



Biology matters: Variation in vocal tract anatomy and language

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Abstract

There are about 7,000 or so languages currently used, and they vary in myriad ways at all their levels. We argue here that part of this cross-linguistic diversity might be explained by factors that are external to language itself, but which differ between groups of speakers and to which language adapts. In particular, we present evidence that there is widespread variation between individuals and groups in what concerns the anatomy of the vocal tract, variation that results in biases (that generate constraints and affordances) which may affect phonetics and phonology. We propose that factors such as the frequency of the biased speakers, their status and position in the communicative network of a speech community form a pool of standing variation which interacts in complex ways with the community's language and may result in the community-wide amplification of such biases. While more work is necessary, we suggest that these processes play a role in explaining the observed linguistic diversity.

Keywords: linguistic diversity, language change, vocal tract anatomy, articulatory phonetics

1 Introduction

Where do the 7,000 or so present-day languages (Hammarström et al. 2018) come from? Why are we seeing a number of languages on the order of a few thousands, and

not either of the (logically possible) extremes of one (i.e., a single, universally shared language that everybody on the planet understands) or a few billion (i.e., one or more languages per person, individually unique and mutually un-intelligible)? While the two extremes can be relatively easily ruled out, as language (as we understand it) would not be of much use unless shared by a group bigger than one individual, on one hand, and transmission errors and barriers to communication due to geography and culture ensure the steady divergence of languages, on the other, it is less clear why we don't see a few tens, a few hundreds, a few tens of thousands, or millions of languages¹ (Dediú et al. 2013). It may very well be that this currently observed number is an accident of history (the spread of a few large families in the last thousands of years) or that such an order of magnitude is an attractor resulting from complex interactions between the size of human groups sharing a language in a given ecological, technological and cultural context (Nettle 1999), the geography and ecology of the earth, and historical contingencies.

What seems generally agreed upon is that language *change*, language *divergence* and language *contact* (Campbell 2004; Dediú et al. 2013; Thomason & Kaufman 1988) are unavoidable realities of life, producing a rich network of differentiation and convergence between the world's languages. Most of these changes are driven by *language-internal* processes, as studied in detail by historical linguistics (Bowerman & Evans 2014; Campbell 2004), whereby patterns at all levels of language (including phonetic-phonological, morpho-syntactic, semantic and pragmatic) are continuously innovated or lost, and may spread to the whole speech community or fail to do so due to properties of the language itself or its socio-linguistic context.

However, a rather neglected possibility is that some of the drivers of change are *external* to the (socio-)linguistic system and, as opposed to the language-internal factors, which are in a fundamental way neutral (or random), are *adaptive*. Here, adaptation must be understood in the wider context of *cultural evolutionary* approaches (Cavalli-Sforza & Feldman 1981; Croft 2008; Richerson & Boyd 2008; Richerson & Christiansen 2013) which see culture (and, in particular, language) as a full-blown evolutionary system which may respond to pressures from its environment by becoming better at functioning in that environment. Such adaptive pressures may

¹ However, this also depends on how one defines a language in the abstract as well as on the specific practical issues of cataloguing and counting languages.

come from the physical environment (for example, air humidity), the socio-cultural environment (e.g., the percent of non-native speakers in the community) or, as we will argue here, the biological environment (namely, aspects of human anatomy, physiology and neuro-cognition). The language may respond to such pressures by changing in ways which enhance its use and/or transmission given the pressures. If the pressures are uniformly spread across the Earth (i.e., they are equally shared by all language users), then they should result in *language universals* or *universal tendencies* (a topic of interest since at least the mid of last century), but, if their distribution is not uniform – a possibility much less seriously considered until recently – then we should see the emergence of patterns of *linguistic diversity*.

