and effort minimization. However, a more reasonable explanation based entirely on dispersion is that the single non-peripheral vowel settles at a distinct height level also in order to maximize horizontal distances from the nearest vowels. As long as it keeps away from the height levels of other vowels, it strives to be as high as possible in the acoustic space, where horizontal distances are largest.

Such an explanation is more consistent with formalizations of dispersion based on the 'bottleneck approach', where only the shortest between-vowel distance(s) count and should be maximized, and distances from vowels farther away are ignored (ten Bosch 1991b, Flemming 2005, Becker-Kristal 2007). Figure 4-8 illustrates the difference between the two approaches, using a simplified two-dimensional space with arbitrary distance units and a fixed five-vowel periphery (grey dots). The single non-peripheral vowel (black dot) is maximally high in the inventory in (a) but is one unit lower in the inventory in (b).

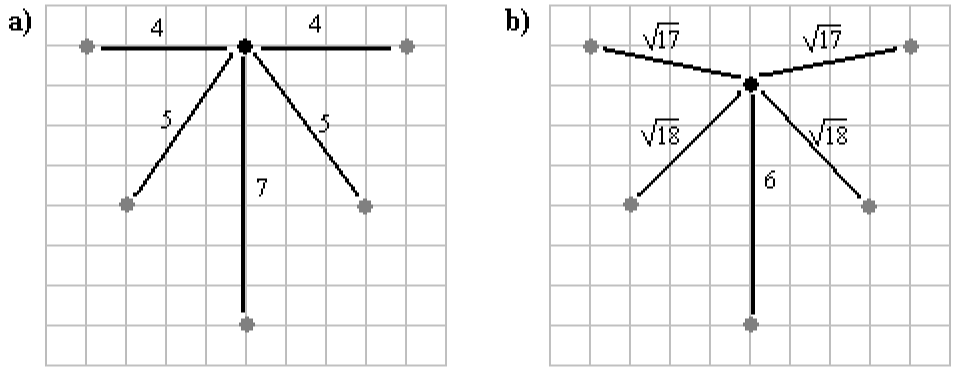


Figure 4-8: A simplified two-dimensional space with an inventory comprising five peripheral vowels (grey dots) and one non-peripheral vowel (black dot), which is maximally high (a) or lowered (b). Also displayed are the distances, in arbitrary distance units, of the non-peripheral vowel from all the peripheral vowels in the inventory.

As the periphery is fixed, the penalty scores of both inventories differ only as a function of the position of the non-peripheral vowel. According to the aggregate approach, the penalty scores contributed by the distances associated with the non-peripheral vowels are:

(4.8) maximally high: $\frac{1}{16}+\frac{1}{16}+\frac{1}{25}+\frac{1}{25}+\frac{1}{49}=0.2254$

(4.9) lowered: $\frac{1}{17}+\frac{1}{17}+\frac{1}{18}+\frac{1}{18}+\frac{1}{36}=0.2565$

The aggregate approach favors the maximally high non-peripheral vowel due to its lower penalty score. Conversely, the bottleneck approach would favor the lower non-peripheral vowel, because the minimal distance from other vowels, which is in both cases associated with the peripheral high vowels, is longer for the lower non-peripheral vowel than for the maximally high non-peripheral vowel due to the contribution of the vertical dimension.

4.5.2 F2 of non-peripheral vowels as a function of peripheral configuration

According to Dispersion Theory, the same principles that were shown in Section 4.3.2 to govern the horizontal position of the low vowel apply in the case of non-peripheral vowels. Non-peripheral vowels should be more retracted in inventories with left-crowded periphery, more advanced in inventories with right-crowded periphery and between the two in inventories with symmetrical periphery. However, unlike the analysis of low vowels, the analysis of non-peripheral vowels cannot use absolute F2 frequencies, because, due to the correlation between F1 and F2 in non-low vowels (as discussed in Section 4.4.2), which differs across back and front vowels, the same F2 frequency signals different relative horizontal position at different F1 frequencies. The analysis therefore has to use proportional F2 frequencies relative to the characteristic F2 spans for given F1 frequencies.

In order to enable a coherent analysis, models of characteristic F2 frequency span as a function of F1 were devised, following the system used in Section 4.4.2, as follows. First, simple regression models of F2 as a function of F1 were calculated, using all peripheral non-low vowels in inventories containing non-peripheral vowels. Separate models were calculated for each non-peripheral configuration, because it was shown in Section 4.4.2 that different non-peripheral configurations yield different characteristic F2 frequencies of peripheral non-low vowels. These models, which are shown in Table 4-13 are very similar to the ones appearing in Table 4-10 in Section 4.4.2, but differ slightly as they cover peripheral high vowels as well.

Non-peripheral configuration		observations	model (F2=…)	r^2
NP=1	front	172	2608.4 – 1.419 x F1	0.636
	back	163	689.2 + 0.550 x F1	0.185
$NP \geq 2^{VER}$	front	156	2706.5 – 1.532 x F1	0.749
	back	153	538.0 + 0.846 x F1	0.436
$NP \geq 2^{HOR}$	front	72	2742.2 – 1.552 x F1	0.683
	back	72	444.5 + 0.999 x F1	0.474

Table 4-13: Regression models of F2 as a function of F1 for peripheral non-low vowels according to different non-peripheral configurations.

Next, every non-peripheral vowel in the corpus was assigned a relative F2 index based on the proportional position of its F2 frequency in the span between the characteristic F2 frequencies of the front and back vowels sharing its F1 frequency. Characteristic F2 frequencies for the front and back vowels were calculated using the appropriate model from Table 4-13, given the known non-peripheral configuration in which the specific non-peripheral vowel appears. For example, a non-peripheral vowel with F1=400Hz, F2=1500Hz as part of a vertical series is assigned the relative F2 index 0.512 (according to $(F2-F2_{back})/(F2_{front}-F2_{back})$, translated into: [1500-(538.0+0.846x400)]/[(2706.5-1.532x400)-(538.0+0.846x400)] = 0.512).

Finally, all non-peripheral vowels, with their relative F2 indices assigned, were grouped according to peripheral configuration. The total average index was 0.562 (±0.186), and the average indices were 0.556 (sd = ±0.201) for left-crowded periphery inventories (72 vowels in total), 0.582 (sd = ±0.173) for symmetrical periphery inventories (150 vowels) and 0.522 (sd = ±0.190) for right-crowded periphery inventories (67 vowels). While non-peripheral vowels in left-crowded periphery inventories indeed seem slightly more retracted than in symmetrical periphery inventories, as Dispersion Theory predicts, the non-peripheral vowels in right-crowded periphery inventories, which are supposed to be the most advanced, are in fact the most retracted. However, in the three unpaired t-tests comparing the three sets, only the comparison between non-peripheral vowels in right-crowded vs. symmetrical periphery inventories turned out to be barely significant ($t(215)=2.312$, $p=0.022$, two tailed).

Whether or not the F2 frequencies of non-peripheral vowels are sensitive to peripheral configuration remains an open question, but in either case, the predictions of Dispersion Theory as proposed at the beginning of this section are not borne out this time. It is possible that the horizontal position of the low vowel, which leans towards the less crowded side of the periphery, balances the repelling pressure on vowels in the non-peripheral region, so there is in fact little or no difference between the different peripheral configurations in this regard.

4.6 **Even spacing**

In formal models, dispersion is formalized as numerical penalties for short perceptual distances between vowels, and maximization of dispersion is typically achieved when vowels are evenly spaced, that is, when the shortest between-vowel distance in the inventory is repeated in many vowel pairs. Between-vowel distance and even spacing depend heavily on model-specific representations, like the perceptual scale(s), the perceptual dimensions, the distance metric and weighting factors. However, a first crude approximation of even spacing is the single-dimension simple (non-weighted) distances within vertical and horizontal series. More specifically, the scale on which such within-series distances are closest in magnitude is the scale most likely for successful dispersion-oriented modeling of acoustic geometries. The purpose of this section is to test whether such simple even spacing is possible at all, and if it is, on which scale. Section 4.6.1 analyzes F1 distances in peripheral vertical series, and Section 4.6.2 analyzes F2’ distances between non-peripheral vowels and the front and back peripheries.

4.6.1 F1 of peripheral vowels and even spacing

In Sections 4.2-4.4 it was shown that the vertical behavior of peripheral vowels adheres to dispersion principles, and it is therefore likely that the different height levels in the periphery are evenly spaced. In the analyses, only inventories with five or more vowels in the periphery, i.e. inventories with at least three distinct height levels, will be considered. In order to simplify the analyses and reduce statistical noise caused by ‘vertically misbehaving’ individual vowels, height levels will be represented as F1 averages of corresponding front and back vowels, so, for example, in a 7S periphery, the F1 frequencies of /i/ and /u/ will be averaged, as will /e/ and /o/ and so on. In odd-numbered peripheries, the very few inventories with asymmetrical peripheries will be ignored, and in all other inventories the low vowel will be treated as a single-vowel height level. In even-numbered peripheries, which are by definition asymmetrical, the lowest vowel and the lowermost vowel of the more crowded side (the second lowest vowel) will be treated as sharing the same height, because (a) in some inventories the second lowest vowel is indeed a low vowel, and (b) even in the other inventories with only one low vowel, even spacing within each side should yield even spacing between height levels when both sides are averaged.

With regard to peripheries with five height levels (22 inventories with 9S periphery, three with 10L and three with 10R), it has been shown in Section 4.4.1 that in 9S peripheries are too often characterized by extreme proximity of the second and third height levels, and thus defy the notion of even spacing. Similar proximity of these two heights was attested also in some of the ten-vowel periphery inventories, and it was clear that these peripheral structures are not evenly spaced.[30] This is of little concern if it is acknowledged that the viability of 9S0, 10L0 and 10R0 inventories depends on vowel harmony (Section 3.6.5), and that inventories with ten vowels or more are extremely rare and probably not viable to begin with (Schwartz et al. 1997a). It was nevertheless decided to include the five height level peripheries in the analyses by pooling the second and third heights together and treating these peripheries as four height levels instead of five. The analyses for four height levels were performed both with and without the five height peripheries.

Averaged F1 frequencies for distinct height levels were calculated for 249 inventories with peripheries containing five vowels or more, including 143 inventories with 5S, 6L or 6R peripheries and three height levels: high, mid and low (H, M, L) and 106 inventories with 7S, 8R, 8L, 9S, 10R or 10L peripheries and four height levels (of these 78 inventories with 7S, 8R, 8L peripheries): high, higher-mid, lower-mid and low (H, HM, LM, L). For each two adjacent height levels, a spacing index was calculated by subtracting the F1 frequency of the higher level from that of the lower level, giving two spacing indices for three-level inventories (M-H, L-M) and three spacing indices for four-level inventories (HM-H, LM-HM, L-LM). Then, each pair of spacing indices was tested for significant difference by a paired t-test, giving four t-tests, one for the three-level space indices (M-H vs. L-M) and three for the four-level space indices (HM-H vs. LM-HM; HM-H vs. L-LM; LM-HM vs. L-

[30]Even when only the ten inventories with nine- and ten-vowel peripheries and no vowel harmony were considered, the average F1 distance between these two heights increased only to 67Hz, which is too small compared to 92Hz between the first and second heights and 144Hz between the third and the fourth height.

LM). The F1 frequency data were converted to four different perceptual scales: ln(Hz), ERB, Bark and Mel. All indices and t-tests were calculated using the linear Hz scale and each of the four perceptual scales. As a result, there were five t-tests for three height level peripheries (1 spacing index pair x 5 scales) and 30 t-tests for four height level peripheries (2 datasets x 3 index pairs x 5 scales). Thus, the total number of t-tests was 35, and the two-tailed significance threshold was accordingly Bonferroni-corrected to 0.0014 (=0.05/35). Table 4-14 summarizes the average spacing indices and index comparisons as a function of number of height levels and scale. Notice that indices and results for four level peripheries change very little when the five level peripheries (with the pooled height levels) are added.

				Hz	**ln(Hz)**	**Bark**	**ERB**	**Mel**
three levels	**indices**	M–H		144±49	0.366±0.118	1.32±0.43	2.14±0.69	147±48
		L–M		215±67	0.379±0.123	1.73±0.54	2.50±0.79	190±60
	***t*-tests**	M-H vs. L-M	$t(142)=$	9.522**	0.883 *n.s.*	6.568**	3.825**	6.150**
four levels	**indices**	HM – H		101±35	0.285±0.103	0.95±0.35	1.60±0.58	107±39
		LM – HM		141±51	0.295±0.096	1.21±0.42	1.84±0.62	134±46
		L – LM		170±62	0.276±0.107	1.32±0.49	1.86±0.71	145±54
	***t*-tests**	HM-H vs. LM-HM	$t(77)=$	6.194**	0.637 *n.s.*	4.637**	2.687*	4.208**
		HM-H vs. L-LM	$t(77)=$	7.325**	0.495 *n.s.*	4.675**	2.169*	4.278**
		LM-HM vs. L-LM	$t(77)=$	2.799*	1.065 *n.s.*	1.270 *n.s.*	0.443 *n.s.*	1.175 *n.s.*
four levels + five levels (levels 2 and 3 pooled)	**indices**	HM – H		100±36	0.284±0.100	0.94±0.34	1.59±0.56	106±38
		LM – HM		145±49	0.304±0.094	1.25±0.41	1.90±0.60	138±45
		L – LM		172±64	0.278±0.108	1.33±0.50	1.88±0.72	146±55
	***t*-tests**	HM-H vs. LM-HM	$t(105)=$	8.622**	1.688 *n.s.*	6.700**	4.267**	6.165**
		HM-H vs. L-LM	$t(105)=$	8.775**	0.362 *n.s.*	5.723**	2.792*	5.259**
		LM-HM vs. L-LM	$t(105)=$	3.057*	1.725 *n.s.*	1.183 *n.s.*	0.216 *n.s.*	1.062 *n.s.*

Table 4-14: F1 spacing indices and t-tests comparing them for inventories with three-level peripheries, four-level peripheries and four+five level peripheries (with the second and third height levels pooled), calculated in the linear Hz scale and in four perceptual scales: ln(Hz), Bark, ERB and Mel. "*" denotes near-significance at $p<0.05$ and "**" denotes significance at the Bonferroni-adjusted threshold of $p<0.0014$.

In the linear Hz scale, spacing indices increase as the F1 frequencies involved increase (i.e. between lower height levels), which is in line with quasi-logarithmic perceptual scaling. However, while all perceptual scales succeed in equalizing the middle and lower spacing indices in the four-level peripheries, as evident from the similar index levels and the non-significant t-test results, none of the other indices got equalized on any scale except the ln(Hz) scale, where *all* indices got equalized. Figure 4-9 displays the F1 averages and standard deviations of the various height levels in both configurations in the Hz scale on the left and ln(Hz) scale on the right (the four-level statistics are based only seven- and eight-vowel peripheries). The equalizing effect of the ln(Hz) scale is apparent.

