Tendencies in phonological structures: the influence of substance on form

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ABSTRACT

Placing ourselves in the framework of substance-oriented linguistics, we attempt to demonstrate that certain main tendencies in the sound structures of the languages of the world can be explained, in part, by sensorimotor constraints. We re-situate this hypothesis within the historical framework of the emergence of phonology at the end of the 1920's. Following the route opened up by Lindblom & Liljencrants in 1972, we illustrate the possibility of giving substance to phonology, thanks to advances due to phonetics in the fields of language typology and the prediction of sound structures. Sufficient elements are available to provoke a new interplay between phonetics and phonology, which has been rendered more and more necessary by contributions from the production and the perception of speech. This framework not only provides an input to the patterning of speech sounds in human languages, but it also offers a crucial anchor point for any global theory of speech communication.

1. The form/substance debate

1.1 Language and speech: a dichotomy put in place by linguistics

Throughout the 20th century, several axioms of the core of structuralist, and subsequently generativist, approaches have conditioned relationships between phonetics and linguistics:

- the language/speech dichotomy;
- the independence of these two concepts;
- the primacy of language over speech.

This distinction is the result of a particular methodological approach. Linguistics, in order to render empirical data intelligible, separates the domain of its investigation – the study of a sound system – from the issue of its physical realisation, which may be variable and polymorphous (Ducrot & Schaeffer, 1995, p. 245). Among the systems which develop during the first years of infancy – such as prehension and locomotion – communication by speech is particularly specific. Of course, at this stage of ontogenesis, there exist other systems of communication by hearing, sight, and touch, but these cannot really be formalised; that is, they cannot be described in terms of units and combinatorial rules. Speech communication functions on two highly-structured levels, the system itself and its physical realisation; it is for this reason that it is so efficient when compared to other methods of exchange used by man or animal. The terms language and speech refer to these two levels, isolated by Saussurean structural linguistics, and which generative grammar was to reconsider under the terms competence and performance, which are to a certain degree comparable. To this dichotomy, Saussure added:

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for speech, a principle of extoriety:
"the vocal organs are as exterior to language as the electrical apparatus that serves to transmit the Morse code is external to that code; and phonation, that is to say the process of execution of acoustic images, does not in any way affect the system itself." (Saussure, 1916, 1972 p. 36).

for language, a principle of superiority:
"In attributing to the science of language its true place in the whole study of language systems, we have at the same time assigned a place to the whole of linguistics. All the other elements of language, which constitute speech, by their very nature are subordinate to this first science, and it is thanks to this subordination that all of the different parts of linguistics will fall into their natural place. [...] The study of language is thus composed of two parts: one, which is essential, is concerned with the linguistic structure; the other, which is secondary, is concerned with the individual aspect of language, namely speech, including phonation." (Saussure 1916, 1972, pp. 36 and 37)

These two principles, cumulative in their effects, marginalised any attempt to reveal interactions between the broad tendencies observed in the phonological systems of the languages of the world – their universals – and the characteristics of the processes of production and perception. They isolated linguistics in a reductionist internalism and influence the presuppositions on which phonology was founded. On the threshold of the 21st century, certain currents (by no means the weakest) of contemporary linguistics and phonology are still characterised by a strong internalist stance, which is often presented as an asset, and goes as far as outright refusal to take into consideration hypotheses, models, and results highlighted by other work carried out in the framework of neighbouring disciplines that also have language and speech as their object of research (Saussure, 1916, 1972, p. 317, down to Milner 1983).

This refusal to compare evidence, reiterated throughout this century, is perhaps a unique example in the history of twentieth-century science: the testing of data and models, whatever their provenance, should form an intrinsic part of any scientific approach. This attitude helps to explain the position which phonology was to adopt from the moment it emerged, regarding the interplay between form and substance.

1.2 Form and substance: a separation imposed by phonology

1.2.1 A narrow theoretical frame

It is possible to put forward the hypothesis that the interaction, and essential tensions, between phonetics and phonology arise from the relation between form and substance (Boë, 1997ab). Since the beginning of the 20th century, the phonetic sciences have absorbed and extended the work developed in the study of speech in previous centuries, notably in physiology, acoustics, and psychology, whereas the phonology of the Prague School emerged as a continuation of Saussurean linguistics and transformed into the generativist framework.

Phonology has proceeded, in particular, according to two principles:
• the principle of linguistic arbitrariness, which consists in maintaining that the minimal units put to use by a language are founded on nothing other than their linguistic function, and have no independent existence outside the study of the linguistic system.
• the principle of value, according to which linguistic signs cannot be defined by absolute properties, but only with respect to their relative position within the system. Thus for Martinet (1957), the distinctive features used by a language cannot be described by a simple phonetic characterisation, since they are only defined by their relationship to other distinctive features in the same language.

According to such choices, phonological units cannot be defined other than within the system of which they are a part, and the question of their universality no longer arises.
1.2.2 Towards a new interplay between form and substance

With the appearance of Preliminaries to Speech Analysis (PSA) in 1952, Jakobson, Fant, and Halle established the foundations of a new conception of phonology and they can be credited with a veritable "resubstantialisation" of the field. To evaluate the innovative theoretical contribution of PSA, it suffices to compare the opposite of Saussure's proposals with the major points proposed by Jakobson, Fant, and Halle.

Directly or indirectly, all of their proposals lie at the origin of a very considerable amount of research on acoustic correlates and phonetic perception. Even if their proposed features – which are too general and poorly quantified – have not solved the problem of the transformation of form into substance, the process of discussion has revived the interplay that had been interrupted for almost two decades.