This opinion paper is structured as follows: first, we will overview a few examples of extra-linguistic biases (rooted in the physical environment and cultural practices) that may shape languages. Then, we will argue that human biology, and in particular the perception and production systems, may play a much bigger role than assumed; in the process, we will clarify the observed patterns of human biological diversity and we will argue that, far from promoting racism and discrimination, openly discussing the distribution and causes of diversity are the best cure against such evils. We will focus on two examples, one linked to infections of the middle ear, and the second to the anatomy of the anterior part of the mouth. Finally, we will discuss the nature of variation, from the “normal” to the “idiosyncratic” and the “pathological” and how such variation may be sometimes amplified by cultural evolution in structured communities of non-identical speakers.

2 The physical environment

It is an almost trivial observation that certain aspects of the environment inhabited by humans are universal and shape language and speech in fundamental ways: for example, the sound transmission properties of air affect all spoken languages. But our focus here is on factors that *differ* between human groups and that may plausibly drive *adaptive* difference between the languages of those groups. Thus, while geographical location trivially differs between groups (i.e., humans tend not to live on top of each other but rather within spatially extended, relatively fluid, territories) and drives linguistic divergence, it cannot be said that this divergence is adaptive (except,

perhaps, as a group marker, but even then the particular aspect(s) of language chosen are more or less arbitrary). However, geographical location is associated with other characteristics, such as altitude, climate, distance to water, and other ecological variables, characteristics that may differ (or be similar) between groups (e.g., two groups in the Alps just a few kilometers apart might live at very different altitudes and ecological zones, while a group in the Alps and one in the Himalayas might experience similar altitudes and ecologies). Concerning *altitude*, it has been argued (Everett 2013) that languages spoken higher up (as opposed to languages spoken in the lowlands) tend to feature *ejective sounds* more often in their inventories, an observation supported by statistical analyses but also by aerodynamic and articulatory arguments (essentially, air pressure is lower at higher altitudes, and lower air pressure reduces the effort needed for compressing air in the supralaryngeal cavity during the production of ejectives²). Climate also differs between geographical locations, and one important component of climate is *air humidity*: air dryness has recently been linked to an absence of *tone* distinctions (Everett et al. 2015, 2016) and, more generally, to less reliance on *vowels* (as opposed to consonants) (Everett 2017). Here, besides the statistical cross-linguistic association, the mechanism proposed is that dry ambient air increases the desiccation of the vocal folds and reduces thus the degree of their control (Everett 2017; Everett et al. 2016). Finally, geographical location (and altitude and climate) result in different ecological environments in which humans live and communicate and to which languages must adapt. For example, Coupé (2017) and Maddieson & Coupé (2015) suggest that *dense vegetation*, heavy rainfall and high ambient temperatures are associated with a reduced number of *obstruents* because dense vegetation affects the speech sounds and in particular of consonants.

No matter how these proposals (and others, not mentioned here) withstand the passage of time and further testing³, we can see that they share a basic pattern of argumentation: a component of the physical environment, that plausibly could influence certain aspects of language, differs between groups of speakers whose languages vary in ways that may reflect these differences. The mechanism is represented by the language “adapting” to these differences, either by “avoiding” *constraints* (e.g., avoiding ejectives at low altitude or tones in dry climates) or,

² A different argument adduced concerns the fact that ejective use results in less water vapor loss during speech.

³ See, for example, the exchange in the first issue of the *Journal of Language Evolution* concerning the climate – tone hypothesis (Everett et al. 2016).

complementarily, by “exploiting” *affordances* (e.g., using ejectives at high altitude or more vowels in dense vegetation) resulting from these environmental factors in *interaction* with human biology (e.g., articulatory mechanisms). This is similar to processes in evolutionary biology and takes place through time, either across generations of language transmission (Kirby & Hurford 2002) or on the much shorter timescales of repeated linguistic interactions (Dediu et al. 2013; Dediu & Moisik under review). Crucially for our discussion here, what varies is the environment; the language users themselves are seen as being essentially identical.