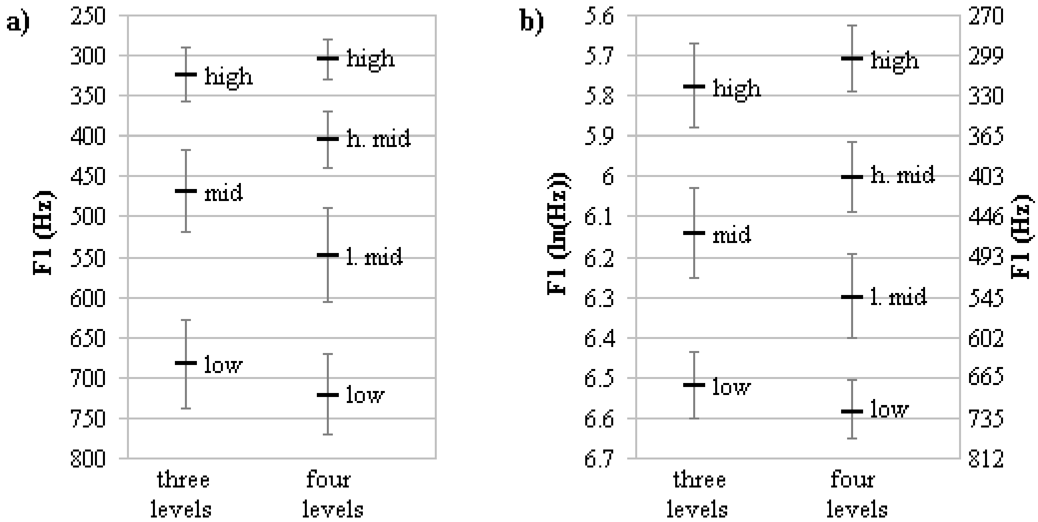


Figure 4-9: Averages and standard deviations of characteristic F1 frequencies of vowel height levels in peripheries with 5-6 vowels (three heights) and with 7-8 vowels (four heights), on the Hz scale (a) and the ln(Hz) scale (b). Hz equivalents of the ln(Hz) values are shown on the right edge of the right panel.

Two important conclusions can be derived from this analysis. First, that there is at least one commonly used perceptual scale where vertical spacing is even, which constitutes yet another piece of evidence in favor of Dispersion Theory. Second, that this scale is the logarithmic Hz scale, rather than any of the more sophisticated, auditory-based scales. Unfortunately, the only simulation studies that used the logarithmic Hz scale are ten Bosch et al. (1987) and Roark (2001), neither of which provides fully explicit predictions of inventories in terms of IPA-labeled vowels. Liljencrants & Lindblom (1972) used the Mel scale and Lindblom (1986), Schwartz et al. (1997b), de Boer (2000), Becker-Kristal (2007) and Sanders & Padgett (2008a,b) all used the Bark scale. It is possible that at least some improvements in the predictive adequacy of these models would have been achieved if they had used the logarithmic Hz scale instead.

4.6.2 F2' of non-peripheral vowels and even spacing

Recall that, in Section 4.5.2, the relative position of non-peripheral vowels on the F2 span was examined as a function of peripheral configuration, and that they turned out to be slightly more advanced than the midpoint of the F2 span in Hz, with an average relative position of 0.562. These findings are meaningless as far as Dispersion Theory is concerned, because perceptual spans and distances are based on F2' on quasi-logarithmic scales, rather than F2 on the linear Hz scale.

In order to estimate the relative perceptual horizontal position of non-peripheral vowels, the procedure performed in Section 4.5.2 was repeated, but this time using the F2' estimates described in Section 3.4.3. First, regression models of F2' of front vowels were calculated as a function of F1 for the various non-peripheral configurations (for back vowels, where F2' is assumed to be the same as F2, the F2 regression models from Section 4.5.2 were used). All models had r^2 values above 0.700.[31] Then, for each non-peripheral vowel, the F1-specific F2' frequency span was determined by using its F1 frequency in the appropriate model according to the non-peripheral configuration type of its inventory. The F2' estimate of the non-peripheral

[31] These high correlations are not surprising given that F1 contributes both to the estimate of F3, which participates in determining F2', and to the estimate of F2' itself.

vowel, together with the F2’ estimates of the span extrema, were converted to the same four perceptual scales used also in Section 4.6.1, ln(F2’), Bark, ERB and Mel. The relative position index of the non-peripheral vowel on the span was calculated on each scale separately.

The average relative position index was 0.592 (sd = 0.180) on the ln(F2’) scale, 0.575 (sd = 0.182) on the Bark scale, 0.578 (sd = 0.181) on the ERB scale and 0.559 (sd = 0.182) on the Mel scale, with a cross-scale average of 0.576 (sd = 0.181). Regardless of scale, non-peripheral vowels tend to be more advanced and closer to front than to back vowels. Anywhere between 65% (on the Mel scale) and 73% (on the ln(Hz) scale) of the vowels had indices above 0.5, implying that horizontal dispersion is not simply even spacing along the F2’ span, as most formal dispersion models suggest. It is interesting to note that relative F2’ position indices were very similar to their corresponding relative F2 position indices on the Hz scale, and the correlation between the two index types was extremely high (r^2=0.992). This implies that the relative position of non-peripheral vowels on the F2 span in Hz is a highly reliable measure for their relative perceptual position.

It was suspected that the advanced positions of non-peripheral vowels could be explained by fact that front-rounded vowels are common in inventories of European languages, which are are overrepresented in the survey (see Section 2.2.2). For this purpose, the relative F2’ position indices of the 290 non-peripheral vowels, averaged from all four scales, were divided according to whether or not they were contributed by inventories belonging to European languages. Table 4-15 describes the distribution of non-peripheral vowels according to inventory structure and European vs. non-

European affiliation. The tendency towards more advanced non-peripheral vowels in European languages is evident for each inventory structure.

Non-peripheral configuration	European		non-European		total	
	obs.	*F2' position*	*obs.*	*F2' position*	*obs.*	*F2' position*
NP=1	22	0.555 ± 0.201	49	0.516 ± 0.188	71	0.528 ± 0.191
NP≥2^{VER}	74	0.627 ± 0.122	64	0.571 ± 0.179	138	0.601 ± 0.153
NP≥2^{HOR}	37	0.612 ± 0.168	44	0.544 ± 0.235	81	0.575 ± 0.201
Total	133	0.611 ± 0.151	157	0.546 ± 0.199	290	0.576 ± 0.181

Table 4-15: averages and standard deviations of relative F2' position indices of non-peripheral vowels (averaged from all four perceptual scales) in inventories of European vs. non-European languages, as a function of non-peripheral configuration.

Figure 4-10 plots all the non-peripheral vowels on the F1xF2' ln(Hz) plane, distinguishing between vowels from inventories of European (dark circumference, light interior) and non-European languages (light circumference, dark interior). Also plotted are three curves: the curve on the left is 0.1 ln(Hz) unit below the ln(Hz) equivalent of characteristic F2' frequencies of front vowels as a function of F1 in inventories with non-peripheral vowels (averaged from the three configurations), the curve on the right is its back vowel equivalent (0.1 ln(Hz) unit above the equivalent of the average of the three models), and the curve in the middle is the F2' midline. 97% of the non-peripheral vowels are found in the area between the front and back curves. The paucity of non-peripheral vowels from European inventories right of the midline is apparent, as are the sparseness of the region F2'<1200Hz and the absence of truly high retracted non-peripheral vowels (F1<330Hz).

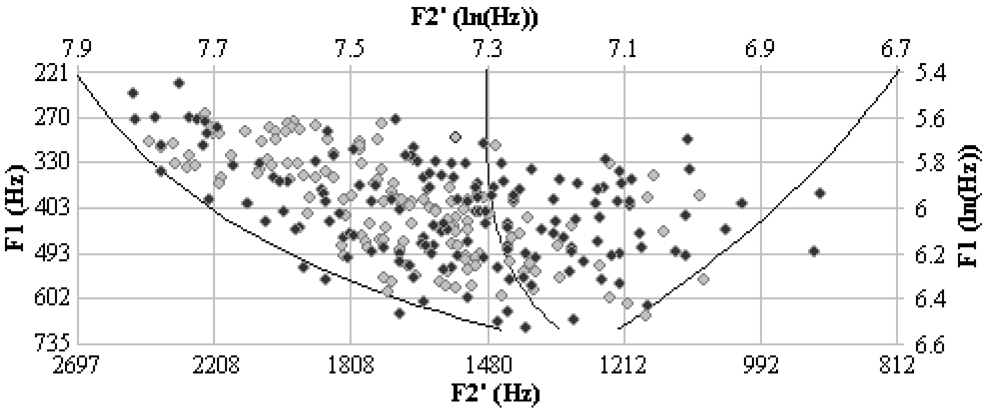


Figure 4-10: Distribution of non-peripheral vowels from inventories of European (dark circumference, light interior) and non-European languages (light circumference, dark interior) on the F1xF2' plane in ln(Hz) units, with Hz equivalents on the secondary axes. The curves on the left and right are respectively 0.1 ln(Hz) unit below and above the representative curves of F2' as a function of F1 for front and back vowels, and the curve in the middle represents the F2' midline.

In unpaired t-tests, non-peripheral vowels in European languages were significantly fronter than in non-European languages for the entire dataset ($t(285)=3.119$, $p<0.001$) and marginally also for vowels in vertical series configuration ($t(109)=2.097$, $p=0.019$), but neither for the single non-peripheral vowel configuration ($t(69)=0.782$, $p>0.21$) nor for the non-peripheral vowels with horizontal contrasts, where there is inherent F2' variability within each inventory ($t(62)=0.760$, $p>0.22$). However, the most important result is that, even in non-European languages, non-peripheral vowels are more advanced than the perceptual midline. Since a typologically representative sample would include a non-negligible proportion of non-peripheral vowels from inventories of European languages, it would inevitably yield an even more advanced average position than the non-European average here (probably between 0.55 and 0.56).[32]

[32] Notice that in a more typologically representative sample, the proportion of non-peripheral vowels from European languages should be greater than the proportion of these languages among the languages of the world, because the relevant proportion is among languages whose inventories contain non-peripheral vowels, which are relatively more frequent in Europe than in most other regions. This is evident from the fact that, while European languages account for 95 (31%) of the 304 language-specific, structure-specific inventory entries, they account for 66 (41%) out of the 159 inventory entries containing non-peripheral vowels, and for 133 (46%) of the 290 indivual non-peripheral vowels.

It is worth noting that the advanced position of non-peripheral vowels is not an artifact of the choice of wordlist elicitation, rather than the more canonical isolation elicitation, as the target for between-method normalization. If vowels were normalized towards isolation elicitation, the F2 of front vowels would have shifted forward slightly more than the backward shift in back vowels (because the extrapolation anchor is at 0.466 of the F2 span, i.e. slightly behind the midline), and F2' of front vowels would have shifted forward even more. However, on quasi-logarithmic perceptual scales, the backward shift of back vowels would have been greater. At the same time, most non-peripheral vowels would have shifted slightly to the front. Consequently, the relative position of non-peripheral vowels would have been even more advanced.

In summary, the relative position of non-peripheral vowels on the F2' span is not equidistant from front and back vowels as Dispersion Theory predicts, but tends to be more advanced and closer to front vowels. This lends support to the concepts underlying Dispersion Focalization Theory (DFT, Schwartz et al. 1997b). According to this theory, non-peripheral vowels should be halfway between the front and back vowels if only dispersion is operating, but fronter non-peripheral vowels can emerge instead, whenever the model activates the optional parameter of focalization, or preference of vowels with formant proximity, which is characteristic of F2 and F3 in front rounded vowels. In either case, more retracted non-peripheral vowels should be the rarest and the last to emerge in inventories, in agreement with the trends established here.

Additional support for DFT and the role of focalization is found in the fact that the tendency of non-peripheral vowels to be relatively fronter increases with vowel height, as apparent in Figure 4-10. Although non-peripheral vowels of all heights tend to be fronter than the F2’ midline, lower non-peripheral vowels are concentrated much closer to it, and many more of them are found to its right. Higher non-peripheral vowels on the other hand are almost exclusively to the left of the midline and farther away from it. The only apparent reason why high non-peripheral vowels should be very advanced while mid non-peripheral vowels are closer to the midline and more variable overall is that only in high non-peripheral vowels can F2 reach close to F3 and maximize focalization. Conversely, in mid non-peripheral vowels, the F2 frequency cannot reach high, and hence F2-F3 focalization is modest at most, and its fronting effect is only marginal as a result.

Interestingly, this apparent manifestation of focalization lends further support for the preference of the logarithmic Hz scale over the more commonly used Bark scale. DFT views focalization as proximity between *any* pair of formants, not only F2 and F3, and therefore should favor vowels characterized by proximity of F1 and F2 as well. However, it has been shown in Section 4.3.2 that, in low vowels, there is no evidence for preference of [ɑ], the only low vowel with F1~F2 proximity. The question is, of course, what distance counts as proximity, and on which scale. If the vowel [œ], with characteristic F2 frequency of 1500Hz and F3 frequency of 2350Hz, can be considered as representative of the threshold of effective focalization, i.e. vowels with smaller F2-F3 distance are focal while vowels with greater F2-F3 distance are not, then this threshold is about 3Bark (1500Hz ≈ 11Bark, 2350Hz ≈ 14Bark). If the same threshold is applied on the F1-F2 distance in low vowels with characteristic F1 frequency of 720Hz (≈ 6.7Bark), then vowels with F2 frequency below 1225Hz (≈ 9.7Bark) should be regarded as focal. However, if the threshold is set based on the logarithmic Hz scale, i.e. a Hz-frequency ratio of 1.567 (2350/1500 = 1.567), then applying the same threshold on the F2/F1 ratio in low vowels would assess as focal only vowels with F1 frequency below 1130Hz (1130/720 ≈ 1.567). Such vowels are hard to produce without pharyngealization, and would still be considered only as modestly focal. Substantial focalization as in [y] (F3/F2 ratio of 1.35 and below) cannot be achieved in low vowels unless F2 is brought below 1000Hz, which requires extreme pharyngealization. Thus, while Bark-based focalization might favor low back vowels (and also mid back rounded vowels) just as much as it would favor front rounded vowels, focalization based on the logarithmic Hz scale would maintain the uniqueness of front rounded vowels. It should nevertheless be acknowledged that an ERB-based focalization threshold would have yielded very similar assessments as the log(Hz) threshold, so the possible role of focalization may be taken as evidence against the Bark scale but not necessarily in favor of the logarithmic Hz scale alone.

Finally, the data on average relative F2' positions of non-peripheral vowels in Table 4-15 indicate that single non-peripheral vowels are both more variable and closer to the F2' midline than multiple non-peripheral vowels in one vertical series. This difference in relative position was significant for the entire dataset ($t(117) = 2.786$, $p<0.007$, unpaired, two tailed, unequal variance assumed), but did not reach significance in either dataset (European and non-European) on its own (European: $t(26) = 1.598$, $p>0.12$, unpaired, two tailed, unequal variance assumed; non-European: $t(111) = 1.589$, $p>0.11$, unpaired, two tailed, equal variance assumed).