Generative phonology retained from PSA the idea of a universal system of binary features. In The Sound Pattern of English (SPE) in 1968, Chomsky and Halle replaced the traditional acoustico-perceptual specification by a phonetic representation, universal in scope, expressed in terms of more numerous articulatory features which were precisely defined and well-documented. This advance can be considered to be very important in the framework of phonetic description and the relationship between form and substance. It might have been expected that generativist phonologists could have propped up their work using articulatory verifications. In fact, the descriptive prolegomena of SPE have remained unfollowed, and the proposed features have not been used in phonological descriptions as part of a pure symbolic formalism, as the authors themselves stated (Chomsky & Halle, 1968, p. 274). To compensate for this fundamental absence of naturalism, Chomsky and Halle reintroduced the Theory of Markedness (inherited from the phonology of Trubetzkoy). More recently, Optimality Theory has proposed preserving those universal constraints which reveal the unity of language. For Prince and Smolensky (1993), the universal grammar is essentially composed of an ensemble of constraints, often conflicting, which regulate the well-formedness of representations from which individual grammars are constructed. These constraints are always active, and languages are then distinguished by the way in which conflicts are resolved; once again, however, it is necessary to proceed by criteria which do not reduce to simple tautology.

1.2.3 A substance-based linguistics

In fact, the Saussurean dogma taken up by Chomsky (1965):

"The classical Saussurean hypothesis of the logical priority of the study of language (and of the generative grammar that describes it) seems almost incontrovertible."

has not truly been called into question, except in 1972, with a new perspective that paved the way towards a whole new sweep of research; that of "substance-oriented" linguistics (Lijenerants & Lindblom, 1972).

It is in this perspective that we place ourselves, using recent work on the typology of sound structures, and trying to show that broad tendencies refer in part to constraints on production and perception, that is, to linguistic substance and not to linguistic form.

In order not to fall prey to the weaknesses of the inductive approach, which consists in inferring general laws from isolated observations – which can lead to the error of presupposing the conclusion – we adopt an epistemological framework which appeals to data that are external to phonological description: production and perception constraints to which it is possible to add data on ontogenesis and language disturbances (cf. Jakobson, 1942). Following this approach opened up by Lindblom, models currently permit the prediction of the broad tendencies observed in sound structure. It is thus possible to take a close look at the problem of structures and their changes systematically, to establish a precise diagnosis of what can be attributed to
production/perception, and to catalogue the questions which must instead be addressed to linguistics and sociolinguistics.

2. The constraints of substance on form

2.1 Prediction of the phonological structure of vowel systems: the DFT

2.1.1 General principles

Since the beginning of the 70s, several proposals have been made to predict the phonological structure of vowel systems with non-phonological principles, be they listener-oriented (perceptual contrast and stability) or speaker-oriented (articulatory contrast and economy). The so-called "sufficient perceptual contrast" theory (Lindblom, 1986) provides the best global fit with phonological data. However, to overcome its two main problems (that is, the excessive number of high non-peripheral vowels in the model predictions and the impossibility to predict the [i y u] series within the high vowel set), we proposed at ICP the Dispersion-Focalisation Theory (DFT) (Schwartz et al., 1997b). The DFT allows us to predict vowel systems through a competition between two perceptual costs: for a given number of vowels, the most frequent system in the world's languages is supposed to be obtained by minimising a global criterion combining a structural dispersion cost and a local focalisation cost.

2.1.2 Implementation

Each vowel is characterised by the formants of its spectrum, that is \( F_1, F_2, F_3 \) and \( F_4 \), expressed in a perceptual Bark scale. The \((F_2, F_3, F_4)\) set allows to compute an integrated "effective perceptual formant" \( F_2 \). The dispersion cost involves auditory distances between vowel spectra, computed through an Euclidean distance in the \((F_1, F_2)\) space, and favours large inter-vowel distances. The focalisation cost involves distances between consecutive formants within each vowel spectrum, and favours focal vowels, that is, vowels with close \( F_1 \) and \( F_2 \), \( F_3 \) and \( F_4 \), or \( F_1 \) and \( F_4 \). The model is controlled by two parameters: \( \lambda \) specifying the weight of \( F_2 \) in respect to \( F_1 \) in the dispersion cost, and \( \alpha \) specifying the respective weight of the focalisation cost relative to the dispersion cost.

2.1.3 Phase spaces

For a given number of vowels, from 3 to 9 (beyond this limit, vowel systems introduce a new dimension, mainly nasality and less often quantity, Vallée, 1994), we can predict, in the DFT framework, different vowel systems in the \((\lambda, \alpha)\) space. This leads to the determination of what we call "the phase space", a well-known procedure in thermodynamics used to predict the states of a substance (such as the states of water: steam, liquid and ice), as a function of pressure and temperature. The general trend is that, for a given number of vowels in a system, decreasing \( \lambda \) favours peripheral systems while increasing it favours systems with one and then two high non-peripheral vowels; and increasing \( \alpha \) favours focal vowels, and particularly stabilises [y] within an [i y u] high series, while this series is unstable when \( \alpha \) is set to 0.

Previous work allowed us to verify that these predictions were more or less compatible with the observed preferred phonological vowel systems in the UPSID\(_{31}\) database (Maddieson, 1984).

Considering that peripheral systems are generally preferred from 3 to 7 vowels and that the [i y u] series of high vowels exists in a significant amount of cases in the database (about 5% of the cases in the whole database, and 13% of the cases for systems with 7 vowels or more), we showed that setting the \( \lambda \) value around 0.2 - 0.3
and the $\alpha$ value around 0.3 - 0.4 led to quite acceptable predictions (Schwartz et al., 1997b). In the present work, we try to go one step further: we shall attempt to determine where in the phase spaces one can find the different systems, preferred or not, existing in UPSID$_{E1}$, and what kinds of "superstructures" can be derived from this analysis.

2.1.4 Structural symmetries between vowel systems: a typological equivalence criterion

2.1.4.1 Prototypical structures in phase spaces

Our previous simulations led to "prototypical systems". These are winning n-vowels systems in the DFT framework, in the sense that they have a minimal global Dispersion-Focalisation (DF) energy, according to the values of the two free parameters $\lambda$ and $\alpha$.