A slightly different take is represented by recent work (Bentz et al. 2018) where we investigate the *phylogenetic signal* of longitude, latitude, altitude, climate, distance to water and population size in many language families across the world, and we find that, while there is variation across families, the hypotheses of *independent evolution* can be rejected for most variables and families, that *neutral evolution* (or drift) fits some cases, but that most do not fit either. What this means is that, in general, languages diversify non-independently from their environment and, thus, that the distribution of linguistic diversity cannot be understood by abstracting away from this environment: humans preferentially disperse across space (for example, to climates to which their agricultural practices fit) and they (and their languages) further adapt to these environments.

3 The socio-cultural environment

A very interesting case of extra-linguistic factors affecting language is represented by the influence of *community size* on linguistic complexity (Lupyan & Dale 2010, 2016). Various proposals might, in fact, be related to this, starting with the distinction between *esoteric* and *exoteric* languages (Wray & Grace 2007), where languages of the first type are mostly used for within-group communication, being very complex, while the second for communication outside the closed group, being simpler. Lupyan & Dale (2010) have shown that there is a cross-linguistic statistical association between the number of speakers of a language and the language’s morphological complexity; this association was further supported by computational modeling (Dale & Lupyan 2012). This is probably due mainly to the different properties of *child language acquisition versus adult language learning* (Dale & Lupyan 2012; Lupyan

& Dale 2016), with the first making possible complex, irregular paradigms, while the second being strongly biased against them. Thus, speaker population size would represent a proxy for the proportion of second language speakers a language has.

It is important to point out that, in this case, factors that have nothing with the language itself do nevertheless affect important properties of language; second, here the *language users differ* (some being native speakers, others being adult second language learners presumably with varying degrees of command over the second language) and it is precisely these differences that drive language adaptation. However, even in this case, these between-speaker differences are *circumstantial* (or accidental) in the sense that there's nothing setting, say, John and Pierre apart except that the first happened to grow up speaking English natively and the second learned it (imperfectly) much later in life, with the interaction between them pushing English to simplify in certain ways.

4 Inter-individual and inter-group variation

However, humans are not clones and we differ in myriad ways at all levels in almost all respects one cares to study. For example, we patently differ in the details of our *genetic* and *epigenetic* makeup (and even “identical” twins do; (Czyz et al. 2012)), we differ in the way we react to drugs (Tracy et al. 2016), in how we may get addicted to smoking or alcohol (Benowitz 2009), in height (Allen et al. 2010) and risk for disease (McCarthy 2008), to mention just a few. These differences, far from being “noise” or “imperfections” resulting from the use of “sublunary matter” to instantiate some perfect Platonic archetype of humanity, are, to the contrary, the “spice of life” and – as clearly understood since Darwin – how life actually works, by allowing organisms to adapt to a continuously changing environment.

Most inter-individual variation affects *continuous* (or metric) characteristics that differ in degree between people (such as height or the rate of metabolizing a drug), but also *discrete* characters may be concerned (say, presence/absence of wisdom teeth). Sometimes such variation seems to be distributed at random between people, but, in most cases, it is *patterned*. Just to focus on body *height* (Durand & Rappold 2013; Silventoinen 2003; Visscher et al. 2010; Wood et al. 2014), its distribution across a large enough population is normal (*gaussian*), with the extremes usually

considered as pathological. While the distributions of height in the two sexes overlap, there is nevertheless a statistical difference between the two, with the males tending to be slightly taller than females⁴ (but see Schilling et al. (2002)). Likewise, there seem to exist statistical differences in height between human populations, but this picture is complicated by the environmental influences on height (e.g., nutrition, hygiene and access to health care) that have resulted in so called *secular trends*⁵. Moreover, we now understand that height has a strong *genetic component* (Yang et al. 2010) and we even know *hundreds of genetic loci*, most having a tiny contribution to height individually, but adding up to explain a sizeable proportion of the observed variation (Visscher et al. 2010; Wood et al. 2014). Thus, what makes height such an instructive example for us here is that even if it has a strong (and relatively simple) genetic foundation, it is nevertheless affected by the environment (even across generations) and it shows *statistical inter-individual and inter-group variation*.