In Section 4.5.1 it was shown that a single non-peripheral vowel occupies a distinct height level and relies on both F1 and F2' for contrast with peripheral vowels, whereas multiple non-peripheal vowels in a vertical series rely mostly on F2’ for this contrast. If a vertical series of multiple non-peripheral vowels is indeed significantly fronter than a single non-peripheral vowel, then F2’ even spacing is sacrificed for stronger focalization precisely when F2’ distance (and presumably even spacing) is needed the most. While this may appear contradictory to Dispersion Theory, it is consistent with the view that the perceptual role of focalization is to enhance formant percepts, and more particularly, that F2-F3 focalization enhances the percept of F2’. Schwartz et al. (1997b:259) conjecture that focalization “could result in an increased ‘perceptual value’ because of acoustic salience”. Interestingly, while Schwartz et al. (1997b) translate acoustic salience into assigning a higher weight to F1 than to F2’ in the between-vowel distance metric, they do not formalize focalization in the same manner (weight increments), but as a separate component independent from dispersion in the inventory energy score. An alternative formalization proposed in Becker-Kristal (2007) translates focalization into increments of formant weights, which affect dispersion directly by enhancing between-vowel distances. This approach is more consistent in its treatment of acoustic salience, regardless of whether salience is an inherent property (of F1) or due to focalization. It is also more consistent with the observation that non-peripheral vowels are fronter, hence more focalized (with higher weight of F2’), when F2’ distances are more crucial, i.e. when there are multiple non-peripheral vowels.[33]

[33] According to the ‘focalization within dispersion’ approach, focalization (weight increment) of non-peripheral vowels compensates for the shortening of the acoustic distance between them and front unrounded vowels (which are also focal), while it enhances the distance of non-peripheral vowels from back rounded vowels (which are non-focal, especially if the perceptual scale is the logarithmic Hz or ERB scales, which render F1-F2 distances in back-rounded vowels too large for effective focalization).

4.7 Summary

4.7.1 Summary of the analyses

Sections 4.2-4.6 used the corpus data to examine various aspects of the relationship between structural (phonological) and acoustic-perceptual (phonetic) properties of vowel inventories in the context of Dispersion Theory and its predictions. With very few exceptions, the predictions of Dispersion Theory were validated, and many subtle dispersion-based effects turned out to be statistically significant in this large corpus. In Section 4.2, entire inventory formant spans and area sizes were found to be positively correlated with the number of vowels in the inventory, with the number of peripheral vowels affecting the F1 dimension more, and the number of non-peripheral vowels affecting the F2 dimension. Sections 4.3 and 4.4 showed that, within the dispersion-affected acoustic area covered by the inventory, dispersion is manifested in subtle shifts of peripheral vowels (front, low and back) in response to structural differences. When a vowel is added along the inventory periphery, it pushes vowels above and below it up and down (Section 4.4.1), the low vowel gets pushed to the other side (Section 4.3.2), where vowels are pushed further up (Section 4.4.1). During this chain process of pushing and transferring pressure, some pressure is absorbed and the magnitude of shifts becomes smaller and smaller, and typically fades out before reaching the high point vowel on the other side. As a result, the high vowel closer to the added vowel is raised but the high vowel on the other side is not (Section 4.3.3). The addition of non-peripheral vowels pushes peripheral mid vowels sideways towards more cardinal qualities (Section 4.4.2). This effect is more pronounced when the non-peripheral vowels are forced into the same height levels as peripheral vowels, and yet even more as the non-peripheral region itself gets horizontally crowded. Single non-peripheral vowels settle at distinct height levels in order to use F1 as part of their contrast with peripheral vowels, but as soon as another non-peripheral vowel is added, one of the two vowels becomes level with the high vowels while the other is pushed down. Upon the addition of more non-peripheral vowels to form a longer vertical series, the series seems to extend further up and down, in a manner similar to the front and back series (Section 4.5.1). The different height levels tend to be evenly spaced along the logarithmic Hz scale (Section 4.6.1). The horizontal behavior of non-peripheral vowels does not necessarily follow Dispersion Theory, as they are not repelled away from a more crowded peripheral region (Section 4.5.2) and tend to be more advanced than the midline between front and back on perceptual scales (Section 4.6.2). However, the latter finding is consistent with the Dispersion-Focalization Theory, which favors advanced non-peripheral vowels owing to their focal quality due to proximity of F2 and F3, and Section 4.6.2 shows that the distribution of non-peripheral vowels is skewed towards focal vowels precisely where focalization is strongest. Across all analyses, inventories with robust ATR harmony often violate the principles of dispersion, in formant spans, in even vowel spacing and in phonetic adjustments in response to structural changes. These deviations are understandable if such inventories are not treated as one large system but as two parallel smaller subsystems.

4.7.2 Dispersion Theory and structural typology

Taken together, the analyses suggest that dispersion plays a central role in the phonetic realization of vowel inventories. The typical realizations of vowel categories are adaptive, rather than fixed, and follow dispersion principles. For example, while the low vowel may share similar phonological functions across different languages (e.g. attract stress) and as such forms a coherent cross-linguistic category, the cross-linguistic phonetic realization of this vowel category would seem to vary in a manner regulated by dispersion: higher in smaller inventories, more advanced in right-crowded inventories and so on.

These dispersion-oriented realizations are subtle and would often escape the attention of the descriptive linguist interested only in the contrastive phonemic role of vowels and their behavior in the phonological system. This is why typological sources that use impressionistic, contrast-based inventory descriptions fail to capture the adaptive nature of cross-linguistic categories. For example, even though UPSID (Maddieson 1984) employs a relatively fine grid of vowel transcription symbols for low vowels [a̟ a ɐ ɑ], the symbols other than [a] are rarely used, and consequently the typological tendency of 3S and 4L inventories to have respectively [ɐ] and [ɑ] rather than [a] remains unnoticed. Similarly, the failure of descriptive sources to transcribe the single non-peripheral vowel in 5S1 inventories as occupying a distinct height level between high and mid, results in an artificial split in UPSID between inventories with [ɨ] and inventories with [ə]. Such limitations are marginal as far as the goals of UPSID are concerned, i.e. the discovery of the most general structural patterns of sound inventories. However, they become acute once UPSID or other typological sources are used as reference for phonetic theory, be it when artificially consistent transcriptions of point vowels are interpreted as indicative of acoustic stability by Quantal Theory (Stevens 1972), or when the role of dispersion is marginalized to explain only local gaps in inventories (Boersma 1998), or when the successful prediction of 5S1 inventory with [ɨ] is taken to be criterial (Liljencrants & Lindblom 1972, Schwartz et al. 1997b), when [ɘ] should have been predicted instead.

The robustness of dispersion and its manifestation in the adaptive behavior of vowels, and the fact that the most universally common inventory structures (e.g. 3S0, 5S0, 5S1, 7S0) usually follow its principles, corroborate the hypothesis that dispersion plays a major role also at the structural, phonological level. Dispersion not only determines how a given structure is phonetically realized, but also which structures are better to begin with. For example, both 7S2 (e.g. /i e ɛ a ɔ o u y ø/) and 5S4 (e.g. /i e a o u y ø ɯ ɤ/) structures may manifest various dispersion principles in their acoustic realization, like expansion of the F2 span relative to 7S0 and 5S0 respectively. However, the fact that 7S2 is a common structure, while 5S4 is extremely rare, suggests that 7S2 is better than 5S4 regardless of the phonetic realizations of its constituent vowels. The preference of 7S2 over 5S4 cannot be due to feature-based organization, because 5S4 is more elegantly organized, with its eight non-low vowels exhaustively exploiting all the 2x2x2 combinations of [±high ±back ±round], while 7S2 has a gap in its non-peripheral series (two vowels instead of three). Articulatory constraints cannot explain the preference of 7S2 either. However, the overcrowded interior region in 5S4 probably renders acoustic and perceptual distances between vowels too short to distinguish all vowels reliably, regardless of how the vowels are realized. Dispersion thus disprefers 5S4 as a matter of principle, even though it may still determine its realization if it does occur.

4.7.3 Towards a better formal model of Dispersion Theory

The role of dispersion at the phonological level, and the preference for certain structures over others, is precisely what formal dispersion models try to explain.

Unfortunately, the acoustic geometries established as part of the current work suggest that the predictions of such models have so far been inadequate.

The primary limitation of these models is that the balance between maximization of dispersion and minimization of articulatory effort was typically ignored altogether (Liljencrants & Lindblom 1972, Lindblom 1986, Schwartz et al. 1997b among others), and when implemented, it proved very difficult to control (ten Bosch 1991b). The ultimate model would have to find a way to balance these two factors, and it is hoped that, now that the targets are well defined (the acoustic geometries in Appendix B) finding the proper balance would be easier.

Another limitation is that the formalization of dispersion based on all between-vowel pairs in the inventory (the 'aggregate approach') leads to the arrangement of vowels along the edges of the acoustic space, including its 'ceiling', i.e. the high vowel region. This approach is responsible not only for predicting a maximally high single non-peripheral vowel, which is a minor structural inadequacy, but also for the more severe inadequacy of predicting the second non-peripheral vowel as maximally high as well (Liljencrants & Lindblom 1972, Lindblom 1986, Schwartz et al. 1997b), creating a four-way horizontal contrast among the high vowels, a structure rarely attested in real inventories with only two non-peripheral vowels. In this regard, it is worth noting that Becker-Kristal's (2007) preliminary report of a revised Dispersion-Focalization model based on the 'bottleneck approach' (the only such model for which explicit predictions were reported), consistently predicts a mid vowel as the second non-peripheral vowel in inventories (although a single non-peripheral vowel is still always maximally high).

The use of perceptual scales like Mel and Bark, which, though motivated by empirically demonstrated properties of the auditory system, fail to capture even between-vowel spacing, is yet another limitation of previous models. In this regard it is worth noticing that Schwartz et al. (1997b), while commenting about the limitations of their Bark-scaled model, conjectured that the ERB scale, which magnifies the contribution of F1 relative to F2 much more than the Bark scale, should have been used instead. Although they were concerned only with the contribution of the vertical dimension relative to the horizontal dimension, the more logarithmic-like ERB scale may have yielded more adequate predictions also within the vertical dimension itself, compared to the Bark scale, whose behavior is near-linear along most of the F1 frequency range. Along the same line, Roark (2001) argued that the logarithmic Hz scale enhances the contribution of the vertical dimension most effectively, and the current analysis suggests that this scale captures even between-vowel spacing best.

One other factor, which has not been discussed in this study, is the complementary role of symmetry, or the organization of non-low vowels in equally populated series. The idea that inventory structure manifests both dispersion and symmetry has been raised in the past (Crothers 1978, Ferrari-Disner 1984, Boersma 1998). While careful examination of structural typology suggests that the role of symmetry has been overestimated (Schwartz et al. 1997a), which is also suggested by the many asymmetrical structures and/or geometries in the current corpus, symmetry is too frequent to result from chance. For example, in both UPSID and the current corpus, about 80% of seven-vowel inventories belong to either the 7S0 structure, whose non-low vowels are arranged in two columns of three vowels, or the 5S2a structure, whose non-low vowels form three columns of two vowels (or two rows of three vowels). The high frequency of both structures is somewhat surprising, given that the dominance of fully peripheral structures seems to be limited to inventories with five vowels or less, and the dominance of structures with two non-peripheral vowels is characteristic of nine-vowel inventories (see Crothers 1978, Schwartz et al. 1997a and the current corpus). Moreover, considering that six-vowel inventories have zero or one non-peripheral vowel (0.7 on average), while most eight-vowel inventories tend to have one or two (1.4 on average), it seems that, for seven-vowel inventories, one non-peripheral vowel would have been the optimal balance. Yet 6L1 and 6R1 inventories, though not extremely rare, account together only for 20% of seven vowel inventories – a 'typological notch' rather than a 'typological peak'.

The reason seems to be that, from a purely organizational point of view, the structures 6L1 and 6R1 are an asymmetrical disaster: unlike the elegant 3x2 (or 2x3) organization of the non-low vowels in 7S0 and 5S2a, these structures require three series of three different lengths (3, 2 and 1) both horizontally and vertically. It is likely that the optimal dispersion solution is in 6L1 (and/or 6R1) inventories, which is why they nevertheless form a non-negligible minority, but at the same time dispersion is often sacrificed slightly in favor of a geometry that naturally lends itself to elegant symmetrical arrangement.

Along the same line, it is very likely that the typological dominance of the structure 5S0, which, according to both Crothers (1978) and UPSID, accounts for 90% of all five-vowel inventories and 30% of vowel inventories of all sizes, should be attributed to this structure simultaneously constituting a dispersion optimum and organization optimum. Nevertheless, the odd occurrence of 4L1 structures in unrelated languages, with remarkably similar acoustic geometries, suggests that the five-vowel dispersion optimum is somewhere between the two structures, and that 5S0 is overwhelmingly preferred again because of the amorphic organization in the case of the 4L1 alternative. This is further corroborated by the six-vowel inventory typology, where 5S1 seems to be the ‘first among equals’, slightly more common than 6L0 and 6R0.

In summary, the inventory structure for any given number of vowels seems to be the result of four factors. The two major factors are maximization of dispersion and minimization of articulatory effort, with focalization and symmetry playing a minor role. Following is a sketch of how these factors could be combined into one model. This sketch is highly speculative, and might be unfeasible altogether. It nevertheless combines the insights gained from the current work.

Maximization of dispersion should be formalized based on the least dispersed vowel pair in the inventory (the ‘bottleneck approach’), using the logarithmic Hz scale or the sufficiently similar ERB scale, in order to predict evenly spaced inventories. Some weighting of perceptual dimensions (most likely F1 vs. F2’) is necessary in order to achieve the desired balance between peripheral and non-peripheral vowels. The general geometrical shapes of 4L0 (four vowels), 6L1 (seven vowels) and 7S2 (nine vowels) seem like the most appropriate targets for modeling, and if this proves feasible, it is likely that shapes between 6L0 and 5S1 (six vowels) and between 7S1 and 6L2 (eight vowels) would be accurately predicted by the same model. Minimization of effort should adjust these shapes so they would cover the appropriate space size. Focalization is necessary in order to accurately predict non-peripheral vowels more advanced than the front-back midline, owing to F2-F3 proximity (in particular in high non-peripheral vowels). Finally, a symmetry component should be able to often convert the seven-vowel structure 6L1 into either 5S2 or 7S0. With such abilities, this component should easily be able to convert an inaccurate five-vowel structure between 5S0 and 4L1 (e.g. 5S0 with an excessively front /u/) into the universally dominant 5S0.

4.7.4 Future research

The corpus and its analyses described here demonstrate the importance of accumulating masses of comparable cross-linguistic numerical data for the purpose of testing phonetic theories, identifying their merits and limitations, and refining them. Many predictions of Dispersion Theory are manifested in patterns too subtle to be found in comparisons between individual languages, and it is only through the analyses of data from hundreds of languages that these patterns emerge as consistent. As such, probably the most important aspect of future research is to further expand this corpus. Too many inventory structures with intermediate cross-linguistic frequency are currently represented by fewer than ten entries – enough for giving a sense of the prototypical acoustic geometry and validating general dispersion-related trends, but too few to ensure uniformity necessary for quantitative modeling, in particular in the case of structures like 4L0 and 6L1, which might be the key for an accurate model of dispersion. This is also true in reference to structures where it is known, based on other typological sources or on very large standard deviations of formant frequencies of some vowel categories, that they should be split, as in the case of 6L0, where the lower front vowel can be either lower-mid or low. Moreover, some sufficiently frequent structures, like 6L3 or 4R0, have too few representative inventories in the survey to allow any generalization at all. Of course, it is important that, as the survey is expanded, the strong bias towards European languages be reduced. This should happen naturally as formant analysis becomes more and more commonplace as part of descriptions and elementary analyses of languages spoken in developing countries.

Another direction of research is to repeat some of the less conclusive analyses once the corpus is expanded, and also to extend the analyses to involve additional variables, like the effects of vowel quantity. It is quite plausible that acoustic geometries would have distinct variants as a function of short vs. long vowels. A related question is whether space-size reduction in short vowels is uniform, or whether there are spatial regions that are affected more than others.