We have focused our study on values of $n$ from 3 to 7 because they allow us to capture the most significant phonological tendencies of the UPSID database. The DFT simulation results are given in Figures 1-5, respectively for $n = 3, 4, 5, 6$ and $7$. For each value of $n$, the phase space determines regions in the $(\lambda, \alpha)$ space in which a given system wins (with its vowel qualities displayed as black points on a prototypical grid). We see that there are two prototypical systems for $n = 3$, which we call $S_3T_1$ and $S_3T_2$. There are four prototypical systems for $n = 4$, $5$, $6$, and five prototypical systems for $n = 7$; let us call them $S_nT_i$, with $n$ from 3 to 7, and $i$ from 1 to 5. The global trend is that increasing $n$ increases the dispersion cost of peripheral systems, hence it decreases the $\lambda$ boundary necessary for making these systems optimal. Hence peripheral systems are favoured with small values of $\lambda$. When $\lambda$ is too small, the vowel space is completely vertically stretched (since higher formants play a minimal part in the determination of vowel phonetic quality); this favours asymmetrical peripheral configurations because of the interactions between front and back peripheral vowels in the systems. Non-peripheral configurations, that is systems with more than two high vowels, appear with large $\lambda$ values, and when $\alpha$ increases, focal vowels (especially [i] with close F$_3$ and F$_4$, other front unrounded vowels together with [y], all with close F$_3$ and F$_4$, and back rounded vowels, with close F$_3$ and F$_4$) are favoured. Decreasing $\alpha$ leads to replacement of the high rounded vowel [y] with a high vowel acoustically more central (namely [i] or [u]).

2.1.4.2 Reverse prototypical structures

We hypothesised that two structures having the same number of peripheral vowels but systematically replacing front unrounded vowels by back rounded ones with the same height, and vice-versa, are equivalent structures in the sense of DFT, that is to say that they have roughly the same DF energy for a given value of $n$ and of the $(\lambda, \alpha)$ pair. This was systematically verified by comparing the energy of the $S_nT_i$ prototypical systems with reverse systems that we called $S_nT_i*$. For example, for $n = 4$ we compared $S_4T_1 = [i o a a]$ with $S_4T_1* = [i e o a]$, and $S_4T_2 = [i 'e' a u]$ with $S_4T_2* = [i 'o' a u]$, $S_4T_3 = [i y u a]$ and $S_4T_4 = [i i u a]$ having no reverse counterpart. Indeed, we confirmed that $S_nT_i*$ structures have a DF energy quite close to the $S_nT_i$ ones whatever the region of the phase space, that is to say whatever the $\lambda$ and $\alpha$ values. Pushing the analogy with physics one step further, this reminds us of the "polymorphism" of a number of solids (e.g. metals, or crystals). In this situation, while fusion produces a homogeneous liquid phase, solidification leads to mixtures of two or more variants of the solid phase, all stable and more or less with the same energy. This is exactly what happens here with the two variants within a given phase. Hence we will consider in our typologies of phase spaces "superstructures" grouping prototypical structures and reverse ones (displayed with white points instead of black ones in Figures 1-5). The relevance of these superstructures for describing the UPSID database will now be discussed in the next section.
2.1.5 Comparing UPSID data with DFT simulations

2.1.5.1 UPSID data reanalysed

Since Trubetzkoy and his Principles (1939), taxonomy has not only been an approach of historical linguistics: associated to research on synchronic trends, it constitutes today a main stage in linguistic theories. Institutionalised in 1961, under the aegis of the Social Science Research Council during the New-York Conference on Language Universals, this research field aims at finding common basic structures in languages – in diachrony as well as in synchrony. The Language Universals Project (1967-1976) led to the building up of the Stanford Phonology Archives (Greenberg et al., 1978), with which many important studies dealing with typological classification and phonological tendencies, were achieved (Sedlik, 1969; Crothers, 1978 to Maddieson, 1984, Vallée, 1994). But all those studies present variegated contents: data are constantly enriched, questions on the materials vary from one author to the other: "A database designed to give more reliable and more readily available answers to questions concerning the distribution of phonological segments in the world's languages has been created as part of the research program of the UCLA Phonetics Laboratory". The UPSID (UCLA Phonological Segment Inventory Database) (317 then 451 languages) gathers phonological systems of languages in the world, sampling more or less uniformly all linguistic families. UPSID$_{317}$ (Maddieson, 1984), then UPSID$_{451}$ (Maddieson & Precoda, 1989) were chosen to approximate a properly constructed quota sample on a genetic database of the world’s existing languages.

UPSID was implemented at ICP several years ago and we have been using it for vowel and consonant research. In order to test our hypotheses, we have reanalysed the UPSID database of vowel systems, thanks to a two-step methodology.

The languages in UPSID have 3 to 28 vowels. First, from raw data, that is to say without any typological equivalencies, we obtain 252 types of phonological structures from 3 to 17 vowel qualities. What we call vowel qualities corresponds to “basic segments” (vs. “elaborated” and “complex” segments) in the sense of Lindblom & Maddieson (1988). We note that more than 96% of the languages have from 3 to 10 basic vowel qualities, and if we focus our study on systems with 3 to 7 qualities, we obtain 77% of the 451 languages (348 systems). This is due to the fact that there are in many cases more vowels than vowel qualities in a given system; for instance /i e a o u/ is the phonological structure of four UPSID languages of which three have more than 5 vowels: Chipewyan with 14 vowels /i e a o u i: a: u: i a: o: u: e: /, Siriono (12)/i I e ê a ã o õ u ê t/1, Tamang (10)/i e a o u j e a u /l. In the case of systems with nasal, laryngeal, pharyngeal or retroflexed vowels sharing no vowel qualities with a basic segment as in Chipewyan, we have decided to discard them for follow-up analyses. This results in eliminating less than 3% of UPSID’s languages and 3.4% of languages having from 3 to 7 vowels from our next analyses. This is equivalent to seven languages with 6 vowels qualities and five languages with 7 qualities, for instance the Cherokee system /i e ‘ë ‘ë a ‘o u/ or the Tarascan system /i i e a o u/. At this stage we retain 336 systems of the database.