Discussing such variation has long been perceived as dangerously close to supporting *racism*, *sexism* and other forms of *discrimination*, generating parallels to eugenics, 19th century hierarchies of human “races” and 20th century apartheid policies, and being effectively banned (or at least strongly discouraged) from the scientific discourse. However, we, together with other scientists (see, for example, the very recent and lucid discussion in (Reich 2018)), argue that this is precisely the wrong approach for several compelling reasons. First, as briefly discussed above, humans do differ, and, as scientists, we have a primary duty to describe nature as it is and not as (we think) it should be. Second, we should celebrate human diversity and see it for the positive force it is⁶. Third, actually, the patterns of human diversity we see out there are one of the most powerful refutations of racism and discrimination, as we see that most of this variation is continuous, gradual, multidimensional and overlapping, resulting from a complex interplay of forces and the continuous movement and admixture of humans throughout our existence⁷. Fourth, we should

⁴ Which does not mean that all (or most) males are taller than all (or most) females, nor that there aren't many females taller than many males.

⁵ The consistent increase in height across generations in a population, usually associated with North American and Western European countries, but now visible in Asian and Southern European countries as well (Chen & Ji 2013; Cole 2003; Larnkaer et al. 2006).

⁶ Denying diversity has systematically produced monsters, such as the various communist, fascist and religious conservative regimes forcing everybody to be “the same”, identical and replaceable units, having passed through deadly versions of the Procrustes's bed.

⁷ Especially modern genetics has turned the spotlight on these patterns, from the fact that most variation is to be found between individuals and not groups, to the illusion of “autochthony” and the

realize that racism, sexism and other forms of discrimination are social and cultural phenomena, projecting hierarchies on any sort of real or invented patterns of variation⁸ (Fredrickson 2002; Lippert-Rasmussen 2014; Rattansi 2007; Ridgeway 2011; Rudman & Ashmore 2007). Finally, we believe that a proper understanding and appreciation of variation will only empower those currently disempowered by being “different” in a culture that does not accept differences.

5 Inter-group variation and speech

There is no reason to think that the biological and neuro-cognitive architecture of speech and language are somehow exempt from these patterns of inter-individual and inter-group variation, and it is much more probable that the apparent lack of clear examples is more due to a limited attention to the subject (i.e., absence of evidence is not evidence of absence). We will focus here on a few very interesting examples, on the one hand, concerning the perception, and on the other, the production of speech (all these examples are currently speculative to a certain degree and in need of more work, but they do point in the right direction).

Probably the best understood and most striking example concerns the complete change of modality, from speech to gesture, driven by *hearing loss*, and, in particular, the emergence of new sign languages. Here we can investigate how language changes across generations (Meir et al. 2010), how it is affected by the number of signers (both deaf and hearing) and, especially for the so-called village sign languages, how the co-evolutionary spiral between sign language and the deafness-causing genetic variants in the population works (Gialluisi et al. 2013; Zeshan & Vos 2012). However, this can be seen as too strong an effect and dismissed as a “fringe case” that is not relevant for how language in general interacts with inter-individual and inter-group variation.

However, Andy Butcher (Butcher 2006; Butcher et al. 2012) has recently suggested that several striking phonetic and phonological properties of the Australian Aboriginal languages that are otherwise cross-linguistically rare (such as the relatively

widespread nature of population movement, admixture and extinction (Barbujani & Colonna 2010; Jobling et al. 2013; Reich 2018).