The current study has important implications on computer simulations intended to evaluate dispersion models. First, the contiguous F1xF2xF3 range of the normalized vowels in the corpus forms a more representative search space for possible vowels than in previous simulations. Second, the distribution of the vowels in the space provides reliable criteria for labeling vowels in a simulation as front, low, back or non-peripheral (Section 3.6.1). This would allow the simulation to objectively determine the structural configuration of predicted inventories even if the search space used in the simulation is continuous, a problem avoided in some simulation studies by representing the search space by a finite set of vowel prototypes. Third, the acoustic typologies in Appendix B can be implemented as reference for automatic evaluation of model prediction. Fourth, once a better simulation is constructed and used to evaluate existing dispersion models, these models themselves may be improved, by adjusting their existing parameters to better approximate the predictions of inventories resembling the acoustic geometries in Appendix B, and perhaps also by principles outlined in Section 4.7.3.

Another important direction of research, which emerges from the current study, is the need for more empirical data on perceptual representations of vowels, and F2' data in particular. The concept of F2' has been central in the development of Dispersion Theory, but it is based on a remarkably small number of empirical studies. Much can be learned about dispersion from the preferred F1xF2' patterns of native speakers in two-formant studies, for example, to what extent is the role of higher formants in F2' of front vowels a function of bottom-up auditory processing or of a top-down search for contrast enhancement from non-peripheral vowels. Ideally, a language-independent paradigm for F2'-matching experiments should be developed and used to obtain F1xF2' data representative of many languages and inventory structures.

Last but not least, the raw survey data, even in their current form, allow the development of more accurate normalization algorithms than the crude procedures devised here. Improvements may come from methods for correcting unlikely universal centroid approximation indices (UCAs) in oddly shaped inventories and/or sensitivity to the behavior of vowels in specific acoustic regions in the elicitation method normalization. Utilizing the partly available F3 data (and perhaps even the limited amount of F4 data) may also contribute to the entire normalization procedure and reduce within-geometry acoustic variance further, rendering analyses and modeling significantly more reliable and informative.

APPENDIX A

Following are the identification details of the 555 entries in the survey, grouped according to language and ordered according to structure. For each entry, the following details are specified: serial number within the language-specific entry group (SN), dialect (if known), source, inventory quantity constituent (QC: U = uniform, S = short, L = long, O = overlong, M = mixed, C = combined), structural configuration (Str) and elicitation method (EM). The full bibliographical details of the sources are on the reference list.

Code	Language	SN	Dialect	Source	QC	Str	EM
aeb	Tunisian Arabic	1	Kairouan	Badeddrime (1980)	L	3S0	W
		2	Tunis	Metoui (1989)	L	4L0	W
		3	Tunis	Metoui (1989)	S	4L0	W
afn	Defaka	1		Shyrock et al. (1995)	C	7S0	W
afr	Afrikaans	1		Taylor & Uys (1988)	S	5S3	W
		2		Botha (1996)	M	6L3b	I
aii	Assyrian Neo-Aramaic	1	Koine	Odisho (1988)	C	5S1	C
ajp	Palestinian Arabic	1	Jordan	Altamimi et al. (2004)	S	3S0	I
		2	Jordan	Altamimi et al. (2004)	S	3S0	W
		3	Jordan	Altamimi et al. (2004)	L	5S0	I
		4	Jordan	Altamimi et al. (2004)	L	5S0	W
		5	Ramallah	Shahin (2000)	L	5S0	W
aka	Akan	1	Kwawu	Hess (1987)	U	9S0	C
ale	Aleut	1		Cho et al. (1997)	L	3S0	W
		2		Cho et al. (1997)	S	3S0	W
aln	Gheg Albanian	1		Halimi (1980)	L	5S1	W
		2		Halimi (1980)	S	5S1	W
amh	Amharic	1	Standard	Messele (2007)	U	5S2a	W
ami	Amis	1		Maddieson & Wright (1995)	U	3S0	W
amu	Amuzgo	1	Guerrero	Herrera Zendejas (2009)	U	7S0	W
apw	Apache	1	Western	Potter et al. (2000)	L	4L0	W
		2	Western	Potter et al. (2000)	S	4L0	W
arg	Aragonese	1	Chistabino	Mott (2007)	U	5S0	W
ary	Moroccan Arabic	1		Altamimi et al. (2004)	L	3S0	I
		2		Altamimi et al. (2004)	L	3S0	W
arz	Egyptian Arabic	1	Cairo	Norlin (1984, 1987)	S	3S0	C
		2		Elgendy (1982)	S	3S0	I
		3	Cairo	Norlin (1984, 1987)	L	5S0	C
		4		Elgendy (1982)	L	5S0	I
bar	Bavarian	1		Traunmüller (1982)	L	9S4	C
bbc	Toba Batak	1		Podesva (1999)	U	5S0	C
bcr	Babine	1	Witsuwit'en	Hargus (2007)	U	6L1	W
bdu	Oroko	1	Mbonge	Anderson-Starwalt (2008 and p.c.)	U	7S0	W
ben	Bengali	1	Calcutta	Basu-Ghosh (1986), Barman (1986)	U	7S0	W
		2	Bangladesh	Alam et al. (2008)	U	7S0	C
bjv	Bedjond	1	Beda	Djarangar (1991)	L	6R0	C
		2	Bediondo	Djarangar (1991, 1992)	L	6R0	C

Code	Language	SN	Dialect	Source	QC	Str	EM
bnh	Banawa	1		Ladefoged et al. (1997)	U	4L0	W
boa	Bora	1		Parker (2001)	L	4L2b	I
		2		Parker (2001)	L	4L2b	W
bov	Tuwuli	1		Anderson-Starwalt (2008 and p.c.)	U	7S0	W
bre	Breton	1	Argol	Bothorel (1982)	U	7S2	M
bru	Brou	1	Eastern	Miller (1967)	L	8R2	C
		2	Eastern	Miller (1967)	S	8R2	C
brx	Bodo	1		Talukdar et al. (2004)	U	5S1	I
bul	Bulgarian	1		Tilkov (1970)	U	5S1	W
		2	Standard	Lehiste & Popov (1970)	U	5S1	M
bvi	Viri	1		Hombert & Point (1987)	U	6R0	I
bvr	Burarra	1		Trefry (1983)	U	5S0	W
bvx	Dibole	1	Dzeke	Anderson-Starwalt (2008 and p.c.)	U	7S0	W
cat	Catalan	1	Sitgeta	Recasens & Espinosa (2009)	U	5S0	M
		2	Rossellones	Recasens & Espinosa (2009)	U	5S0	M
		3	Gironi	Recasens & Espinosa (2009)	U	6L0	M
		4	Felanitxer	Recasens & Espinosa (2009)	U	6R1	M
		5	Eastern	Recasens i Vives (1986)	U	7S0	I
		6	Eastern	Recasens i Vives (1986)	U	7S0	C
		7	Valencian	Recasens & Espinosa (2006)	U	7S0	M
		8	Western	Recasens & Espinosa (2006)	U	7S0	M
		9	Eastern	Recasens & Espinosa (2006)	U	7S0	M
		10	Majorcan	Recasens & Espinosa (2006)	U	7S1	M
chf	Chontal	1	Oaxaca	Maddieson et al. (2009)	U	5S0	W
chr	Cherokee	1	Western	Poell (2004)	L	4L2a	W
		2	Western	Poell (2004)	S	4L2a	W
chv	Chuvash	1	Northern	Kotlejev (1980)	U	6L3b	W
cic	Chickasaw	1		Gordon et al. (1997)	L	3S0	W
		2		Gordon et al. (1997)	S	3S0	W
cmn	Mandarin	1	Taiwan	Chang (1998)	U	3S2	W
		2	Standard	Lu (1982)	U	3S2	I
		3	Standard	Svantesson (1984)	U	3S2	C
cng	Northern Qiang	1	Hongyan	Evans (2006)	S	3S1	W
cnt	Tepetotutla Chinantec	1		Herrera Zendejas (2009)	U	5S2a	W
cog	Chong	1		Luangthongkum (1991)	L	7S2	W
		2		Luangthongkum (1991)	S	7S2	W
cym	Welsh	1	North Eastern	Mayr & Davies (2009 and p.c.)	L	5S1	W
		2	North Eastern	Mayr & Davies (2009 and p.c.)	S	5S2a	W
		3		Oftedal (1969)	L	5S2a	I
		4		Oftedal (1969)	S	5S2a	I
dan	Danish	1	Standard	Frøkjær-Jensen (1966)	L	7S3a	W
		2	Standard	Fischer-Jorgensen (1972)	L	7S3a	W
		3	Standard	Fischer-Jorgensen (1972)	S	7S3a	W
		4	Standard	Fischer-Jorgensen (1972)	L	7S3a	I
ddo	Tsez	1	Asax	Maddieson et al. (1996)	U	5S0	W
deg	Degema	1		Fulop et al. (1998)	U	9S1	W
deu	German	1	Standard Northern	Sendlmeier & Seebode (2006)	S	5S2a	W
		2	Standard Central	Iivonen (1987a, 1989)	S	5S2a	W
		3	Standard Swiss	Iivonen (1983)	S	5S2a	W
		4	Vienna	Iivonen (1987b)	S	5S2a	W
		5	Standard Northern	Jorgensen (1969)	S	5S2a	W
		6	Standard Northern	Patzold & Simpson (1997)	L	5S2a	M
		7	Standard Northern	Patzold & Simpson (1997)	S	5S2a	M
		8	Vienna	Moosmüller (2007)	L	5S2a	C
		9	Vienna	Moosmüller (2007)	S	5S2a	C
		10	Vienna	Moosmüller (2007)	L	5S2a	M
		11	Vienna	Moosmüller (2007)	S	5S2a	M
		12	Vienna	Moosmüller (2007)	L	5S2a	R

Code	Language	SN	Dialect	Source	QC	Str	EM
deu	German	13	Vienna	Moosmüller (2007)	S	5S2a	R
		14	Standard	Sendlmeier & Seebode (2006)	L	6L2	W
		15	Standard Central	Iivonen (1987a, 1989)	L	6L2	W
		16	Standard Swiss	Iivonen (1983)	L	6L2	W
		17	Vienna	Iivonen (1987b)	L	6L2	W
		18	Standard Northern	Jorgensen (1969)	L	6L2	W
dgo	Dogri	1		Ghai (1991)	S	3S0	W
		2		Ghai (1991)	L	7S0	W
dib	Southern Dinka	1		Malou (1988)	S	7S0	W
did	Didinga	1		Yigezu (2002)	C	10R0	W
dik	Southwestern Dinka	1	Luanyjang	Remijsen & Gilley (2008 and p.c.)	S	6R0	M
		2	Luanyjang	Remijsen & Gilley (2008 and p.c.)	L	7S0	M
dks	Eastern Dinka	1		Malou (1988)	S	7S0	W
drd	Darma	1		Willis (2007)	U	6L0	W
dru	Rukai	1	Budai	Chen (2006)	U	3S1	W
duf	Ndumbea	1	Naniouni	Gordon & Maddieson (1995)	S	7S0	W
dyo	Diola	1	Kujamutay	Greenberg & Sapir (1978)	C	10L0	W
egl	Emilian	1		Uguzzoni & Busa (1995)	L	7S2	W
		2	Frignano	Uguzzoni (1988)	L	7S2	W
ekk	Estonian	1	E. Saaremaa	Niit (2005)	L	6L1	W
		2	W. Saaremaa	Niit (2005)	L	6L1	W
		3	E. Saaremaa	Niit (2005)	S	6L2	W
		4	W. Saaremaa	Niit (2005)	S	6R2a	W
		5	Muhu Old	Niit (2007)	L	6L3b	I
		6	Muhu Old	Niit (2007)	S	6L3b	I
		7	Standard	Liiv & Remmel (1970)	C	6R3	W
		8	Standard	Eek & Meister (1994)	C	6R3	W
		9	Muhu New	Niit (2007)	L	6R3	W
		10	Muhu New	Niit (2007)	S	6R3	W
		11	Standard	Eek & Meister (1998)	L	6R3	M
		12	Standard	Eek & Meister (1998)	S	6R3	M
ell	Greek	1		Jongman et al. (1989)	U	5S0	C
		2		Fourakis et al. (1998)	U	5S0	C
		3		Fourakis et al. (1998)	U	5S0	M
		4	Thesaloniki	Samaras (1974)	U	5S0	W
		5	Athens	Tseva (1989)	U	5S0	W
		6	Standard	Sfakianaki (2002)	U	5S0	W
		7	Standard	Nicolaidis (2003)	U	5S0	R
		8	Sfakian	Trudgill (2009 and p.c.)	U	5S0	R
eng	English	1	New Zealand>Southern	Watson et al. (1998)	L	3S2	W
		2	Australian>General	Watson et al. (1998)	L	3S2	W
		3	British>RP Old	Hawkins & Midgley (2005)	L	3S2	W
		4	British >RP New	Hawkins & Midgley (2005)	L	3S2	W
		5	British >RP	Deterding (1997)	L	3S2	W
		6	New Zealand >Wellington	Easton & Bauer (2000)	L	3S2	R
		7	British >RP	Deterding (1990)	L	3S2	W
		8	British >RP	Holtse (1972)	L	3S2	W
		9	American >N. Midwestern	Hillenbrand et al. (1995)	S	4L0	W
		10	American >General	Nishi at al. (2008)	S	4L0	W
		11	American >General	Nishi at al. (2008)	S	4L0	C
		12	British >RP Old	Wells (1963)	L	4R1	C
		13	Australian >Sydney	Cox (1999)	L	4L2a	W
		14	New Zealand Southern	Watson et al. (1998)	S	5S1	W
		15	New Zealand >Wellington	Easton & Bauer (2000)	S	5S1	W
		16	Australian >General	Watson et al. (1998)	S	6L0	W
		17	Australian >Sydney	Cox (1999)	S	6L0	W
		18	British >RP Old	Hawkins & Midgley (2005)	S	6R0	W
		19	British >RP New	Hawkins & Midgley (2005)	S	6R0	W
		20	British >RP Old	Wells (1963)	S	6R0	W
		21	British >RP	Deterding (1990)	S	6R0	W