Second, we take into account the so-called "transparency rule" (Schwartz et al., 1997a). This rule states that schwa should be conceived as a separate class, considering that it does not seem to interfere with the other vowels in a system: indeed, schwa added or removed from a system does not disrupt the structural organisation of this system. The "transparency rule" concerns 64 languages from 4 to 8 vowel qualities. For instance we have classed the Ivatan structure /i ‘o ‘o u/ as S$_2$T$_2$, Achumawi /i ‘e ‘o u/ as S$_3$T$_2$, Ndut /i e a o a o u/ as S$_6$T$_1$, and Fur /i e ‘o ‘o u/ as S$_3$T$_2$. The "transparency rule" results in slightly increasing the number of systems in the analysis, thanks to six 8-vowels systems which become 7-vowels ones. Hence at this last stage we stay with 342 systems (75.8% of the database).
2.1.5.2 Distribution of UPSID data within phase spaces

We now have at our disposal both a series of predictions organised around the typology $S_3T_1 / S_0T_1^*$ defined in Section 2.1.4, and an inventory of 342 systems (the three-fourths of UPSID$_{451}$) with 3 to 7 vowel quantities. The final goal of this work was to try to associate to most of these 342 systems a region in the phase space where they would be optimal (i.e. viable in the sense of the DFT). This is displayed in Figures 1-5, where we have plotted within each region of the phase spaces the number of systems fitting with the corresponding structure. Let us now discuss the obtained results in more detail.

First, it appears that 303 of the 342 3-to-7 vowel systems (88.6 %, or 67.2 % of the whole UPSID$_{451}$ database) fit with one of the $S_3T_1$ or $S_0T_1^*$ types. The 39 rejected systems (fitting with no prototypical or reverse type) correspond to one system in $S_3$; 5 in $S_2$, 9 in $S_1$, 10 in $S_0$, 14 in $S_1^*$; hence their number increases with $n$, which is logical since the complexity of the distribution of vowel qualities increases.

Second, the most widespread types in Figures 1-5 are those corresponding to $S_3T_1$ (and sometimes to $S_0T_1^*$). This provides a first confirmation on UPSID$_{451}$ of our results on UPSID$_{317}$ (Vallée, 1994), namely that the ($\lambda$, $\alpha$) region defined by $0.2 \leq \lambda \leq 0.3$ and $0 \leq \alpha \leq 0.4$ is compatible with preferred 3-to-7 vowels systems in UPSID.

But the data in Figures 1-5 provide some new confirmation of this result. Indeed, it appears that systems corresponding to types associated to large $\lambda$ or $\alpha$ values are quite few. On the contrary, most systems on Figures 1-5 are located at low $\lambda$ values. Indeed, apart from the "best" $S_3T_1$ structures, other structures generally occupy nearby regions (mostly of types $S_nT_1$ or $S_0T_1^*$) and if we define a broad acceptable region such as $0.1 \leq \lambda \leq 0.3$ and $0 \leq \alpha \leq 0.4$, we obtain a total of 293 systems, that is 85.6 % of the 342 systems of our inventory, which is quite important. Altogether, this confirms with a strong reliability the need to "stretch" the acoustic space along the F1 dimension in auditory spectral distances, which indicates the dominant role played by the lower formant F1 in vowels’ phonetic quality.

The next observation deals with the symmetry between front and back peripheral vowels. Globally, the data in Figures 1-5 confirm the well-known fact that vowel systems "prefer" both peripheral vowels and front-back symmetry. In the asymmetrical cases, when the numbers of front and back vowels are different, the (classical) trend is that there are more front than back ones: for example, $9 \ S_3T_1 [i \ o \ e \ a] \ vs \ 0 \ S_0T_1^* [u \ o \ a]$ structures, $8 \ S_3T_2 [i \ u \ o \ e \ a] \ vs \ 4 \ S_0T_2^* [i \ u \ o \ e \ a]$, $14 \ S_2T_1 [i \ u \ e \ o \ a] \ vs \ 10 \ S_0T_1^* [i \ u \ e \ o \ a]$ structures. When the number of front and back vowels are the same, the (less classical) trend is that front vowels have often a more open degree than back ones; though this is not true for 3-vowels systems ($2 \ S_3T_1 [i \ o \ e \ a] \ vs \ 0 \ S_0T_1^* [o \ e \ a]$ structures), it is clearly the case for 5-vowels systems ($4 \ S_5T_1 \ vs \ 16 \ S_0T_1^*$ and for 7-vowels systems ($0 \ S_7T_1 \ vs \ 2 \ S_0T_1^*$).

In what concerns focalisation, its role is more important for stabilising the vowel structures of larger systems, particularly those containing [y]; this vowel appears in only 2 % of UPSID’s languages from 3 to 7 vowel qualities, but almost 7 % of all languages; notice that more than half of them are Indo-European and Uralo-Altaic languages (Alcantara, 1998). In our simulations, /y/ is only present in the $S_3T_1 [i \ y \ u \ o \ e \ a]$ structure (3 examples, that is only 1% of our reduced database).
Figure 1: Phase space for three vowel systems. $S_{n\cdot T_1}$ structures have their vowel qualities displayed as black dots on a prototypical grid. $S_{n\cdot T_1^*}$ vowels are displayed as white dots replacing the black ones. The number in the oval is the total number of UPSID languages with the $S_{n\cdot T_1}$ and $S_{n\cdot T_1^*}$.

Figure 2: Phase space for four vowel systems.

Figure 3: Phase space for five vowel systems.
2.2 Consonant systems

Whereas we have clearly established a theory for the prediction of vowel systems, no similar theory for consonants seems to exist. Therefore we will first describe in detail a typology of consonants, and then suggest ways to explain some of the tendencies observed.

2.2.1 Typology

2.2.1.1 Taxonomic elements

Since the 1960's, typological works have dealt more with vowels than with consonants. This is partly due to the wide range of consonant inventory sizes and the large number of classification parameters that make type emergence difficult. Although the nature of some external constraints influencing the content of vocalic systems is coming to light (Schwartz et al., 1997a), we are still far from understanding the constraints influencing the consonantal systems of the world's languages.

Investigating existing languages is the traditional way to search for universal tendencies, but we also need to look at the question of the capacity to acquire relatively different linguistic systems. We present here a set of consonant inventory trends compared to available language acquisition data—more precisely, at the babbling stage. Indeed, among the different ontogenetic stages, babbling seems to be essential since it marks “precursors” of universal speech attributes, following MacNeilage’s Frame/Content theory (MacNeilage & Davis, 1990; MacNeilage, 1998).

