Investigating the "hidden" structure of phonological systems[1]

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1. Introduction

Observed phonological systems are only a very small subset of what is theoretically conceivable considering the possibility of the human vocal tract. In other words, given the number of possible phonetic features (corresponding to the vocal tract generative capacity), the number of attested segments is incredibly lower than what is combinatorily possible. The same observation is valid when comparing the number of attested systems with the set of theoretical ones predicted from the attested number of segments.

Obviously, it cannot be doubted that phonological systems are not just unorganized sets of segments picked up at random and, consequently, phonological theories and typological studies have focused on showing that these systems are structured according to various constraints from the perceptual, articulatory or cognitive levels (Troubetzkoy, 1929, Sedlak, 1969, Crothers, 1978, Maddieson, 1984).

Yet the task of identifying these constraints and the way they interact is still relevant today, even if numerous works have investigated some of them especially in the case of vocalic systems (Liljencrants and Lindblom, 1972, Lindblom 1986, Stevens, 1989, Vallée, 1994). However, the constraints affecting consonantal systems have been only partially investigated and our comprehension is still limited (Lindblom and Maddieson, 1988, Vallée & al. 2002). Lindblom and Maddieson, sketch out – in one of the first attempts to study consonantal systems – the basis of an "all-inclusive universal phonetic space" (hereunder UPS) which can be considered as the first study of phonological systems as a whole.

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UPSID (UCLA Phonological Segment Inventory Database, Maddieson, 1984, Maddieson and Precoda, 1990) provides a powerful tool to observe the attested systems in the languages of the world. Moreover, considering the whole set of features or segments found in the database gives a way to approximate the UPS. Our main hypothesis is that whatever the level of the constraints is (articulatory, perceptual, etc.), we can take advantage of this twofold information (attested systems and possible systems) to reveal their effects on the structure of the phonological systems[2]. Consequently, we propose to explore the UPSID database in an unbiased perspective leaving aside *a priori* considerations about perceptual or articulatory levels.

Three main questions are addressed in this paper:

- Will this “data mining” approach reveal information about the structure of phonological systems?
- Will the nature of the features used influence these results?
- Do phonological systems exhibit properties compatible with the complex adaptive system paradigm?

The first question is obviously the core target of this research, and is the focus of the next sections. The second question deals with the identification of possible methodological bias due to the nature of the data. The third question is a way to address the relations existing between the constituents of the systems (features and segments) and the systems themselves. The theoretical framework and our goals are further developed in Section 2. We have developed a set of descriptive indices and structural parameters that are defined in Section 3. Results and interpretations are also given in Section 3 while the specific question of the influence of the feature description on the indices is addressed in Section 4.

2. Framework and Aims

2.1. Universal Phonetic Space and Phonological Inventories

For a long time, vowel and consonant systems have been studied apart due to their different role and nature. However, it is likely that the structural constraints affecting both systems are not totally independent. For this reason, studying phonological systems as a whole may be informative. This point of view adopts the notion of the UPS introduced by Lindblom and Maddieson.

This systemic perspective is subsumed under the general “size principle” first defined by (Maddieson, 1984). According to him, the content of a particular phonological system is a function of its number of segments. This principle also specifies that the constraints at work belong to two main classes, one of articulatory ease and one of perceptual salience. In this sense, phonological systems are trade-offs between the “ease of articulation” which tends to generate

[2] We are aware that considering only the phonological inventories is a serious limitation to any kind of conclusion, nevertheless the structure of UPSID does not provide material to investigate dynamic and phonotactic constraints.

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similar segments (articulatory economy) and "perceptual salience" which (ideally) requires very different ones (maximum or sufficient acoustic distance).

From a typological point of view, it seems that small phonological systems recruit few dimensions (height, frontness and rounding for vowels, place, manner and voicing for consonants) since perceptual salience is guaranteed by the low density of segments in the theoretical space defined by these dimensions. On the contrary, when the size of the systems gets larger the need for perceptual contrast seems to imply new (secondary) dimensions (Vallée et al. 2002). Consequently, and following Lindblom and Maddieson, the dimensions structuring phonological systems are not invariant in number as well as in quality. Nevertheless, even if the number of dimensions is related to the number of segments, some dimensions seem to be more elementary. Thus each language considers *some* other dimensions of the UPS and one can ask 1. which dimensions are recruited (among all the potential dimensions) and 2. how segments spread along these dimensions.

Our approach rests on this hypothesis of variable phonetic space. We depart from classical typological studies on two main points: i) by not considering patterns' frequency of distribution and ii) by trying to unify consonantal and vocalic levels.