Code	Language	SN	Dialect	Source	QC	Str	EM
eng	English	22	British >RP	Deterding (1997)	S	6R0	W
		23	British >RP	Holtse (1972)	S	6R0	R
		24	American >North Midwestern	Hillenbrand et al. (1995)	L	7S0	W
		25	American >General	Nishi at al. (2008)	L	7S0	W
		26	American >General	Nishi at al. (2008)	L	7S0	C
		27	Australian >General	Burgess (1968)	M	8L0	C
		28	Australian >Broad	Burgess (1968)	M	8L0	C
		29	American >New England	Bradlow (1995)	M	8L1	W
		30	American >General Old	Peterson & Barney (1952)	M	8L1	W
		31	British >Somerset	Nevalainen & Aulanko (1996)	M	9R1	W
		32	Canadian>Winnipeg	Hagiwara (2006)	M	9S1	R
		33	American >South Californian	Hagiwara (1994)	M	9S1	C
		34	American>Southwestern	Yang (1996)	M	10L1	C
eto	Eton	1		van de Velde (2008)	C	7S1	R
eus	Basque	1		Salaburu Etxeberria (1984)	U	5S0	W
		2	Bilbao	Iribar & Turrez (2001)	U	5S0	W
		3	Bilbao	Iribar & Turrez (2001)	U	5S0	R
		4	Viscaino	Urrutia et al. (1995)	U	5S0	M
		5	Guipuzcoano	Urrutia et al. (1995)	U	5S0	M
		6	Alto Navarro Septentrional	Urrutia et al. (1995)	U	5S0	M
		7	Bajo Navarro Occidental	Urrutia et al. (1995)	U	5S0	M
		8	Bajo Navarro Oriental	Urrutia et al. (1995)	U	5S0	M
		9	Labortano	Urrutia et al. (1995)	U	5S0	M
		10	Suletino	Urrutia et al. (1995)	U	5S1	M
evn	Solon	1	Yaohe	Svantesson (1985)	L	8L2	W
fin	Finnish	1	Standard	Wiik (1965)	L	6L2	W
		2	Standard	Wiik (1965)	S	6L2	W
		3	Tampere	Kuronen (2000)	L	6L2	M
		4	Tampere	Kuronen (2000)	S	6L2	M
		5	Standard	Savela (1999)	?	6L2	M
		6	Helsinki	Iivonen & Harnud (2005)	L	6L2	W
		7	Helsinki	Iivonen & Harnud (2005)	S	6R2a	W
fla	Montana Salish	1		Flemming et al. (1994)	U	5S0	W
fmp	Fe'fe'	1		Hombert (1979)	U	6R2a	W
fod	Foodo	1		Anderson-Starwalt (2008 and p.c.)	U	9S0	C
fra	French	1	Standard New	Kim & Lee (2001)	U	7S3a	I
		2	Standard New	Tubach (1989)	U	7S3a	W
		3	Standard New	Gendrot & Adda-Decker (2005)	U	7S3a	R
		4	Standard Old	Guth (1969)	U	8R3a	I
		5	Standard Old	Debrock & Forrez (1976)	U	8R3a	W
		6	Quebec	Martin (2002)	U	8R3a	W
		7	Quebec>Chic.-Jonq.	Paradis (1985)	U	8R3a	R
frr	North Frisian	1	Fering	Bohn. (2004 and p.c.)	S	5S2a	W
		2	Fering	Bohn. (2004 and p.c.)	L	6L2	W
fry	Frisian	1	West	Ferrari-Disner (1983)	L	7S2	W
ggu	Gban	1	N'da	Le Saout (1976)	U	7S0	M
gla	Scottish Gaelic	1	Bernera	Ladefoged et al.(1998)	L	7S2	W
glg	Galician	1		Gonzalez & Regueira (1994)	U	7S0	C
gug	Paraguayan Guarani	1		Miotti (2008)	U	5S1	W
guj	Gujarati	1		Dave (1968)	U	6L1	W
		2		Dave (1977)	U	6L1	I
guk	Gumuz	1		Pearce (2008)	U	5S1	R
gup	Kunwinjku	1		Fletcher et al. (2007 and p.c.)	U	5S0	C
		2		Fletcher & Butcher (2002)	U	5S0	R
gwj	Gswi	1		Nakagawa (2006)	U	5S0	W
hak	Hakka	1	Meixian	Cheung (2007)	U	5S0	C
hau	Hausa	1	Kano	Lindau-Webb (1985)	S	3S0	C
		2	Kano	Lindau-Webb (1985)	L	5S0	C
hbs	Serbo-Croatian	1	Belgrad	Kostic & Rhea (1969)	C	5S0	W

Code	Language	SN	Dialect	Source	QC	Str	EM
heb	Hebrew	1	Standard	Most et al. (2000)	U	5S0	C
		2	Standard	Aronson et al. (1996)	U	5S0	I
		3	Standard	Maimon (2002)	U	5S0	R
		4	Standard	Schwarzwald (1972)	U	5S0	W
		5	Standard	Becker-Kristal (in preparation)	U	5S0	M
hts	Hadza	1		Sands et al. (1993)	U	5S0	W
hun	Hungarian	1	Standard	Magdics (1963)	L	5S2a	M
		2	Standard	Magdics (1963)	S	5S2a	M
		3	Standard	Tarnoczy (1965)	M	7S2	W
hup	Hupa	1		Gordon (1996)	S	3S0	W
		2		Gordon (1996)	L	3S0	W
iai	Iaai	1		Maddieson & Anderson (1994)	L	7R3	W
ibo	Igbo	1		Ladefoged (1964)	U	8R0	W
ife	Ife	1	Tchetti	Anderson-Starwalt (2008 and p.c.)	U	7S0	W
ind	Indonesian	1		van Zanten (1989)	U	5S1	I
		2		van Zanten (1989)	U	5S1	C
isl	Icelandic	1	Standard	Garnes (1973, 1974)	L	6L2	W
		2	Standard	Garnes (1973, 1974)	S	6L2	W
		3	Standard	Petursson (1975)	L	6L2	W
		4	Standard	Petursson (1975)	S	6L2	W
ita	Italian	1	Tuscany	Trumper et al. (1989)	U	7S0	W
		2	Roma	Calamai & Sorianello (2003)	U	7S0	R
		3	Roma	Calamai & Sorianello (2003)	U	7S0	M
		4	Roma	Calamai & Sorianello (2003)	U	7S0	W
		5	Pisa	Calamai (2002b)	U	7S0	W
		6	Pisa	Calamai (2002b)	U	7S0	R
		7	Florence	Calamai (2002a)	U	7S0	W
		8	Tuscany	Calamai (2001)	U	7S0	W
		9	Tuscany	Calamai (2001)	U	7S0	M
		10	Standard	Esposito & Stevens (1995)	U	7S0	C
		11	Florence	Ferrero (1972)	U	7S0	I
jpn	Japanese	1	Tokyo	Nishi at al. (2008)	L	4L1	W
		2	Tokyo	Nishi at al. (2008)	S	4L1	W
		3	Tokyo	Nishi at al. (2008)	L	4L1	C
		4	Tokyo	Nishi at al. (2008)	S	4L1	C
		5	Standard	de Graaf & Koopmans-van Beinum (1983)	C	4L1	I
		6	Standard	de Graaf & Koopmans-van Beinum (1983)	C	4L1	W
		7	Standard	de Graaf & Koopmans-van Beinum (1983)	C	4L1	R
		8	Standard	Morimoto (1988)	?	4L1	W
		9	Tokyo	Keating & Huffman (1984)	S	4L1	R
		10	Tokyo	Keating & Huffman (1984)	S	4L1	W
		11	Tosu	Inozuka et al. (1993)	S	4L1	W
		12	Karatsu	Inozuka et al. (1993)	S	5S0	W
		13	Saga	Inozuka et al. (1993)	S	5S0	W
kal	Greenlandic	1	Holsteinborg	Wood (1971)	U	3S0	W
		2	Holsteinborg	Wood (1971)	U	3S0	R
kan	Kannada	1	Mysore	Venkatesh (1995)	L	5S0	C
		2	Mysore	Venkatesh (1995)	S	5S0	C
		3	Shimoga	Maheshwaraiah (1986)	C	5S0	W
kat	Georgian	1	Standard	Shosted & Chikovani (2006)	U	5S0	W
kaz	Kazakh	1		Dzhunisbekov (1972)	U	5S4	I
		2		Kenesbaev et al. (1969)	U	5S4	W
kca	Khanty	1	Ob’	Kurkina (2000)	L	3S1	W
		2	Ob’	Kurkina (2000)	S	3S1	W
kdt	Kuy	1		Luangthongkum (1986)	L	8R3a	W
		2		Luangthongkum (1986)	S	8L3a	W
ker	Kera	1		Pearce (2008)	U	5S1	R
khk	Khalkha	1	Bajanhongor	Svantesson (1985)	L	6R2b	W
khk	Khalkha	2	Standard	Svantesson (1985)	L	7R0	W

Code	Language	SN	Dialect	Source	QC	Str	EM
khm	Khmer	1	Battambang	Wayland (1998)	L	6R2a	W
		2	Battambang	Wayland (1998)	S	7S2	W
kiy	Kirikiri	1		Clouse & Clouse (1993)	U	7S0	W
kma	Konni	1		Cahill (2007)	U	9S0	W
koe	Baale	1		Yigezu (2002)	C	9S0	W
kor	Korean	1	Chungnam	Seong (2005)	S	5S2b	C
		2	Pyongyang	Kang (1996)	C	6L0	C
		3	Hamkyong	Kang (1997)	C	6L2	C
		4	Standard New	Kim & Lee (2001)	L	6R1	I
		5	Seoul	Lee (2000)	L	7S1	C
		6	Seoul	Lee (2000)	S	7S1	C
		7	Seoul	Yang (1996)	U	7S3b	W
		8	Standard Old	Han (1975)	U	7S3b	W
kpo	Ikposo	1	Uwi	Anderson-Starwalt (2008 and p.c.)	U	9S1	W
kpv	Komi	1	Zyrian	Savela (1999)	U	5S2a	M
ktn	Karitiana	1		Everett (2008)	C	4L1	C
kwv	Nar	1	Doro	Djarangar (1991,1992)	L	6R0	C
kxm	Northern Khmer	1	Surin	Thomas & Wanna (1988)	L	10R4	W
		2	Surin	Thomas & Wanna (1988)	S	10R4	W
kyr	Kuruaya	1		da Silva (2008)	U	5S1	W
laj	Lango	1		Noonan (1992)	U	9S1	W
lav	Latvian	1	Standard	Grigorjevs (2001)	L	6R0	I
		2	Standard	Grigorjevs (2001)	S	6R0	I
		3	Standard	Kaukeniene (2004)	L	6R0	I
		4	Standard	Kaukeniene (2004)	S	6R0	I
lit	Lithuanian	1	Standard	Kaukeniene (2002)	S	5S0	W
		2	Standard	Kaukeniene (2004)	S	5S0	I
		3		Bacevičiūtė (2004)	S	5S0	I
		4		Bacevičiūtė (2004)	S	5S0	M
		5	Standard	Kaukeniene (2002)	L	6L0	W
		6	Standard	Kaukeniene (2004)	L	6L0	I
		7	Šakiu	Bacevičiūtė (2004)	L	6L0	I
		8	Šakiu	Bacevičiūtė (2004)	L	6L0	M
		9	Standard	Kudirka (2005)	L	6L0	W
liv	Livonian	1	Eastern	Pajupuu & Viisto (1986)	C	6L2	I
lln	Lele	1		Pearce (2008)	U	5S0	R
luo	Dholuo	1		Jacobson (1977)	U	9S0	W
		2		Jacobson (1978)	U	9S0	I
mad	Madurese	1	Standard	Cohn & Lockwood (1994)	U	6R2b	C
mai	Maithili	1		Yadav (1984)	U	7S1	I
		2		Yadav (1984)	U	7S1	W
		3		Jha (2001)	U	7S1	C
maj	Jalapa Mazatec	1	Jalapa de Diaz	Silverman et al. (1994)	U	5S0	W
mas	Maa	1		Guion et al. (2004 and p.c.)	U	9S0	W
mbe	Molalla	1		Pharris (2006)	S	3S0	W
		2		Pharris (2006)	L	4R0	W
mcw	Mawa	1		Pearce (2008)	U	5S1	R
mcx	Mpiemo	1	Nola	Thornell & Nagano-Madsen (2004)	U	7S0	W
mdj	Mangbetu	1		Demolin (1989)	U	9S0	W
mdm	Mayogo	1		McCord (1989)	U	9S1	W
mdw	Mbosi Olee	1		Anderson-Starwalt (2008 and p.c.)	U	7S0	W
mir	Isthmus Mixe	1		Dieterman (2002)	U	5S1	R
mlt	Maltese	1	Gozo	Puech (1987)	S	4L0	I
mnh	Mono	1	Bili	Olson (2001)	U	6R2a	W
mos	Moore	1		Calamai & Bertinetto (2005)	S	8L0	W
moz	Moukoulu	1		Pearce (2008)	U	5S1	R
mpe	Majang	1		Pearce (2008)	C	9S0	R
		2		Yigezu (2002)	C	9S1	W

Code	Language	SN	Dialect	Source	QC	Str	EM
mri	Maori	1	North	Maclagan et al. (2004)	L	4L1	R
		2	North	Maclagan et al. (2004)	S	4L1	R
mse	Musey	1	Djodo	Schirru (2003a)	C	5S0	W
mus	Creek	1	Muskogee	Johnson & Martin (2001)	L	3S0	W
		2	Muskogee	Johnson & Martin (2001)	S	3S0	W
mvf	Inner Mongolian	1	Chakhar	Svantesson (1985)	L	6R2b	W
		1	Chakhar	Iivonen & Harnud (2005)	S	8R2	W
		2	Chakhar	Iivonen & Harnud (2005)	L	8R3b	W
		3	Baarin	Svantesson (1985)	L	8L3b	W
		4	Shiliingol	Svantesson (1985)	L	8L3b	W
mwm	Sar	1	Douyou	Djarangar (1991)	L	6R0	C
mxp	Ayutla Mixe	1		Romero-Mendez (2008)	U	6R1	C
mya	Burmese	1	Standard	Zlatoverkhova (1966)	U	7S0	W
myb	Mbay	1	Moissala	Djarangar (1991,1992)	L	6R0	C
myf	Bambassi	1		Pearce (2008)	U	5S0	R
myu	Munduruku	1		Picanco (2005)	U	4L1	W
nab	Nambikwara	1		Kroeker (1976)	U	5S0	W
nan	Min	1	Nan (Southern)	Zee (1980)	U	5S0	C
nap	Neapolitan	1	Naples	Trumper et al. (1989)	U	7S0	W
		2	N. Calabrian>Rocca Imperiale	Trumper et al. (1989)	U	7S0	W
		3	N. Calabrian>Trebisacce	Trumper et al. (1989)	U	7S0	W
nav	Navajo	1		James (1974)	L	4L0	W
		2		James (1974)	S	4L0	W
naw	Nawuri	1		Casali (2002)	L	9S0	W
nde	Ndebele	1		Manuel (1987)	U	5S0	C
nds	Low German	1	Eastphalian	Goschel (1967)	L	7S0	R
ndv	Ndut	1		Gueye (1986)	S	8L1	M
		2		Gueye (1986)	L	8L1	M
nep	Nepali	1	Eastern	Khatiwada (2009)	U	6R0	I
new	Ngwe	1		Ladefoged (1964)	U	8R5	W
ngk	Dalabon	1		Fletcher & Butcher (2002)	U	5S1	R
nia	Nias	1		Catford (1988)	U	5S1	W
njm	Angami	1		Blankenship et al. (1993)	U	5S1	C
njo	Ao	1	Mongsen	Coupe (2003)	U	3S2	W
nld	Dutch	1	Southern>Limburg	Adank et al. (2007 and p.c.)	L	3S1	C
		2	Southern>Limburg	Verhoeven & van Bael (2002)	L	3S1	C
		3	Southern>East Flanders	Adank et al. (2007 and p.c.)	L	3S2	C
		4	Southern>West Flanders	Adank et al. (2007 and p.c.)	L	3S2	C
		5	Southern>East Flanders	Verhoeven & van Bael (2002)	L	3S2	C
		6	Southern>Brabant	Adank et al. (2004,2007 and p.c.)	S	4L1	C
		7	Southern>Antwerp	Verhoeven & van Bael (2002)	S	4L1	C
		8	Southern>Brabant	Adank et al. (2004,2007 and p.c.)	L	5S2a	C
		9	Southern>Antwerp	Verhoeven & van Bael (2002)	L	5S2a	C
		10	Southern>East Flanders	Adank et al. (2007 and p.c.)	S	6L1	C
		11	Southern>West Flanders	Adank et al. (2007 and p.c.)	S	6L1	C
		12	Southern>East Flanders	Verhoeven & van Bael (2002)	S	6L1	C
		13	Southern>Limburg	Adank et al. (2007 and p.c.)	S	6L2	C
		14	Southern>Limburg	Verhoeven & van Bael (2002)	S	6L2	C
		15	Northern>Randstad	Adank et al. (2004,2007 and p.c.)	M	7S2	C
		16	Northern>South Gelderland	Adank et al. (2007 and p.c.)	M	7S2	C
		17	Northern>Limburg	Adank et al. (2007 and p.c.)	M	7S2	C
		18	Northern>Groningen	Adank et al. (2007 and p.c.)	M	7S2	C
		19	Standard Northern	Pols et al. (1973)	M	9S3	W
		20		de Graaf & Koopmans-van Beinum (1983)	M	9S3	I
		21		de Graaf & Koopmans-van Beinum (1983)	M	9S3	W
		22		de Graaf & Koopmans-van Beinum (1983)	M	9S3	R
nmn	!Xoo	1	Lone Tree	Traill (1985)	U	5S0	W
nnb	Kinande	1		Gick et al. (2006 and p.c.)	U	9S1	W
		2	Yira	Anderson-Starwalt (2008 and p.c.)	U	9S1	W