Basically, our typological study is built on the places and manners of articulation, two very usual parameters in consonant classification. UPSID_{45} lists 920 phonemes with 654 consonant segments distributed across 13 places (Figure 6) and 16 manners.

![Diagram of consonant articulation places (UPSID_{45}).](image)

In our typology, manners have been grouped into 7 types: plosives (with implosives, ejectives, glottal stops); nasals; fricatives (with ejectives and h-sounds); affricates (with ejectives); approximants; trills/taps/flaps; clicks.

Compared to UPSID, our place classification, based on Creissels (1994) and Ladefoged & Maddieson (1996) is more detailed (17 simple articulation places and 5 double articulation places).

We have kept the retroflex category as a place, as suggested in Maddieson (1984), Ladefoged & Maddieson (1996) and the IPA (1996), though it refers to a manner: the distribution of retroflex consonants across their different places of articulation (alveodental, alveolar, prepalatal, etc.) would require an investigation of the sources of transcription.

We have to stress that making the comparison to previous taxonomies is not easy in so far as they all differ in their data preparation and classification methodologies.

2.2.1.2 Distribution

UPSID_{45} languages most often use from 18 to 25 consonants: minimum 6 for Rokotas (a Papuan language, 11 phonemes), maximum 95 (with 48 clicks) for !Xu (Khoisan family, 141 phonemes). The average size of consonant inventories is 22, with 7.8 plosives, 4.1 fricatives, 3.3 nasals, 2.9 approximants, 2 affricates, 0.6 ejective, 0.5 trill/flap, and 0.2 click.

Table 1 shows the distribution of consonants across the different places of articulation.

Regrouping all manners, alveodentals are the most numerous (15.3 %), followed by bilabials (14.3 %), and velars (12.6 %).
It is important to note that the coronal class (i.e. dental, alveodental, alveolar, postalveolar and retroflex consonants grouped together) represents far and away the largest class of segments, with 44.5% in UPSID_{317} far ahead of bilabials. Though the coronal class represents a wide range of articulation types (Ladefoged & Maddieson, 1996), its use in our typology is acceptable: in inventories, coronal place features seldom serve as phonological distinctions between consonants of this type, except for affricates, and never for anterior coronals (Keating, 1990).

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
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<tr>
<td>alveodental</td>
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<tr>
<td>bilabial</td>
<td>14.3%</td>
</tr>
<tr>
<td>velar</td>
<td>12.8%</td>
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<tr>
<td>palatal</td>
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<tr>
<td>apico-alveolar</td>
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<tr>
<td>glottal</td>
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<td>lamino-postalveolar</td>
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<td>uvular</td>
<td>1.7%</td>
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</table>

Table I: Frequency of occurrences for consonant articulation places from UPSID_{317} (Stefanuto, 1996).

The UPSID_{317} consonant distribution shows that some manners are more represented than others: plosives 38.6%, fricatives 20.2%, nasals 14.6%, approximants 13%, affricates 9.6%, trills/taps/flaps 3.9%. Voiceless oral coronal plosives (type /l/) are the most frequent (they are present in 97.5% of languages); bilabial and coronal nasals (types /m/ and /n/) exist in more than 9 languages out of 10; /t/, /t̪/, /l̪/, /t/ exist in more than 80% of languages; /w/ and /s/ in 2 out of 3 languages; /d/, /b/, /h/, in more than 60% of languages; one language in 2 has /l/, /g/, /y/, /l/.

2.2.1.3 Systems

* Size of articulation place systems per articulation manners

If the study of the size of consonant inventories gives very little information about their content, contrary to vowels (Schwartz et al., 1997a), the development of a place/manner typology reveals a strong correlation between (i) the size of place systems and (ii) the different articulation manners (Table II).

* In the majority of languages, plosives occupy, respectively, from 3 to 6 and from 1 to 6 places. The plosive manner is the only one that sound systems universally exploit. Moreover, it is also the only one that systematically uses place contrasts: languages distinguish at least 3 of them. Compared with fricatives, stops (including nasals) are almost always more numerous (see Figure 7).

* Fricatives and approximants are the consonant classes which recruit the greatest number of place contrasts: fricatives are more widely distributed on the different system sizes. Fricatives have systems of contrasts often more complex than plosives. 8% of languages do not show them (vs. plosives, which are universally used).

* For trills, flaps and taps, systems hardly ever present a place contrast – and never spread over more than 2 places. We find the same trends in affricates.
Table II: Size of the place systems in UPSID_{317}.

The number of place oppositions changes according to the manners, from 0 (i.e. 1 place per system) to 28 (8 places). The presented values do not include the voicing feature. 43.2% of the 317 languages have a 4 place plosive system, and 49.8% have approximants spreading on 3 places.

More broadly speaking:

- Languages systematically use place contrasts for plosive consonants; almost 1 language in 2 distributes its plosives in a 4 place system.
- Place contrasts are rare for affricates, and exceptional for trills/taps/flaps.
- Approximants frequently spread among 3 articulation places.
- Fricatives spread more widely across the different sizes of place systems.

Figure 7: Quantity of fricatives regarding quantity of stops plus nasals in UPSID_{451}’s phonological systems.

The line corresponds to languages with an equal number of stops plus nasals and fricatives.
Place systems for each manner

Table III reports the content of place systems for each manner. It presents the spreading of plosives, nasals, fricatives and affricates according to the number of articulation places.