Regarding i), instead of building classes of types and studying their frequency of distribution in the world's languages we decided not to consider these frequencies and to examine the structure of the set of "possible phonological elements" obtained from the UPSID database. This relies on the hypothesis that by analyzing the set of possible phonological elements provided by the UPSID database (100 features, 833 segments, 451 languages) it is possible to reveal the "hidden" structure of phonological systems or, at least, to identify part of the main constraints responsible of their shape.

Regarding ii), our approach aims at studying the whole phonological system even if there are some pitfalls due to the distinction between vowel and consonant in the feature-based description (for example, a single articulatory phenomenon may be covered by two different terms: eg. "nasals" for consonants and "nasalized" for vowels). This issue is partly addressed in Section 5.

2.2. Aims

As pointed out previously, our main hypothesis is that exploring the UPSID database in an unbiased perspective may reveal how the constraints, whatever they are, influence the phonological systems.

We can now develop in more details the 3 questions introduced in Section1.

The first point may be split in several questions about the correlations and relations between the size of the systems and the nature of their components (number of features and number of segments; relations between the segments; etc.). We also try to answer to the classical question about the complexity of the segments (what is a simple or complex segment, which segments are simple, etc.) without falling in the trap of the frequency/simplicity circularity (or the markedness issue).

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The second question deals with the identification of possible methodological bias due to the nature of the data. This methodological aspect is actually crucial since it can severely affect the results. However, it is not simple to handle with. From the standard feature set used for the UPSID database, we propose to test the effect of a reduction (resp. expansion) of the number of features to describe the languages of the database. The goal is therefore to estimate the impact of theses changes on the relations that arise from our analysis.

Complex Adaptive Systems (CAS) are common in many natural phenomena. Phonological systems may exhibit several characteristics of such a theoretical description: the structure of the systems is not linearly deducible from the constituents and the term “emergent” may be suitable to define several global characteristics of the systems. The CAS paradigm is consequently a way to address the question of the relations existing between the constituents of the systems. In addition, it provides a convenient framework to deal with the notion of inner complexity of a system and to avoid the difficulties encountered when comparing the complexity between different systems (an attempt to perform this kind of comparison is detailed in Marsico et al., 2002).

2.3. Diachronic and synchronic constraints

Phonological systems are constrained at different levels by different forces. Some are manifested at the level of features, and they are likely to be mostly articulatory since they are the results of the way speech sounds are produced; they organize the features at least in groups and probably in a certain hierarchy. Some others are systemic and maybe mostly perceptual, e.g., for the sake of contrast, segments are not randomly recruited. Additionally, the synchronic state of a phonological system is always a function of its history, thus it is necessary that diachronic considerations be part of the explanation.

This covers the traditional distinction between internal and external forces (Labov, 1994, 2001). Internal forces ensure the efficiency of a system, given its size, and in that view several systems of different or same sizes are equally efficient. External forces (social factors, language acquisition) may temporarily modify the state of a system, such that the changes are oriented but not highly constrained and they lead to the appearance of new –possibly non optimal– systems.

Finally, and following (Greenberg, 1978), the frequency of distribution of any type of phonological system is a function of the probability of entering into that given state and of the probability of staying into that state (“transitional and rest probabilities”) (Greenberg, 1978:75). For this reason and because the inventories only provide one 'time slice' sample from the system's diachronic trajectory, we consider that the frequencies of distribution of types must be the end point (validation) of our approach, not the starting point since the past trajectory of a given language is unknown. In this view, frequencies of distribution are emergent properties, resulting from complex interactions at different levels. High frequencies are not more important than low ones, because the model must

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explain not only why certain types are preferred but also why there are so many co-existing different types.

The result from this is that the frequency of distribution of a particular type should be a function of 1) Its responsiveness to synchronic constraints and 2) Its positioning at the crossroads (or not) of evolutionary trajectories. Besides, the impact of the capacity of adaptation of a system (number of possible extensions) will also be addressed; some kinds of systems may indeed be considered as dead-ends or evolutionary sinks from which the evolution would be highly costly and consequently very unlikely.

3. Descriptive indices, structural parameters and initial results

3.1. UPSID Database

The raw data we use are taken from UPSID. This database was purposely compiled for typological studies, thus the sample of 451 languages is representative of both genetic and geographic diversity of the world's languages. These 451 phonological systems are composed of 833 different segments, which in turn are described with 100 different phonetic features. These three levels (features, segments and systems) represent what we call the 'set of possible phonological elements'. Again, considering that the frequency of distribution of these elements are consequences of their "hidden structure", all the elements at any level have the same weight with no regards to their frequency of distribution in the world languages. We thus defined several indices in order to capture the hierarchical ties between features and between segments. They will be presented hereunder along with the associated results.