Code	Language	SN	Dialect	Source	QC	Str	EM
nor	Norwegian	1	Standard	Gamnes (1965), Ferrari-Disner (1983)	L	6R3	W
nun	Anong	1	Mugujia	Thurgood (2007)	U	5S1	W
oci	Occitan	1	Roergue Lengadocian	Müller (in preparation)	U	6L1	C
		2	Vivarolpenc	Müller & Martin Mota (forthcoming and p.c.)	U	6L1	C
ogo	Khana	1		Nagano & Burch (1988)	U	7S0	W
ood	O'odham	1	Pima	Jackson (2008 and p.c.)	L	4R1	R
		2	Pima	Jackson (2008 and p.c.)	S	4R1	R
ori	Oriya	1	Standard	Panda (1986)	U	6R0	I
		2	Standard	Panda (1986)	U	6R0	W
pan	Punjabi	1	Doabi	Singh (2005)	S	3S0	W
		2	Doabi	Singh (2005)	L	7S0	W
pav	Wari'	1		MacEachern et al. (1996)	U	4L2a	W
pbu	Pashto	1	Northern	Invanov (2001)	L	3S0	W
		2	Northern	Invanov (2001)	S	5S1	W
pei	Chichimeca	1		Herrera Zendejas (2009)	U	6L1	W
pes	Persian	1		Salehi et al. (2008)	M	6R0	I
pms	Piedmontese	1	Turin	Schirru (2003b and p.c.)	U	5S0	M
pol	Polish	1	Standard	Strycharczuk & Jurgec (2008 and p.c.)	U	5S1	W
		2	Standard	Krzysko et al. (1999)	U	5S1	W
por	Portuguese	1	Brazilian>Sao Paulo	Escudero et al. (2009)	U	7S0	W
		2	Brazilian>Sao Paulo	Escudero et al. (2009)	U	7S0	C
		3	European>Lisbon	Escudero et al. (2009)	U	7S0	W
		4	European>Lisbon	Escudero et al. (2009)	U	7S0	C
		5	Blumenau Brazilian	Pagel (1986)	U	7S0	W
		6	Brazilian	Godinez (1978)	U	7S0	C
		7	European>Lisbon	Delgado Martins (1973)	U	7S1	W
pri	Paici	1		Gordon & Maddieson (1996)	U	7S3a	W
prk	Wa	1	Kunming	Svantesson (1993)	U	7S2	W
		2	Standard	Watkins (2002)	U	7S2	C
prs	Dari	1		Ivanov (1996	M	8R0	W
pwn	Paiwan	1		Chen (2006)	U	3S1	W
que	Quichua	1	Otavalo	Guion (2003 and p.c.)	U	3S0	C
quz	Quechua	1	Cusco	Parker (2007)	U	5S0	C
roa	Norman	1	Liesville-sur-Douve	Maury (1976)	C	10R4	R
ron	Romanian	1	Stadard	Teodorescu (1985)	U	5S2a	W
		2	Transylvania	Mardarescu-Teodorescu (1992)	U	7S2	W
ruq	Megleno-Romanian	1		Cohut & Mardarescu (1968)	S	7S3a	W
rus	Russian	1		Kuznetsov & Ott (1987)	U	5S1	C
		2		Lobanov (1971)	U	5S1	W
sbz	Kaba	1	Paoua	Djarangar (1991,1992)	L	6R0	C
scn	Sicilian	1	Sallentinian>Lecce	Costagliola (2004)	U	5S0	M
		2	Sallentinian>Parabita	Romano (1999)	U	5S0	W
		3	South Calabrian>Cosenza	Trumper et al. (1989)	U	5S0	W
		4	South Calabrian>Catanzaro	Trumper et al. (1989)	U	5S0	W
sgz	Sursurunga	1		King (2007 and p.c.)	U	5S1	W
shi	Tachelhit	1		Oukarim (1995)	U	3S0	C
shq	Albanian	1	Kosovo Standard	Moosmüller & Granser (2006)	U	5S2a	M
		2	Northern Standard	Moosmüller & Granser (2006)	U	5S2a	M
		3	Central Standard	Moosmüller & Granser (2006)	U	5S2a	M
		4	Northern Standard	Moosmüller & Granser (2006 and p.c.)	U	5S2a	W
		5	Central Standard	Moosmüller & Granser (2006 and p.c.)	U	5S2a	W
		6	Kosovo Standard	Moosmüller & Granser (2006 and p.c.)	U	5S2a	W
		7	Southern Standard	Moosmüller & Granser (2006)	U	6L1	M
		8	Southern Standard	Moosmüller & Granser (2006 and p.c.)	U	6L1	W
skf	Sakurabiat	1		Alves & Galucio (2007)	L	4L1	C
		2		Alves & Galucio (2007)	S	4L1	C
slk	Slovak	1		Isacenko (1968)	L	5S0	W
		2		Romportl (1974)	L	5S0	W

Code	Language	SN	Dialect	Source	QC	Str	EM
slk	Slovak	3		Isacenko (1968)	S	6L0	W
		4		Romportl (1974)	S	6L0	W
slv	Slovenian	1	Standard	Jurgec (2005)	S	5S0	W
		2	Standard	Jurgec (2005)	L	7S1	W
sna	Shona	1	Karanga	Pongweni (1983)	U	5S0	I
		2		Manuel (1987)	U	5S0	C
snw	Sele	1		Maddieson & Gordon (1996)	U	7S0	W
som	Somali	1	Standard	Edmondson et al. (2004)	L	10L0	W
		2	Standard	Edmondson et al. (2004)	S	10L0	W
sot	Sotho	1	Southern	Khabanyane (1991)	U	9S0	C
spa	Spanish	1	Mexican>Tijuana	Godinez (1978)	U	5S0	C
		2	Rioplatense>Buenos Aires	Godinez (1978)	U	5S0	C
		3	Peninsular>Standard	Godinez (1978)	U	5S0	C
		4	Peninsular >Madrid	Bradlow (1995)	U	5S0	C
		5	Peninsular Standard	Morimoto (1988)	U	5S0	W
		6	Eastern Andalusian	Martinez-Melgar (1994)	U	5S0	M
		7	Eastern Andalusian	Sanders (1998)	U	5S0	C
		8	Ecuador>Otavalo	Guion (2003 and p.c.)	U	5S0	C
		9	Peninsular Standard	Alvarez Gonzalez (1981)	U	5S0	C
		10	Canaria	Almeida (1990)	U	5S0	R
		11	Peninsular>Bilbao	Iribar & Turrez (2001)	U	5S0	W
		12	Peninsular>Bilbao	Iribar & Turrez (2001)	U	5S0	R
sro	Sardinian	1	Campadinese	Contini & Boe (1972)	U	7S0	W
ssw	Siswati	1		Kockaert & Godwin (1997)	U	5S0	W
sun	Sundenese	1		Yusuf (1993)	U	5S2a	W
swe	Swedish	1	Standard	Lindblom (1963)	S	5S3	C
		2	Stockholm	Kuronen (2000)	S	5S3	M
		3	Helsinki	Kuronen (2000)	L	5S3	M
		4	Helsinki	Kuronen (2000)	S	5S3	M
		5	Standard	Fant (1959)	S	5S3	I
		6	Standard	Fant (1959), Fant et al. (1969)	L	6L3a	I
		7	Standard	Ferrari-Disner (1983)	L	6L3a	W
		8	Stockholm	Kuronen (2000)	L	6R3	M
tca	Ticuna	1		Soares (1984)	U	6R1	W
tcx	Toda	1		Shalev et al. (1993)	M	6R3	W
tee	Huehuetla Tepehua	1		Smythe Kung (2007)	C	5S0	W
tel	Telugu	1		Dutta Majumder et al. (1978)	L	5S0	W
		2	Rayalaseema	Krishna (2009 and p.c.)	L	5S0	C
		3	Rayalaseema	Krishna (2009 and p.c.)	S	5S0	C
		4	Telengana	Krishna (2009 and p.c.)	L	5S0	C
		5	Telengana	Krishna (2009 and p.c.)	S	5S0	C
		6		Dutta Majumder et al. (1978)	S	6L0	W
		7	Coastal	Krishna (2009 and p.c.)	L	6L0	C
		8	Coastal	Krishna (2009 and p.c.)	S	6L0	C
tgk	Tajik	1	Bukhara	Ido (forthcoming and p.c.)	U	5S1	I
tha	Thai	1	Standard	Abramson (1962)	L	7S2	I
		2	Standard	Abramson (1962)	S	7S2	I
		3	Standard	Kelz & Kummer (1989)	L	7S2	W
		4	Standard	Kelz & Kummer (1989)	S	7S2	W
		5	Standard	Apiluck (1996)	C	7S2	I
tlj	Lubwisi	1		Anderson-Starwalt (2008 and p.c.)	U	9S1	W
top	Totonac	1	Papantla	Herrera Zendejas (2009)	C	3S0	W
		2	Papantla	Alarcon Montero (2008)	C	3S0	W
trv	Truku	1	Hualian	Chiang & Chiang (2005)	U	5S1	W
tsg	Tausug	1	Sulu	Ferrari-Disner (1983)	L	3S0	M
tsn	Setswana	1	Sengwato	Tlale (2005)	U	7S0	C
		2		le Roux (2004)	U	7S0	W
tsu	Tsou	1	Tfuea	Wright & Ladefoged (1994)	U	5S1	W

Code	Language	SN	Dialect	Source	QC	Str	EM
tur	Turkish	1	Istanbul	Fukumori (1999)	U	5S3	C
		2	Istanbul	Fukumori (1998)	U	5S3	R
		3	Istanbul	Türk et al. (2004)	U	5S3	I
twi	Twi	1		Adu Manyah (2003 and p.c.)	L	9S0	C
		2		Adu Manyah (2003 and p.c.)	S	9S0	C
udm	Udmurt	1	Izhevsk	Iivonen & Harnud (2005)	U	5S2a	W
uig	Uyghur	1		Tungchun (1992)	U	6L2	W
ukr	Ukrainian	1	Standard	Ishchenko (2008)	U	6L0	W
urd	Urdu	1		Hussain (1997)	S	3S0	C
		2		Nakhat & Rabea (2003)	S	4L0	W
		3		Hussain (1997)	L	7S0	C
		4		Nakhat & Rabea (2003)	L	7S0	W
vec	Venetian	1	Padua	Trumper et al. (1989)	U	7S0	W
vie	Vietnamese	1	Hanoi	Nguyen & Srihari (2004)	M	8R3a	W
		2	Hanoi	Kirby (in prep. And p.c.)	M	8R3a	W
		3	Hanoi	Han (1966)	M	8R3a	W
vro	Voru	1	Vastseliina	Parve (2000)	S	6L4	R
		2	Navi	Teras (2000)	L	6R3	R
		3	Navi	Teras (2000)	O	8L3b	R
		4	Navi	Teras (2000)	C	8R6	I
wol	Wolof	1	Baol	Calvet (1966)	S	6L1	R
		2	Baol	Calvet (1966)	L	7S0	R
wuu	Wu	1	Shanghai	Chen (2008)	S	3S1	C
		2	Shanghai	Chen (2008)	L	6R3	C
		3	Ningbo	Hu (2005)	U	7S2	C
		4	Ningbo	Hu (2005)	U	7S3a	C
		5	Shanghai	Svantesson (1989)	U	7S3b	C
xal	Oriat	1	Kalmyk	Svantesson (1995)	L	6L2	W
xkz	Kurtoep	1	Educated	Hyslop Lowes (2006 and p.c.)	U	5S2a	W
yas	Gunu	1		Quilis et al. (1990)	L	7S0	W
		2		Quilis et al. (1990)	S	7S0	W
yid	Yiddish	1		Kleine (2008)	U	5S0	R
yor	Yoruba	1		Ferrari-Disner (1983)	U	7S0	I
		2	Standard	Przezdzietski (2005)	U	7S0	C
		3	Moba	Przezdzietski (2005)	U	7S0	C
		4	Akure	Przezdzietski (2005)	U	9S0	C
		5	Ekiti	Anderson-Starwalt (2008 and p.c.)	U	9S0	W
yue	Cantonese	1	Hong Kong	Zee (1983)	S	3S1	C
		2	Guangzhou	Lee (1983)	S	3S1	W
		3	Hong Kong	Lee (1983)	S	3S1	W
		4	Hong Kong	So & Wang (1996)	S	3S1	C
		5	Hong Kong	Zee (1983)	L	5S2a	C
		6	Guangzhou	Lee (1983)	L	5S2a	W
		7	Hong Kong	Lee (1983)	L	5S2a	W
		8	Hong Kong	So & Wang (1996)	L	5S2a	C
zai	Juchitan Zapotec	1		Herrera (2000)	U	5S0	W
???	Akuntsu	1		Aragon & de Carvalho (2007)	U	4L1	R

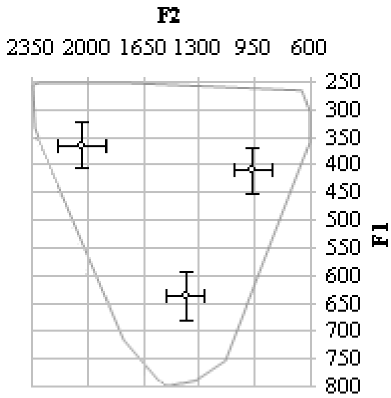
APPENDIX B

Below are the acoustic geometries for the 17 structural configurations that appear in five or more languages in the corpus. For each configuration, its component vowel categories are listed, with averages and standard deviations of their normalized formant frequencies, including F3 and F2’ estimates. For each category, narrow IPA transcription is proposed, based on the average formant frequencies of the category and the proposed F1 and F2 frequencies of IPA transcription symbols in Figure 3-7 in Section 3.6.1. Vowel data are followed by F1 and F2 spans and of the F1xF2 area (in 10000Hz² units) of the polygon whose angles are all the peripheral vowels. Also listed are all the languages (each followed by its unique ISO 639-3 three-letter code) where the particular structure appears. In case the language appears under other structures, its three-letter code is followed by the serial numbers (from Appendix A) of the entries listed with the current structure. The formant charts display average F1xF2 qualities with one standard deviation ranges. Structures appearing in less than five languages in the survey are listed at the end.