<table>
<thead>
<tr>
<th></th>
<th>0 place</th>
<th>1 place</th>
<th>2 places</th>
<th>3 places</th>
<th>4 places</th>
<th>5 places</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>plosive</em></td>
<td>0%</td>
<td>0%</td>
<td>0.2%</td>
<td>31%</td>
<td>43%</td>
<td>21%</td>
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<td></td>
<td>velar</td>
<td>velar</td>
<td>glottal</td>
<td>glottal</td>
</tr>
<tr>
<td><em>nasal</em></td>
<td>3.5%</td>
<td>1.8%</td>
<td>31%</td>
<td>32%</td>
<td>27%</td>
<td>3.5%</td>
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<td>palatal</td>
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<tr>
<td><em>fricative</em></td>
<td>7%</td>
<td>6.6%</td>
<td>18%</td>
<td>28%</td>
<td>20%</td>
<td>11%</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td><em>affricate</em></td>
<td>33%</td>
<td>42%</td>
<td>20%</td>
<td>4.9%</td>
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Table III: Consonant categories (plosives, nasals, fricatives, affricates) from UPSID\(_{451}\) are classified according to the number of articulation places, with the percentage of corresponding languages (e.g., 31% of 451 languages present a plosive system spread over 3 places, etc.; 0 place means an absent category). Only the dominant systems are noted.

There is neither a phonological system without plosives, nor a system with only one. When a system distributes the plosives across 2 places, these places are coronal and bilial. Among 3 places, they are coronal, bilial and velar. The glottal place appears in 4 place systems. Systems with 5 places recruit bilial, coronal, velar, glottal and uvular consonants.

If there is only one nasal in a system, it is a coronal one. If the system has 2 nasal consonants, they are bilial and coronal. A velar nasal appears in 3 place systems. In larger systems (4 places), the palatal articulation emerges.

When the fricatives of a system use only one articulation place, they are alveolar, i.e. coronal. When 2 places are used, they are coronal (alveolar) and glottal. In 3 place systems, labiodentals appear; in 4 place systems, the palatal area is exploited, and in 5 ones, velar fricatives emerge.

As for affricates, they use coronal articulation areas, whatever the place system size (from 1 to 3). On the basis of these place system distributions per category, we can retain the following trends:

- as for vocalic systems (Schwartz et al., 1997a), a n-element system contains a system with n–1 consonant places,
- when there is only one place, whatever the category (plosive, fricative...), coronal consonants are at stake,
• one can mention a possible link between the dominant tendencies of the place systems and the degree of articulatory "complexity" of the segments according to Maddieson (1984) and Laver (1994): "complex" segments (e.g. affricates, trills/taps/flaps) use almost exclusively the coronal area whereas "simple" segments use varied places.

• 95% of the world’s languages contrast with 3 places within the categories (more than 1 language out of 3 for nasals).

• A particular system size dominates each category: 43% of the languages have 4 places for the plosives and 74% have 3 or 4 places; 32% of the languages distribute their nasals on 3 places (59% on 3 and 4); 28% present 3 places for fricatives (48% on 3 and 4); 43% have only one articulation place for affricates.

• Combinations with 5 places exist in only 36% of the languages, mainly for oral plosives (97 languages).

• Combinations with 6, 7 or 8 places are not widely used (15% of the languages). We essentially find them in African systems.

Our results (i) confirm that plosives are far and away the "star consonants", ubiquitous in languages, and (ii) bring to light trends that appear very regular.

• Voiced/voiceless ratio

Within the oral plosive category, voiceless sounds (64%) are a lot more numerous than voiced ones. Whatever the articulation place, the voiceless feature concerns 72% of fricatives. Voiceless affricates are also dominant (74%).

2.2.2 Universal trends and ontogenesis

We have gathered the results of several studies on consonant content of production at different stages of canonical babbling (repetition of identical syllables) or variegated babbling (with different types of closures) – the latter being contemporary with the former (Vihman, 1996).

All of these studies cover a period from 6-10 (Boyd-Bardies, 1996) to 15-24 months (Stoel-Gammon, 1985), for 15 languages including American English and French. Boyd-Bardies found that [p b m t ð n k ð n] constitute 80% of consonant-like productions during the first months of babbling, [p b m t ð] being the most frequent. The review of papers by Locke (1983) gives, by descending order of frequency, the inventory of consonants representing 95% of occurrences produced by children aged from 6 to 15 months of age: [b] and [m], [p], [d], [h] and [n], [t], [g] and [k], [j] and [w], [s]. Robb & Biele’s observations (1994) during a longer period (8 to 25 months of age) show that, for children aged from 8 to 12 months, several types of closures co-emerge. The most frequent productions are the plosives (oral and nasal) in alveolar and bilabial places. They thus confirm Davis & MacNeilage (1994), who showed that during 7-12 months of age, these consonant-like sounds cover 84% of infants’ utterances ([t] [d] 46%, [n] 18%, [p] [b] 15%, [m] 5%); velars and glottals are the last to appear. Some of this experimental evidence has also been corroborated by simulations using linear middlantial articulatory models developed for three different subjects: Vilain et al. (1999) found that pure mandibular raising, all other articulatory commands being frozen, leads to bi-labial, labio-dental or alveopalatal contacts, but never to velar contacts (also Abry et al., 1997).

If one draws a parallel between the results on language acquisition and typological data, one finds that the types of closures produced during the first months of babbling (8-12 months of age), as well as sounds acquired later during the second year, correspond to the consonant phonemes most frequently used in languages (apart from the order of emergence). One also finds that the preferred place systems, as shown for each manner in
typological analysis, are dominant in the production of babbling: alveolar and bilabial before velar and glottal in the plosive manner (oral or nasal); alveolar and glottal in the fricative manner; labiovelar, coronal and palatal in approximants ([l] and [j] being acquired later, at around 13-16 months of age (Robb & Biele, 1994). All in all, we thus note that the consonant-like sounds produced during babbling's mandibular oscillations correspond to the most frequent consonant inventories of the world's languages — in particular, they tightly correspond to languages with small inventories (Stefanuto, 1997).

These findings allow us to form the hypothesis that the consonant sounds of languages are, most probably, drawn from the stock of potential abilities of babbling. Locke & Pearson (1992, p. 26) did not hesitate to conclude: "Infants heavily favor stop consonants over fricatives, and there are languages that have stops and no fricatives but no languages that exemplify the reverse pattern. [Such] "phonologically universal" patterns, which cut across languages and speakers are, in fact, the phonetic properties of Homo sapiens." Ontogenesis thus clearly contributes to supplying some determining elements in the dependencies between certain general tendencies of phonological systems and the sensorimotor abilities of Homo loquens.