3.2. Basicness

This index is elaborated first at the feature level. It represents the quantification of the fact that some features are more necessary than others to the definition of segments. In the literature, we find for example the opposition between primary and secondary features (more often dimensions) and the same idea is found in (Lindblom and Maddieson, 1988), with the scale of simple, complex and elaborated consonants that can easily be projected at the feature level.

The basicness of a feature is a function of its ability to belong to the set of features that can minimally define a segment. In other words, a feature is "basic" if, when removed from the definition of a segment, the remaining set of features does not define an other existing segment (searched in the 833 ones of the database). For example in (1), if we remove the feature "front", {high unrounded} does not correspond to any segment, thus "front" is basic. Whereas in (2), if we drop "long" we still have a valid definition of an existing vowel.

(1) i {high front unrounded}
(2) i: {long high front unrounded}

Therefore, "front" has a basicness of 0 while "long" has a basicness of 1. For most of the features, their basicness is consistent among the segments. However,

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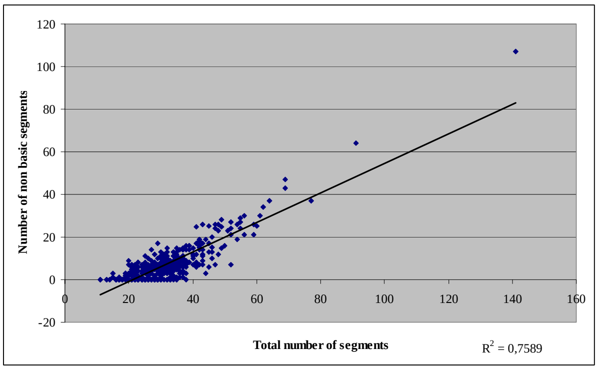
and especially with segments described by many features, removing one feature may result in an unattested segment, even if it may theoretically be produced. To handle with theses features, the basicness value is normalized by dividing it by the number of segments in which the feature appears. Basicness consequently ranges from 0 (true basic features) to 1 (features that are never basic) with intermediate values (features that are essential to the definition of some of the segments in which they occur).

For instance, the feature "palatalized" which is a secondary articulation, would intuitively be classified as a pure non-basic feature with a value of 1. However its value is not exactly one because of the {*palatalized* voiceless alveolar flap]. The fact that no language in UPSID has a "voiceless alveolar flap" makes "palatalized" a partially basic feature. Obviously, even if our index is gradual, it seems more interesting to distinguish between basic segments (0 or almost 0 in basicness) and non-basic ones (1 or almost 1).

The notion of basicness may be intuitively extended to segments and systems: a basic segment would be a segment described by basic features, and a basic system will consist of basic segments or basic features. However, these consolidated indices may be based on two measures whether the basicness of the constituents of the segment (resp. of the system) are summed or averaged. Correlation coefficients (R^2) between all these measures range from 0.53 to 0.95.

Many analyses may be driven studying the basicness at the three levels (features, segments and systems). An example is provided in (3). It shows the way the number of non basic segments is correlated to the total number of segments in the UPSID 451 languages ($R^2 = 0.76$). Moreover, this relation seems to be linear even for very complex system (as for !Xu).

(3) Number of non basic segments as a function of the total number of segments for each phonological system from UPSID.



Basic segments are very common (37.8%). Furthermore, a large amount of the 833 segments are derived from basic segments by adding one feature (46.8%). Finally, more complex segments are pretty uncommon in the inventory of segments (15.4%).

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3.3. Derivationality

The index of basicness applied at the level of segments distinguishes two classes of segments: basic vs. non-basic segments. All non-basic segments are a combination of a basic one plus one or several additional feature; they are by definition more complex than basic segments. Derivationality measures the capacity of a basic segment to be the core of non basic ones by calculating how many existing segments are derived from it by addition of features. For example, a basic segment for which no attested segment is derived has a derivationality of 0.

Though derivationality is defined at the segment level, it may be relevant at the system level since the underlying hypothesis is that the non uniform distribution of segments described by a similar number of features may be due to the fact that the ones with a high derivation capacity may give better adaptive power to the systems (see section 3.5).

(4) displays the five most derivational vowels of UPSID. For example, /a/ may be modified to generate 12 other vowels. It happens that these five vowels are the most frequent in the world languages

(4) Most derivational **vowels** with their description, Derivationality and frequency of distribution in the UPSID languages.