3S0:

IPA	F1	F2	F3	F2’
ɪ	365 (±42)	2034 (±156)	2727 (±101)	2363 (±264)
ɐ̝	637 (±42)	1385 (±123)	2463 (±18)	1405 (±147)
ʊ̞	410 (±42)	959 (±121)		959 (±121)

F1$_{SPAN}$: 275 (±64) **F2$_{SPAN}$:** 1075 (±234) **Area:** 13.52 (±5.52)

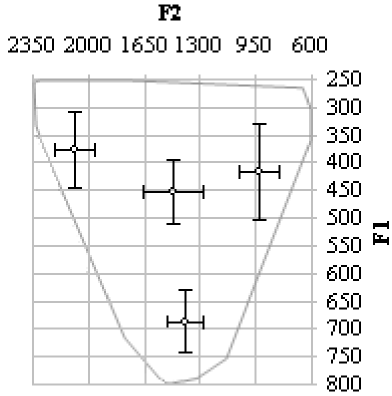


Languages: Tunisian Arabic (aeb:1), Palestinian Arabic (ajp:1-2), Aleut (ale), Amis (ami), Moroccan Arabic (ary), Egyptian Arabic (arz:1-2), Chickasaw (cic), Dogri (dgo:1), Hausa (hau:1), Hupa (hup), Greenlandic (kal), Molalla (mbe:1), Creek (mus), Punjabi (pan:1), Pashto (pbu:1), Quichua (que), Tachelhit (shi), Totonac (top), Tausug (tsg), Urdu (urd:1)

3S1:

IPA	F1	F2	F3	F2’
ɪ	376 (±68)	2084 (±130)	2751 (±73)	2432(±205)
ɐ	686 (±55)	1395 (±113)	2479 (±31)	1416 (±132)
o̞	417 (±86)	925 (±128)		925 (±128)
ə̞,œ̆	454 (±58)	1472 (±189)	2421 (±54)	1526 (±229)

F1$_{SPAN}$**:** 313 (±97) **F2**$_{SPAN}$**:** 1158 (±255) **Area:** 16.03 (±5.58)

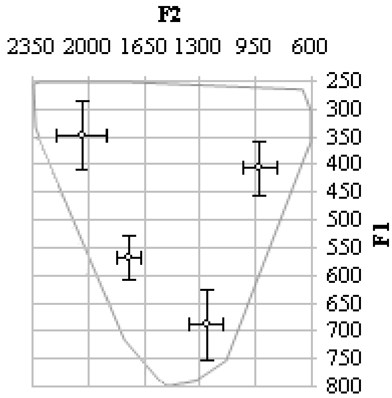


Languages: Northern Qiang (cng), Rukai (dru), Khanty (kca), Dutch (nld:1-2), Paiwan (pwn), Wu (wuu:1), Cantonese (yue:1-4)

4L0:

IPA	F1	F2	F3	F2’
ɪ	348 (±61)	2041 (±156)	2745 (±134)	2396 (±298)
ɛ̞	570 (±40)	1744 (±76)	2507 (±25)	1857 (±99)
ɑ̆	689 (±63)	1259 (±109)		1259 (±109)
o̞	407 (±50)	922 (±103)		922 (±103)

F1$_{SPAN}$**:** 341 (±120) **F2**$_{SPAN}$**:** 1119 (±258) **Area:** 21.42 (±9.98)

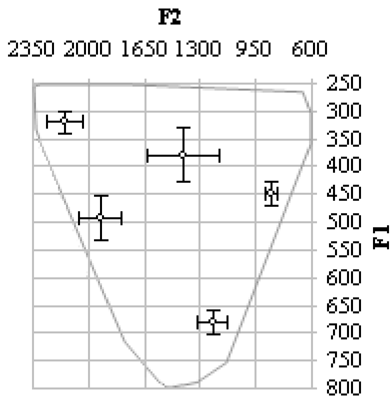


Languages: Tunisian Arabic (aeb:2-3), Apache (apw), Banawa (bnh), English (eng:9-121), Maltese (mlt), Navajo (nav), Urdu (urd:2)

4L1:

IPA	F1	F2	F3	F2’
ĭ	320 (±19)	2145 (±115)	2826 (±86)	2583 (±211)
ɛ̞	492 (±41)	1926 (±136)	2601 (±70)	2131 (±199)
ɑ̞	681 (±21)	1221 (±91)		1221 (±91)
o̞	450 (±22)	849 (±38)		849 (±38)
ɘ,ɵ̞	379 (±48)	1405 (±223)	2377 (±84)	1450 (±282)

F1$_{SPAN}$**:** 360 (±38) **F2**$_{SPAN}$**:** 1296 (±139) **Area:** 27.24 (±15.56)

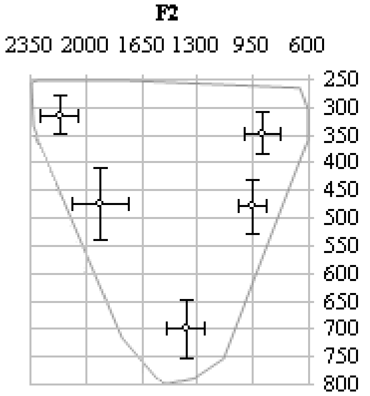


Languages: Japanese (jpn:1-11), Karitiana (ktn), Maori (mri), Munduruku (myu), Dutch (nld:6-7), Sakurabiat (skf), Akuntsu (???)

5S0:

IPA	F1	F2	F3	F2’
ĭ	314 (±35)	2164 (±122)	2849 (±107)	2636 (±253)
ĕ	474 (±64)	1915 (±177)	2612 (±108)	2130 (±282)
ɐ̹	699 (±52)	1373 (±124)	2483 (±31)	1389 (±147)
ŏ	479 (±49)	948 (±85)		948 (±85)
ŭ	346 (±39)	889 (±117)		889 (±117)

F1$_{SPAN}$**:** 389 (±86) **F2**$_{SPAN}$**:** 1289 (±228) **Area:** 27.39 (±9.60)

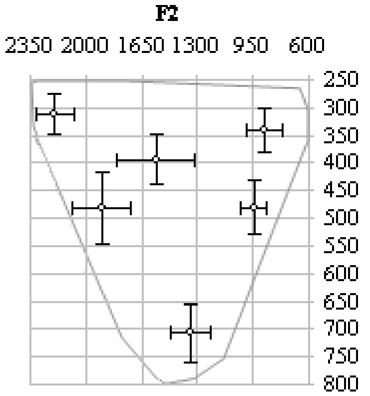


Languages: Palestinian Arabic (ajp:3-5), Aragonese (arg), Egyptian Arabic (arz:3-4), Toba Batak (bbc), Burarra (bvr), Catalan (cat:1-2), Chontal (chf), Tsez (ddo), Greek (ell), Basque (eus:1-9), Montana Salish (fla), Kunwinjku (gup), G|wi (gwj), Hakka (hak), Hausa (hau:2), Serbo-Croatian (hbs), Hebrew (heb), Hadza (hts), Japanese (jpn:12-13), Kannada (kan), Georgian (kat), Lithuanian (lit:1-4), Lele (lln), Jalapa Mazatec (maj), Musey (mse), Bambassi (myf), Nambikwara (nab), Min Taiwanese (nan), Ndebele (nde), !Xoo (nmn), Piedmontese (pms), Quechua (quz), Sicialian (scn), Slovak (slk:1-2), Slovenian (slv:1), Shona (sna), Spanish (spa), Siswati (ssw), Huehuetla Tepehua (tee), Telugu (tel:1-5), Yiddish (yid), Juchitan Zapotec (zai)

5S1:

IPA	F1	F2	F3	F2’
ĭ	312 (±32)	2196 (±85)	2870 (±77)	2689 (±180)
ĕ	481 (±48)	1903 (±169)	2600 (±87)	2107 (±252)
ɐ̹	707 (±46)	1345 (±149)	2482 (±26)	1361 (±166)
ŏ	481 (±54)	945 (±111)		945 (±111)
ŭ	340 (±41)	876 (±94)		876 (±94)
ɘ,ø	394 (±46)	1561 (±243)	2411 (±89)	1652 (±319)

F1$_{SPAN}$**:** 399 (±73) **F2**$_{SPAN}$**:** 1344 (±154) **Area:** 28.53 (±8.63)

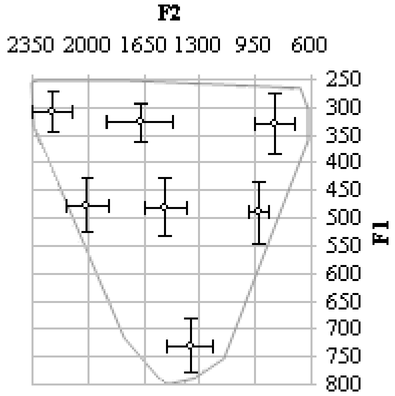


Languages: Assyrian Neo-Aramaic (aii), Gheg Albanian (aln), Bodo (brx), Bulgarian (bul), Welsh (cym:1), English (eng:14-15), Basque (eus:10), Paraguayan Guarani (gug), Gumuz (guk), Indonesian (ind), Kera (ker), Kuruaya (kyr), Mawa (mcw), Isthmus Mixe (mir), Moukoulu (moz), Dalabon (ngk), Nias (nia), Angami (njm), Anong (nun), Pashto (pbu:2), Polish (pol), Russian (rus), Sursurunga (sgz), Tajik (tgk), Truku (trv), Tsou (tsu)

5S2a:

IPA	F1	F2	F3	F2’
i̞	309 (±36)	2228 (±125)	2902 (±124)	2769 (±289)
e̞	477 (±48)	2004 (±138)	2650 (±94)	2257 (±224)
a̠	730 (±49)	1361 (±146)	2521 (±51)	1375 (±172)
o̽	490 (±57)	925 (±64)		925 (±64)
u̞	328 (±54)	829 (±125)		829 (±125)
ɨ,y̽	327 (±35)	1672 (±208)	2381 (±66)	1800 (±277)
ə̟,œ̝	481 (±52)	1517 (±131)	2413 (±63)	1576 (±164)

F1$_{SPAN}$**:** 432 (±77) **F2**$_{SPAN}$**:** 1409 (±239) **Area:** 33.95 (±10.59)

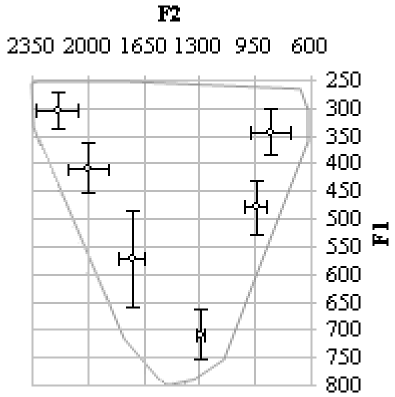


Languages: Amharic (amh), Tepetotutla Chinantec (cnt), Welsh (cym:2-4), German (deu:1-13), North Frisian (frr:1), Hungarian (hun:1-2), Komi (kpv), Dutch (nld:8-9), Romanian (ron:1), Albanian (shq:1-6), Sundenese (sun), Udmurt (udm), Kurtoep (xkz), Cantonese (yue:5-8)

6L0:

IPA	F1	F2	F3	F2’
i̽	304 (±33)	2188 (±134)	2876 (±116)	2693 (±286)
e	409 (±45)	1993 (±125)	2671 (±97)	2268 (±221)
ɛ̞	573 (±86)	1726 (±80)	2510 (±40)	1836 (±122)
ɑ̟	708 (±46)	1296 (±27)		1296 (±27)
o̽	479 (±49)	942 (±71)		942 (±71)
u̽	343 (±41)	855 (±127)		855 (±127)

F1$_{SPAN}$**:** 403 (±79) **F2**$_{SPAN}$**:** 1344 (±242) **Area:** 29.28 (±7.78)

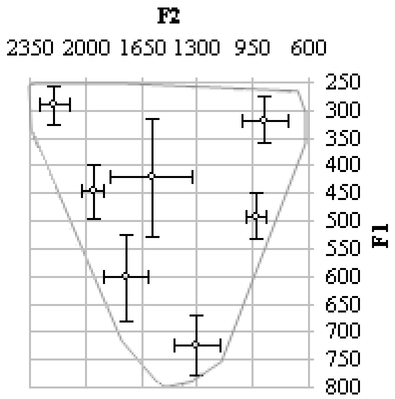


Languages: Catalan (cat:3), Darma (drd), English (eng:16-17), Korean (kor:2), Lithuanian (lit:5-9), Slovak (slk:3-4), Telugu (tel:6-8), Ukranian (ukr)

6L1:

IPA	F1	F2	F3	F2’
i̠	292 (±36)	2197 (±94)	2890 (±78)	2717 (±188)
e̽	447 (±48)	1948 (±69)	2624 (±33)	2175 (±96)
æ̝	603 (±76)	1742 (±138)	2519 (±54)	1854 (±190)
ɑ̟	723 (±55)	1301 (±143)		1311 (±156)
o̽	492 (±41)	930 (±65)		930 (±65)
u̟	318 (±42)	872 (±146)		872 (±146)
ɘ̟,ø	421 (±106)	1585 (±261)	2387 (±64)	1678 (±348)

F1$_{SPAN}$**:** 442 (±71) **F2**$_{SPAN}$**:** 1365 (±163) **Area:** 34.15 (±7.51)

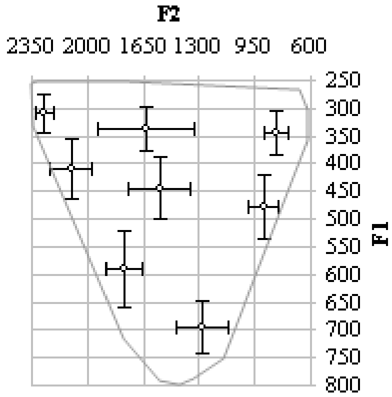


Languages: Babine (bcr), Estonian (ekk:1-2), Gujarati (guj), Dutch (nld:10-12), Occitan (oci), Chichimeca (pei), Albanian (shq:7-8), Wolof (wol:1)

6L2:

IPA	F1	F2	F3	F2’
i̞	309 (±34)	2270 (±58)	2931 (±52)	2835 (±120)
e	409 (±54)	2102 (±134)	2741 (±98)	2444 (±232)
ɛ̞	590 (±68)	1769 (±114)	2523 (±44)	1892 (±163)
ɑ̽	696 (±47)	1279 (±158)		1287 (±179)
o̞	478 (±59)	893 (±92)		893 (±92)
u̞	343 (±39)	816 (±79)		816 (±79)
ɨ,y̽	336 (±40)	1631 (±305)	2368 (±47)	1755 (±387)
ə̞,ø̽	444 (±56)	1547 (±195)	2401 (±74)	1621 (±245)

$F1_{SPAN}$: 391 (±68) **$F2_{SPAN}$:** 1478 (±108) **Area:** 33.34 (±6.51)

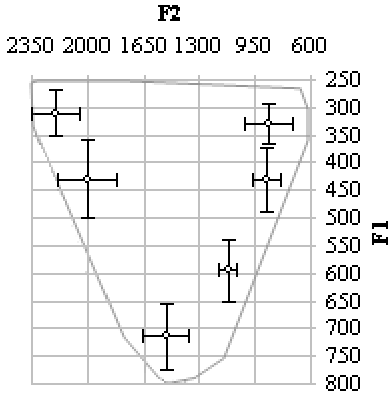


Languages: German (deu:14-18), Finnish (fin), North Frisian (frr:2), Icelandic (isl), Korean (kor:3), Livonian (liv), Dutch (nld:13-14), Uyghur (uig), Oriat (xal)