2.2.3 Hints towards explaining main tendencies

2.2.3.1 Plosive vs. fricative consonants predominance

Plosive consonants are characterised by the occurrence of a complete occlusion of the vocal tract somewhere between the glottis and the lips (Ladefoged & Maddieson, 1996; Crystal, 1997; Stevens, 1998). The main mechanism underlying the production of plosives is the generation of an impulsive acoustic source associated with the sudden release of the occlusion (Pelorson, 1997). From the point of view of control, the main requirement for the articulators is thus to ensure a proper occlusion: this is achieved by aiming at a virtual articulatory target that would be located beyond the actual vocal tract boundaries. For instance, in the case of the production of an apico-dental plosive, the tip of the tongue could be assigned a target that would be located slightly above the surface of the hard palate in the alveolar region: this would result in a full contact between tongue and palate, and thus ensure the complete occlusion of the vocal tract. This strategy has successfully been implemented for plosives (Bailly, 1997). It is important to note that this type of strategy does not require a precise control of the articulators: in a first approximation, a broadly defined target, as far as it is set beyond the physical limit of the involved vocal tract boundary, can ensure the realisation of the occlusion.

The situation of fricative consonants is quite different. Fricatives are characterised by the presence of a constriction somewhere in the vocal tract. This constriction induces a local acceleration of the air particle velocity that in turn induces, in conjunction with the shape of vocal tract, turbulence, and thus produces acoustic friction noise sources (Shadle, 1990; Badin et al., 1995; Stevens, 1998; Mawass et al., 2000). The generation of noise is precisely related to the size of the constriction, and in particular to its minimal constriction area. Specifically, if the constriction area is too small, the vocal tract will behave as in the case of plosives; on the other hand, if the constriction area is too wide, no frication noise will be generated and thus an approximant, or frictionless continuant, will be produced.

It appears thus clearly that articulatory control requires a much higher degree of precision for the production of fricatives than for the production of plosives. This fact constitutes indeed an important argument for the explanation of the preponderance of plosives over fricatives in the languages of the world.
2.2.3.2 Voiceless vs. voiced fricatives' predominance

Most fricatives and plosives in the world's languages can be voiced or voiceless. Before discussing issues about voicing, let us state again the basic principles underlying the generation of both voice and frication acoustic source for fricatives. The presence of voicing, i.e. of vocal fold vibration, is mainly controlled by an average pressure drop across the glottis and by vocal fold adduction (or glottis area at rest) (cf. e.g. Pelorson et al., 1994). In turn, the pressure drop across the glottis depends on both the glottis area and the geometry of the entire vocal tract. Note in passing that the control of the frequency of vocal folds oscillations is more specifically, but not only, associated with vocal fold length. Finally, the generation of frication is essentially governed by the oral constriction area and by the pressure drop across this constriction (Badin et al., 1995; Stevens, 1998).

The coordination between glottis and oral constriction gestures plays thus a crucial role for acoustic excitation sources in the vocal tract, as has been widely recognised and discussed in the literature (e.g. Scully, 1971; McGowan et al., 1995; Badin et al., 1996; Stevens, 1998). From an aerodynamic perspective, the vocal tract can be viewed as two lumped constrictions between which the subglottal pressure is distributed (cf. e.g. Badin et al., 1996; Mawass et al., 2000). Although some refinements could be brought to this crude approximation (cf. Pelorson et al., 1994), it is expected that the discussion below will remain valid.

Denoting by $A_g$ the low frequency component of the glottis area, and by $A_c$ the oral tract minimum constriction area, the pressure drops at the glottis $\Delta P_g$ and at the constriction $\Delta P_c$ are given by the following equations:

$$ P_s = \Delta P_g + \Delta P_c, \quad \text{with} \quad \Delta P_c = \frac{\rho}{2} \frac{U^2}{A_c^2} \quad \text{and} \quad \Delta P_g = \frac{\rho}{2} \frac{U^2}{A_g^2} $$

where $P_s$ is the subglottal pressure, $\rho$ the air density, and $U$ the constant volume flow velocity. It is also known that the amplitude of voicing increases with $\Delta P_g$ and reaches a maximum for a given $A_g$ depending on $\Delta P_g$ (Stevens, 1998), while the amplitude of the frication noise source is proportional to $\Delta P_c P A_c Q$ (Badin et al., 1995).

It follows that, for a given subglottal pressure, simultaneously increasing voicing and frication amplitudes is contradictory: a balance must necessarily be found for voiced fricative consonants. Preliminary perceptual tests, where the ratio between voicing and frication noise amplitude was varied, showed that the consonants in synthetic vowel-fricative-vowel sequences were deemed acceptable voiced fricatives when the ratio was less than 12 dB (Mawass, 1997). Therefore, simulations performed with a complete vocal tract model, including a simplified aerodynamic model (Badin et al., 1996), were used to determine, for a simplified [f] articulation, the region of the $[A_g/A_c]$ control space where balance between voice and frication noise levels is reached within 12 dB (Mawass, 1997; Abry et al., 1998). The boundaries of this region, schematically drawn from the original simulation data are shown in Figure 8. This region where the combinations of $A_g$ and $A_c$ values results in a balance between the voice and noise components is indeed very narrow: a rather strict coordination between the glottis and the oral constriction is therefore needed to produce acceptable voiced fricatives (cf. also Mawass et al., 2000). As already noticed by Ohala (1983) on qualitative grounds, this observation contributes to the explanation of the lower proportion of the voiced fricatives in comparison with the voiceless ones in the world's languages (Stefanuto & Vallée, 1999).
3. Conclusion and perspectives

A whole collection of data gathered during the course of the second half of the 20th century has progressively rendered untenable the principle of strict independence of form and substance. Languages do not construct their sound systems from "amorphous" materials, to quote a Saussurean expression. Entirely on the contrary, typological analyses carried out on phonological data that have been collected, standardised, and organised, indicate according to current evidence that languages, from whatever linguistic family, do not exploit the possibilities of the vocal tract, auditory and visual systems arbitrarily to organise their phonological structures (whether this be the sign of a feature, the choice of that feature, the recruitment of phonemes, or the nature and organisation of syllables). Models that take production and perception constraints into account permit the prediction of broad tendencies and variants for vowel systems. The correspondence between the consonantal phonemes that are most frequent in the languages of the world and the consonants that are most often produced during the first stage of babbling, whatever the language of the infant's native environment, permits the proposal of the hypothesis that the consonant sounds of different languages are undoubtedly drawn from the stock of potential babbling capabilities.