⁸ See, for example, the treatment of the Irish in the pre-20th century US (Negra 2006).

small and centralized vowel system, the lack of fricatives, the large number of oral place of articulation distinctions and arguably the unusual syllable structure; (Butcher 2006)) might derive from the adaptation of these languages to a specific auditory profile particularly prevalent among the speakers of these languages. More precisely, the proposal is based on the observation that *Chronic Otitis Media* (or COM) is particularly frequent among Australian Aborigine children (Coates et al. 2002; Leach 1999) and, as far the evidence can be interpreted, has been even before the European contact, and that it may affect hearing, especially in the low and high frequencies range (Butcher 2006). Therefore, given that a sizeable proportion of the speakers presents an auditory profile that disfavors this frequency range, language “adapts” itself by avoiding speech sounds acoustically occupying this range (e.g., fricatives) and instead capitalizes on the affordances of the system (e.g., place-of-articulation cues)⁹.

On the articulatory side, our group¹⁰ has conducted modelling work and has collected data on variation in the morphology of *vocal tract structures* and their potential impact on speech and language. For example, *computer modelling* using a realistic geometric model of the vocal tract¹¹ has shown that larynx height affects the learning and production of vowels¹² (Janssen 2018), as do details of the shape of the hard palate (Janssen et al. 2018) but only when amplified by the repeated transmission of language across multiple generations (Janssen 2018). A different type of computer modelling, this time using the biomechanical platform ArtiSynth (Lloyd et al. 2012), allowed us to show that the size of the *alveolar ridge* (a shelf-like structure of the anterior hard palate just behind the upper incisors) may influence both the acoustics and the articulatory effort of producing a generalized *alveolar click* (Moisik & Dediu 2017). Interestingly, we found that a small (or “absent”) alveolar ridge facilitates the articulation of clicks, and it is precisely this configuration that is seemingly more

⁹ Of course, this proposal needs more research before being accepted as true. For example, the languages of other populations with a high traditional incidence of COM must be investigated as well as the populations without a high incidence of COM but whose languages show similar features. Also, experimental work concerning the effects of such an auditory profile on language learning and use must be undertaken.

¹⁰ Initially funded by a VIDI grant of The Netherlands Organisation for Scientific Research (NWO) at the Max Planck Institute for Psycholinguistic in Nijmegen, The Netherlands, now composed mainly of the two authors of this article (plus Rick Janssen) and their collaborators.

¹¹ Based on Peter Birzholz’s VocalTractLab2.1 (Birkholz 2013) and modified by us to allow the specification of the detailed anatomy of various components, such as the hard palate.

¹² The effects being visible despite massive compensation from other articulators such as the tongue and lips.

frequently attested among the native speakers of the so-called click languages of southern Africa¹³ (Moisiuk & Dediu 2017). These findings also seem supported by an in-depth analysis of MRI and acoustic data we collected from adults trained to produce clicks (Moisiuk & Dediu 2018), while an ongoing large-scale statistical analysis of the whole database we collected¹⁴ suggests that characteristics of the anterior part of the oral vocal tract influence the probability of correctly producing a trained click sound.

Using the same database of MRI static and real-time scans, we have also shown (Dediu & Moisiuk under review) that the articulatory strategy used to produce a North-American-English-style /r/ does vary between individuals and that it seems to be influenced by the anatomy of oral vocal tract. While the existence of *covert* variation in the articulatory strategy¹⁵ for producing this sound are well-known and may provide a window into co-articulatorily motivated sound changes, the potential influence of anatomical variation is novel and may allow us to better understand how inter-individual and inter-group variation acts on sound change (Dediu & Moisiuk under review).

6 Variation, its cultural amplification, and linguistic diversity

But how does this inter-individual variation become manifest as differences between languages? Intuitively speaking, outside of urban myths about kings whose speech defects changed their kingdom's way of speaking (out of respect or, more likely, fear and flattery), one would not expect these individual variants to be picked up and spread across a whole population (i.e., the long-standing "actuation problem" in the studies of sound change; see (Chen & Wang 1975; Weinreich et al. 1968; Yu 2013)).