6R0:

IPA	F1	F2	F3	F2’
i̽	310 (±43)	2196 (±153)	2881 (±121)	2705 (±299)
e̞	430 (±70)	2003 (±187)	2679 (±130)	2283 (±314)
a̝	715 (±59)	1512 (±143)	2503 (±29)	1556 (±176)
ʌ̞,ɒ̟	594 (±56)	1122 (±52)		1122 (±52)
o	432 (±58)	877 (±91)		877 (±91)
u̞	328 (±36)	861 (±151)		861 (±151)

$F1_{SPAN}$: 408 (±92) **$F2_{SPAN}$:** 1366 (±265) **Area:** 31.36 (±7.51)

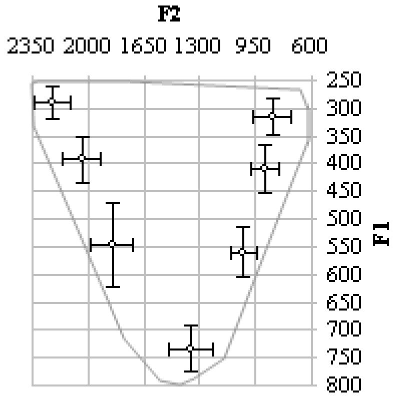


Languages: Bedjond (bjv), Viri (bvi), Southwestern Dinka (dik:1), English (eng:18-23), Nar (kwv:1), Latvian (lav), Sar (mwm), Mbay (myb), Nepali (nep), Oriya (ori), Persian (pes), Kaba (sbz)

7S0:

IPA	F1	F2	F3	F2'
i	289 (±29)	2222 (±115)	2915 (±106)	2780 (±266)
e	393 (±41)	2040 (±117)	2709 (±80)	2349 (±197)
ɛ	546 (±75)	1852 (±135)	2563 (±64)	2015 (±196)
a̠	733 (±40)	1354 (±136)	2499 (±19)	1371 (±148)
ɔ̟	560 (±46)	1023 (±86)		1023 (±86)
o	410 (±43)	895 (±89)		895 (±89)
u	316 (±33)	843 (±118)		843 (±118)

F1$_{SPAN}$**:** 446 (±68) **F2**$_{SPAN}$**:** 1398 (±213) **Area:** 35.41 (±10.50)

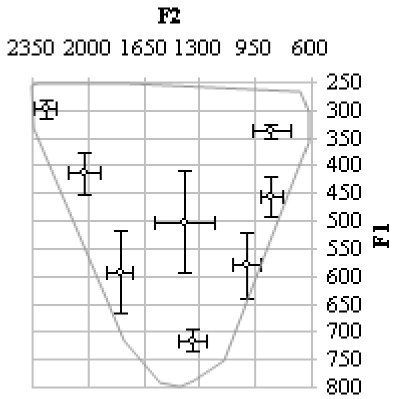


Languages: Defaka (afn), Amuzgo (amu), Oroko (bdu), Bengali (ben), Tuwuli (bov), Dibole (bvx), Catalan (cat:5-9), Dogri (dgo:2), Southern Dinka (dib), Southwestern Dinka (dik:2), Eastern Dinka (dks), Ndumbea (duf), English (eng:24-26), Gban (ggu), Galician (glg), Ife (ife), Italian (ita), Kirikiri (kiy), Mpiemo (mcx), Mbosi Olee (mdw), Burmese (mya), Neapolitan (nap), Low German (nds), Khana (ogo), Punjabi (pan:2), Portuguese (por:1-6), Sele (snw), Sardinian (sro), Setswana (tsn), Urdu (urd:3-4), Venetian (vec), Wolof (wol:2), Gunu (yas), Yoruba (yor:1-3)

7S1:

IPA	F1	F2	F3	F2'
i	299 (±15)	2264 (±70)	2934 (±55)	2836 (±137)
e	414 (±38)	2017 (±101)	2679 (±71)	2298 (±168)
ɛ̞	593 (±74)	1802 (±81)	2533 (±24)	1935 (±118)
ɐ̞	716 (±20)	1342 (±87)	2495 (±17)	1351 (±100)
ɔ̞	581 (±61)	1003 (±94)		1003 (±94)
o̞	455 (±37)	851 (±69)		851 (±69)
u̞	338 (±13)	847 (±121)		847 (±121)
ə	502 (±92)	1393 (±191)	2424 (±63)	1430 (±229)

F1$_{SPAN}$**:** 418 (±35) **F2**$_{SPAN}$**:** 1471 (±149) **Area:** 34.59 (±5.24)

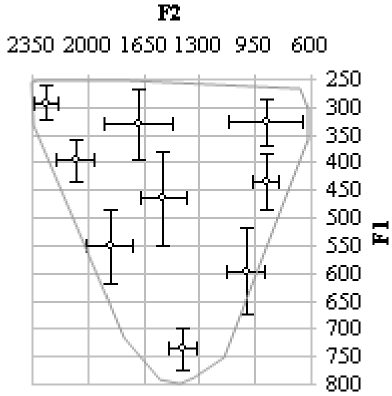


Languages: Catalan (cat:10), Eton (eto), Korean (kor:5-6), Maithili (mai:1-3), Portuguese (por:7), Slovenian (slv:2)

7S2:

IPA	F1	F2	F3	F2’
i	292 (±31)	2263 (±73)	2940 (±75)	2849 (±172)
e	396 (±37)	2078 (±124)	2730 (±88)	2409 (±210)
ɛ	552 (±66)	1864 (±141)	2565 (±66)	2031 (±208)
a̠	735 (±38)	1404 (±92)	2502 (±22)	1423 (±109)
ɒ̝	596 (±78)	1007 (±116)		1007 (±116)
o	434 (±51)	882 (±83)		882 (±83)
u̝	327 (±41)	881 (±237)		881 (±237)
ɨ,y̽	330 (±63)	1682 (±213)	2382 (±68)	1813 (±283)
ə̟,œ	465 (±85)	1527 (±141)	2404 (±81)	1591 (±182)

F1$_{SPAN}$: 451 (±64) **F2**$_{SPAN}$: 1461 (±127) **Area:** 36.76 (±7.01)

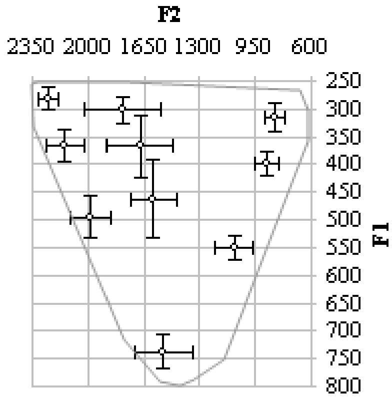


Languages: Breton (bre), Chong (cog), Emilian (egl), Frisian (fry), Scotish Gaelic (gla), Hungarian (hun:3), Khmer (khm:2), Dutch (nld:15-18), Wa (prk), Romanian (ron:2), Thai (tha), Wu (wuu:3)

7S3a:

IPA	F1	F2	F3	F2’
i	282 (±20)	2247 (±62)	2935 (±65)	2828 (±150)
ɪ̟	366 (±30)	2142 (±121)	2791 (±103)	2541 (±233)
e̝	495 (±39)	1985 (±127)	2629 (±80)	2219 (±200)
a	738 (±31)	1529 (±180)	2513 (±35)	1576 (±222)
ʌ,ɔ̟	551 (±23)	1085 (±123)		1085 (±123)
o	397 (±21)	878 (±75)		878 (±75)
u	315 (±25)	823 (±63)		823 (±63)
ɨ̟,y	301 (±23)	1783 (±243)	2384 (±42)	1950 (±329)
ɪ̠,ʏ̟	367 (±55)	1674 (±205)	2388 (±36)	1794 (±282)
ə̟,œ̝	463 (±71)	1592 (±145)	2423 (±42)	1675 (±196)

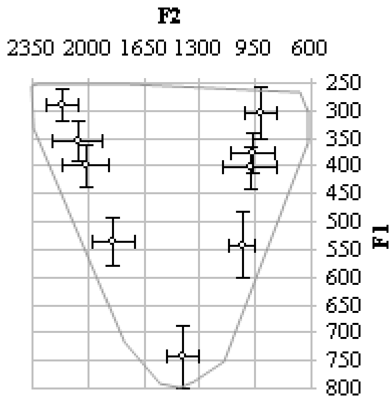
F1$_{SPAN}$: 456 (±49) **F2**$_{SPAN}$: 1432 (±111) **Area:** 36.54 (±8.15)



Languages: Danish (dan), French (fra:1-3), Megleno-Romanian (ruq), Wu (wuu:4), Paici (pri)

9S0:

IPA	F1	F2	F3	F2’
i̠	288 (±29)	2160 (±104)	2866 (±86)	2652 (±210)
ɪ	355 (±37)	2066 (±155)	2753 (±118)	2426 (±288)
e	400 (±38)	2014 (±148)	2691 (±95)	2306 (±243)
ɛ	536 (±43)	1842 (±134)	2553 (±62)	2002 (±193)
a̠	743 (±57)	1409 (±100)	2493 (±25)	1431 (±115)
ɔ̟	542 (±60)	1030 (±82)		1030 (±82)
o̟	403 (±39)	982 (±171)		982 (±171)
ʊ	376 (±36)	966 (±134)		966 (±134)
u̟	304 (±46)	915 (±106)		915 (±106)

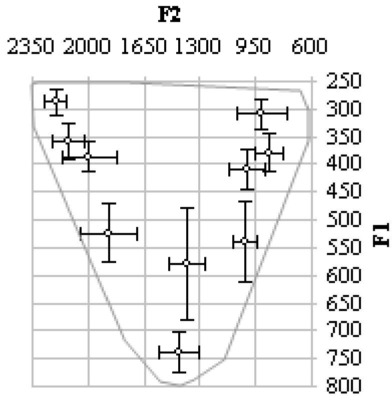


F1$_{SPAN}$: 459 (±92) **F2**$_{SPAN}$: 1313 (±195) **Area:** 33.95 (±12.55)

Languages: Akan (aka), Foodo (fod), Konni (kma), Baale (koe), Dholuo (luo), Maa (mas), Mangbetu (mdj), Majang (mpe:1), Nawuri (naw), Sotho (sot), Twi (twi), Yoruba (yor:4-5)

9S1:

IPA	F1	F2	F3	F2’
i	288 (±23)	2204 (±66)	2896 (±61)	2732 (±142)
ɪ̟,e̝	359 (±33)	2122 (±99)	2781 (±80)	2508 (±182)
e,ɪ̞	386 (±26)	1995 (±168)	2689 (±103)	2284 (±275)
ɛ	524 (±53)	1872 (±182)	2575 (±88)	2051 (±266)
a	738 (±36)	1430 (±122)	2509 (±17)	1457 (±135)
ɔ̟	540 (±73)	1013 (±74)		1013 (±74)
o̟,ʊ̞	409 (±37)	1000 (±115)		1000 (±115)
ʊ̠,o̝	379 (±35)	865 (±83)		865 (±83)
u̟	309 (±28)	909 (±153)		909 (±153)
ɜ̞	580 (±102)	1385 (±115)	2461 (±51)	1408 (±136)



F1$_{SPAN}$**:** 452 (±59) **F2**$_{SPAN}$**:** 1386 (±122) **Area:** 33.90 (±8.30)

Languages: Degema (deg), English (eng:32-33), Ikposo (kpo), Lango (laj), Mayogo (mdm), Majang (mpe:2), Kinande (nnb), Lubwisi (tlj),

Structures occurring in four languages in the survey:

3S2:

IPA	F1	F2	F3	F2’
i̞	308	2313	2969	2934
ɑ̟	725	1310	2514	1320
ʊ̠	366	731		731
y	299	1799	2357	1970
ə̟,œ̝	460	1532	2429	1595

Languages: Mandarin (cmn), English (eng:1-8), Ao (njo), Dutch (nld:3-5)

6R1:

IPA	F1	F2	F3	F2’
i̞	318	2219	2889	2737
ě̽	489	1921	2596	2125
ǎ̽	682	1470	2479	1504
ʌ,ɒ̽	579	1163		1163
ǒ̽	454	910		910
ǔ̽	354	894		894
ɘ̠	413	1471	2371	1526

Languages: Catalan (cat:4), Korean (kor:4), Ayutla Mixe (mxp), Ticuna (tca)

6R2a:

IPA	F1	F2	F3	F2’
i	287	2213	2914	2782
e	420	2080	2749	2452
a	746	1573	2517	1624
ɒ	610	1068		1068
ǒ̽	490	975		975
u	310	817		817
ɨ,y̽	313	1616	2338	1723
ə̝,œ̽	447	1492	2396	1547

Languages: Estonian (ekk:6), Fe’fe’ (fmp), Khmer (khm:1), Mono (mnh)

6L3b:

IPA	F1	F2	F3	F2’
i̞	324	2271	2923	2828
e̞	445	2045	2685	2334
æ̝	590	1742	2544	1874
ɑ̽	693	1273		1273
o̞	478	849		849
ʊ̠	358	806		806
y	332	1979	2449	2212
œ	515	1479	2444	1531
ə	456	1406	2373	1438

Languages: Afrikaans (afr:2), Chuvash (chv), Estonian (ekk:4-5), Voru (vro:1)

6R3:

IPA	F1	F2	F3	F2’
i̞	305	2226	2911	2785
e̞	453	2019	2662	2283
a̝	717	1516	2505	1558
ɑ̝,ɒ̟	660	1118	2439	1124
o̞	456	906		906
u̞	333	825		825
y	307	1984	2431	2214
ø̞	432	1570	2383	1646
ɘ̠,ɵ̟	403	1449	2351	1492

Languages: Estonian (ekk:7-12), Norwegian (nor),Toda (tcx), Wu (wuu:2)

Other structures:

str.	Languages
4L2a	Cherokee (chr) English (eng:12) Wari' (pav)
4L2b	Bora (boa)
4R0	Molalla (mbe)
4R1	English (eng:13) O'odham (ood)
5S2b	Korean (kor:1)
5S3	Afrikaans (afr:1) Turkish (tur) Swedish (swe:1-5)
5S4	Kazakh (kaz)
6L3a	Swedish (swe:6-7)
6L4	Voru (vro:1)
6R2b	Khalkha (khk:1) Inner Mongolian (mvf:1) Madurese (mad)

str.	Languages
7R0	Khalkha (khk:2)
7R3	Iaai (iai)
7S3b	Korean (kor:7-8) Wu (wuu:5)
8L0	Moore (mos) English (eng:29-30)
8L1	English (eng:27-28) Ndut (ndv)
8L2	Solon (evn)
8L3a	Kuy (kdt:1)
8L3b	Inner Mongolian (mvf:2-3) Voru (vro:3)
8R0	Igbo (ibo) Dari (prs)
8R2	Brou (bru) Inner Mongolian (mvf:4)

str.	Languages
8R3a	French (fra:4-7) Kuy (kdt:2) Vietnamese (vie)
8R3b	Inner Mongolian (mvf:5)
8R4	Inner Mongolian (mvf:6)
8R5	Ngwe (new)
8R6	Voru (vro:4)
9R1	English (eng:31)
9S3	Dutch (nld:19-22)
9S4	Bavarian (bar)
10L0	Diola (dyo) Somali (som)
10L1	English (eng:34)
10R0	Didinga (did)
10R4	Northern Khmer (kxm) Norman (roa)

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