Segment name	Derivationality	Frequency (in languages)
/a/ voiced low central unrounded	12	86.9%
/i/ voiced high front unrounded	11	87.1%
/o/ voiced higher-mid back rounded	11	68.7%
/u/ voiced high back rounded	9	81.8%
/e/ voiced higher-mid front unrounded	9	64.5%

(5) provides the same information for consonants. The most derivational segment is /k/ and it is also the most common segment. However, the list shows also that very rare segments may as well present a high derivational power (e.g. /qχ/).

(5) Most derivational **consonants** with their description, derivationality and frequency of distribution in the UPSID languages.

Segment name	Derivationality	Frequency (in languages)
/k/ voiceless velar stop	17	89.4%
/tʃ/ voiceless postalveolar sibilant-affricate	14	41.7%
/t/ voiceless alveolar stop	13	73.8%
/q/ voiceless uvular stop	13	11.5%

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/p/ voiceless bilabial stop	11	83.1%
/ts/ voiceless alveolar sibilant-affricate	11	23.7%
/qχ/ voiceless uvular non-sibilant-affricate	10	0.9%
/b/ voiced bilabial stop	9	63.6%
/d/ voiced alveolar stop	9	46.8%
/s/ voiceless alveolar sibilant-fricative	9	73.4%

3.4. Redundancy

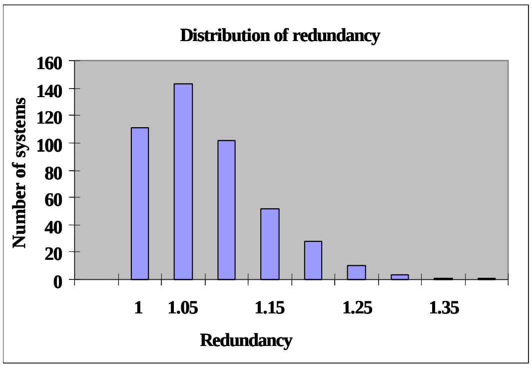
It has long been argued convincingly that phonological systems tend to do a "maximum use of available features - MUOAF" (see among others (Ohala, 1980), (Clements 2003a, 2003b)). A consequence of this hypothesis is that a system would be structured to minimize the descriptive distance between two "neighbor" segments, in terms of number of contrasts.

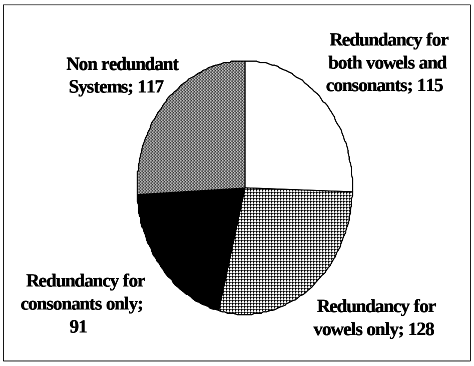
To test this hypothesis, we computed the redundancy factor in order to catch the way systems make use of features for contrasts. This index is calculated by averaging over the system the distances between each segment and its nearest neighbor(s). In this definition, a highly redundant system is therefore one where oppositions between segments can be expressed by more than one feature. On the other hand, a system where pairs of neighbor segments consist only of "minimal pairs" will have a redundancy of 1.

The mean redundancy factor among UPSID is 1.06 (the distribution is displayed in (6) Left). It means that systems do indeed respect the MUOAF principle, either strictly (24.6% of the languages have a redundancy of 1) or more or less strongly (up to a value of 1.36).

(6) Right gives the distribution of systems according to the presence/absence of redundancy in their vowel/consonant inventories.

(6) Left: Distribution of redundancy among UPSID. Right: Distribution of systems according to their use of redundancy





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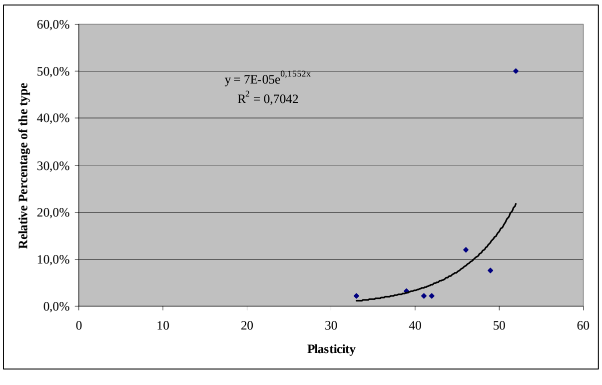
3.5. Plasticity