The phonological typologies and universal tendencies that have been observed are unrelated to the linguistic families which served as the basis for the UPSID sample, currently the most representative database of sound structures. It is even more noticeable that certain features (rounding, length, nasality) are associated with certain families or rather with certain geographical areas. This can only confirm that typological classifications
of sound structures and genetic classifications according to linguistic family are far from being identical, and that typology exhibits geographical tendencies. It is likely that statistical properties over the course of time, within a predetermined zone of the linguistic space, reflect the same constraints as the current general distribution, more or less, and that, as regards certain features, fluctuations of systems in neighboring zones are produced more or less in phase. One of the interesting inferences that can be drawn from this lack of correlation is that the general tendencies of linguistic systems could depend on the material nature of the sound structures of language; it seems that it might be possible to find confirmation of this in ontogenesis, reinforcing the hypothesis that there might exist "phonetic properties of Homo Sapiens".

Substance-based linguistics is an old dream for phoneticians, expressed in the most vigorous and brilliant terms more than twenty years ago by Bjorn Lindblom, until his recent formula: "derive language from non-language." Vowel system prediction undoubtedly provides the most obvious success in this program. It is now possible to use a theory based on local and global perceptual (namely "non-linguistic") arguments, a computational framework, and a quantitative methodology.

The Dispersion-Focalisation Theory (DFT) allows the prediction of vowel systems thanks to competition between two perceptual costs; the associated "phase spaces" determine the DFT winner in this space. We derive from the comparison between experimental phase spaces and UPSID data a region for which the theory predictions fit quite well with the phonological inventories. We have proposed an additional ingredient in our modelling phase-space framework, with the notion of polymorphism of a given phase, or superstructures in phonological organisations. Thanks to this new ingredient, we were able to obtain important results. A next step should consist in adding 8- and 9-vowels systems to the present analysis. Indeed, our analysis of raw UPSID_{451} data demonstrate that more than 9 languages out of 10 (91.5 %) in the database contain 3 to 9 vowel qualities. The difficulty however is that phase spaces become increasingly complex with such a large number of vowels.

But whatever the feasibility of this next step, we believe that the present results provide a new illustration of the convincing ability of substance-based theories, from Stevens' Quantal Theory and Lindblom's Dispersion Theory to ICP Dispersion-Focalisation Theory, to produce realistic predictions and useful typologies, at least for vowel systems.

The typology of consonant systems also shows that languages only use a small inventory of consonants even though they potentially dispose of a considerable number of possibilities. The place systems "preferred" by each manner show that languages' choices are at least partly conditioned by the morphological constraints that facilitate or complicate, make possible or impossible, the articulatory gestures according to the places, e.g. the complexity of the articulatory control of voiced and aerodynamics of fricatives. Although pleading the cause of a non-substantialist linguistics, Trubetzkoy conceded in 1939 (1970 p. 135): "This fact cannot be ascribed to chance, and must be deeply rooted in the nature of the three series in question."

But to see further, it is in the frame of the syllable, associating consonants and vowels, that one must elaborate and test the models predicting general trends of sound structures.

MacNeilage's theory, that he describes as a basic principle influencing the very structuring of speech itself, separates the frame level (syllabic) and the content one (segmental). The nature of mandibular pure frames in the canonical babbling stage is placed by MacNeilage in a labial frame. This hypothesis has been tested with 3 individual articulatory models. We think it should rather be placed in a mandibular coronal frame coupled with a visual bilabial frame — which could explain the [g]/[b] coemergence in babbling. This is supported by arguments from articulatory simulations and by our typological arguments on the world's languages.

Almost 30 years after Lindblom's and Liljencrantz's proposition, the viability of the project of a substance-oriented linguistics seems to be confirmed. Speech is by nature an interdisciplinary object of research, lying at
the crossroads of several sensorimotor systems involved in the production and perception of biological communication signals, and of a major human competence, the faculty of language. Around this particular object of research have arisen groupings of several disciplines (ranging from acoustics, even fluid mechanics, to phonology and phonetics, while traversing biology, psychology, and information processing), placing speech at the centre of research that is as much fundamental as it is applied. All of the mutations that phonetics has undergone have provoked a reorganisation of the scientific connections between the phonetic sciences and adjacent disciplines. New interactions are clearly underway between linguistic science, cognitive science, and certain sectors of the physical and engineering sciences.

One can therefore remark upon the current trend towards "laboratory phonology" which tends to combine experimental phonetics, experimental psychology, and phonological theory (Ohala & Jaeger, 1986). This approach aims to subject hypotheses of phonological organisation to the kinds of validations used in the experimental sciences, which has been lacking to date in generative phonology. At the end of this century, certain phonologists are thus clearly revising their positions:

"Beyond the differences which traverse it, the current phonological movement tends to give an objective status to the entities which are isolated by analysis. The question of substance, which has for so long been taken to be a secondary issue, only just likely to arouse the interest of certain empirical spirits (phoneticians), is the subject of a renewal of interest. [...] The anchoring of the reality of phonological systems in substance now appears to be an indispensable means for thinking of phonology as an interface between physical objects and phonological entities." (De natura sonorum, Laks & Plénat, 1993).

In France, with the Current Trends in Phonology meetings, conceived and organised by Jacques Durand and Bernard Laks in 1995 (Durand & Laks, 1996) and 1998 (to be published), a real space for exchange between phonology and phonetics has been established. The materialisation of sound structures is in process. Phonetic knowledge can thus explore and make precise the natural constraints that all phonological theories must respect in order to satisfy concerns of (neuro)physiological plausibility. The reintegration of phonology into the natural order of things needs no longer involve a subordinate relationship between the two disciplines.

References