¹³ Of course, we are here talking about continuous and gradual variation between groups, with some showing a slightly (but statistically significant) tendency towards smaller structures than others. Moreover, the available anthropological data is far from perfect: it does not cover all groups of interest and there is a lack of matched comparison groups.

¹⁴ The *ArtiVarK project* was a collaboration between the Max Planck Institute for Psycholinguistics, the Donders Institute and the Department of Orthodontics and Craniofacial Biology, UMC Radboud, all in Nijmegen. It involved ~90 adult participants from four self-declared ethnic groups, who followed a standardized training for learning to produce several speech sounds (including dental and alveolar clicks), followed by the recording of their productions during MRI scanning (structural, sustained articulation, and real-time) as well as a detailed 3D optical scan of their mouth.

¹⁵ Apparently, the auditory effects of these strategies are not audible (or used by the hearers).

We prefer to think about this problem in terms of individual speakers having *biases* of various natures and to various degrees (Dediu & Moisik under review). For example, an individual's small alveolar ridge might bias her towards producing (post)alveolar clicks, another individual's childhood COM infection would bias him away from hearing (and producing) fricatives, and yet another cannot produce alveolar trills to save his life. (Of course, in reality such biases are mostly continuous, and individuals vary in the strength and direction of such biases; moreover, these biases appear at all levels of language and speech, not just phonetics and phonology.) So, in a population where individuals vary in such biases, under what conditions would these biases be amplified and transmitted across the whole language community, becoming more than individual idiosyncrasies (or even pathologies to be treated)?

A first important parameter is, of course, the *frequency* and *strength* with which such a bias exists in the population at a given time: clearly, a single individual incapable of producing the alveolar trill (even after speech therapy) in a language using it for /r/ will not change that language towards using, say, an uvular trill or an approximant (presumably, even if he was the local despot)¹⁶. But how about 10%? 25%? (Our hunch is that 75% would definitely do it.) However, speech communities are highly structured, so even the frequency of biased speakers is not entirely meaningful and we must consider their *status* and their *position* in the larger *communicative network* (Meyerhoff 2015). Moreover, we must also keep in mind that, usually, the biases are much *subtler* (possibly even acoustically covert, such as for the North American English /r/) and *weaker*, and that they *interact* in a complex way with the pre-existing linguistic system(s) in the community (e.g., the incapacity to articulate the alveolar trill is irrelevant in most English and French dialects) and among themselves. Computer models and experimental designs suggest that such weak biases can nevertheless be amplified by the repeated use and learning of language, and that this amplification process is largely non-linear and not strictly dependent on the biases' strength (Dediu 2009; Kirby et al. 2014; Smith & Kirby 2008; Tamariz & Kirby 2016; Thompson et al. 2016). However, it is still unclear how

¹⁶ The first author is a case: a native speaker of Romanian (where /r/ is realized as an alveolar trill), he is incapable of producing it (despite some speech therapy as a child), using instead an approximant. (Clearly, there was some childhood abuse linked to this speech idiosyncrasy but, luckily, not much adult discrimination.)

this amplification is affected by complex communicative networks where individuals have different status, positions and vary in their biases.

Thus, we suggest that, far from being noise that is better ignored, inter-individual differences produce a *standing pool of variation* in a structured speech community. This variation is, most of the time, effectively hidden or, at best, its “peaks” visible as “funny” and harmless idiosyncrasies or mild defects amenable to therapy, but it interacts in complex ways with the community’s language and may result in unexpected and unpredictable changes when the right context arises (Dediu & Moisiuk, under review). Such processes, as they depend, on the one hand, on the distribution of variation within a group and, on the other, the group’s linguistic situation, are very likely to lead to different outcomes in different groups and may play an underestimated role in explaining the observed patterns of cross-linguistic diversity. This, of course, should not be seen as “limiting” the possible pathways of language change in some groups relative to others, but simply as changing the probabilities of these potential pathways.

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