The index of plasticity is to some extent equivalent to the derivationality at the system level. Nevertheless, it is hypothetical: whereas derivationality gives the *actual* number of attested non-basic segments derivable from a particular basic one, the plasticity index gives the *putative* adaptive power of a system. This index can be viewed as a diachronic one; it has been conceived to test the idea that preferred systems are systems that can easily respond to external forces of change. One way of doing so is to be able to recruit new phonemes at low articulatory cost, i.e. by using modified existing basic segments instead of new basic ones. Of course, beside the addition of segments, the loss of segments is also frequent. In each case (acquisition or loss), what counts may be that minimal perturbation is brought to the system, and one way to achieve that is by not modifying the core of a system, i.e. the set of basic elements. Thus the more derivational segments a system may have the better its adaptive capacity.

The value of the plasticity index of a system is the sum of the derivationality of its segments minus the number of derived segments already present in the system.

Plasticity may play an important role in the selection of segments by providing a low cost way to recruit new segments in the evolutionary process. However, comparing plasticities is complex as soon as systems with different sizes are concerned. For this reason, (7) only displays an example for the 5 vowel systems. Only systems shared by at least 2 languages are considered. The frequency of distribution of each type is plotted against the plasticity of the system. A rather high correlation is reached ($R^2 = 0.7$), but this result must be considered with caution because of the low number of types.

(7) Example with 5 vowel systems: relative percentage of each type x Plasticity of each type. $R^2 = 0.7$



4. Testing the set of features

Since (Jakobson, Fant and Halle, 1952), several grids of distinctive features have been proposed in phonological theories, e.g. (Chomsky and Halle, 1958). Beside

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the question of the nature of features (monovalent, binary or scalar), choosing the correct set is bound up with the question of what are the best cues engaged in phonological contrasts. This question arises again here in some slightly different terms: what is the impact of the set of features used on the values of our systemic indices? Our assumption is that as the set of available features conflates articulatory, acoustic, aerodynamic and perceptual properties of segments, even if our analysis is feature-dependant, a change in the set of features should lead to comparable results. To test this assumption, we compare the results for three sets of features: standard (100 features), reduced (55) and expanded (159) detailed below.

4.1. Standard set of features

The standard set consists of 100 features and is not far from the features extracted from the IPA chart. There are only few differences between traditional way of describing segments and ours. The treatment of consonants is almost the same, place, manner and laryngeal settings being the primary features, except that we distinguish between “sibilant-fricative” vs. “non-sibilant fricative” and between “sibilant-affricate” vs. “non-sibilant-affricate”. The main differences concern vowels and diphthongs. For the vowel description we add the feature “voiced” in order to be congruent with consonants. Regarding diphthongs, we describe them as being doubly articulated vowels (in a similar way to consonants, e.g. labial-velar stops, /kp/ and /gb/). For instance the diphthong /iu/ is described as “voiced high front-back rounding” and /oi/ as “voiced higher-mid-high back-front unrounding”.

4.2. Reduced and expanded sets of features

The reduced set of features was defined by splitting double features (like labial-velar, lateral-approximant, etc.) into two single ones. The same feature “nasal” is also used for both vowels and consonants, the plain nasals being characterized by the feature “stop”. We thus have for example, /m/ {voiced bilabial nasal stop}. This set amounts to 55 features.

The expanded set is based on the opposite attitude, i.e. joining any co-occurring features dealing with the same articulatory dimension (place, manner, laryngeal settings, etc.). For example, “velar labialized”, “prenasalized sibilant-fricative”, “voiced ejective”, each became one single feature. This set amounts to 159 features.

4.3. Comparison of the three sets of features

(8) gives the correlations between the redundancy computed with each set. The correlation between the standard and the expanded sets is 0.99 indicating that the index is almost invariant to this change of feature set. The correlation with the reduced set is lower (0.77), this may be due to the fact that reducing the number of features automatically increases the description length of segments.

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(8) Table of correlation of the redundancy factor computed with each set.

Redundancy correlation	Reduced set	Standard set	Expanded set
Reduced set	1		
Standard set	0.77	1	
Expanded set	0.77	0.99	1

5. Conclusion and future work

We propose in this paper a new approach to the exploration of phonological inventories. Initial results show that the most frequent vowels are those from which the more segments may be derived while this fact is not as clearly verified for consonants. At the system level, languages seem to maximize the density or use of the available features and the first considerations about plasticity may confirm its role in the frequencies of distribution of each type in the world languages). Further studies are obviously necessary to assess the relevancy of this approach. Finally, studying the relations between the feature, segment and system levels may bring significant information and confirm or reject the interest of a Complex Adaptive System approach.

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