Aerodynamics of phonology

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The function of the speech production system may be viewed as the conversion of muscular movements into sound. This is done by changing slowly-varying (so-called "DC") air pressure variations into the rapid ("AC") air pressure variations called 'sound'. This task is accomplished by a few air chambers interconnected by valves with variable orifice areas. Some of the chambers' volumes and thus air pressure may be varied by piston-like structures.

All of the above is well known within phonetics. What seems to be less well known are the phonological consequences of speech aerodynamics. I give here a brief sketch of some sound patterns in languages that can be derived in part from aerodynamic principles. (See also Ohala 1983, 1994, 1995, in press.) Another goal of this paper is to demonstrate how, with a few well-chosen primitives from an appropriate domain, important phonological generalizations can be achieved.

1. The Aerodynamic Voicing Constraint (AVC)

1.1. The AVC and stops

The aerodynamic voicing constraint (AVC) has long been recognized (Passy 1890:161-162; Chomsky and Halle 1968:300-301). In order for voicing to occur there are two basic requirements: first the vocal cords must have the appropriate degree of tension and the appropriate degree of adduction and, second, there must be air flowing through the vocal cords. During stops, even if the vocal cords are properly configured, the maintenance faces an inherent an obstacle. The air flowing through the vocal cords accumulates in the oral cavity and as a consequence the oral air pressure, P_{oral}, eventually approaches or reaches the same level as the subglottal pressure, $P_{sub\text{-}glot}$. When the airflow falls below a certain level (estimated at 1 to 2 cm H2O), voicing will cease (Catford 1977:29). In the absence of any expansion of the oral cavity, it has been estimated that with typical rates of glottal airflow, the pressure differential across the glottis, $\Delta P_{glot} = P_{sub\text{-}glot} - P_{oral}$, would reach 0 in under 15 msec. Obviously, voicing can continue during stops for a much longer period than that, so there must be some vocal tract expansion, thus making more room for the accumulating air and thus delaying the point where ΔP_{glot} falls below the level needed for vocal cord vibration. This expansion can be passive or active. Passive expansion occurs because the surfaces of the vocal tract have some "give", technically, some *compliance*, to the impinging air pressure. Ohala and Riordan (1979) presented data pointing to a median duration of about 65 msec as the limit of voicing if there is purely passive expansion of the vocal tract walls, more for labials (82 msec) and less for velars (52 msec) due to the different amounts of oral surface area exposed to the impinging air pressure. Each 1 cm^3 gives an estimated additional 10 msec of voicing

Active expansion of the oral area is achieved by lowering the larynx, lowering the tongue, elevating the already closed soft palate a bit more, and expanding the pharyngeal walls. Voiced geminates, which can have well over 100 msec of voicing must certainly exploit active expansion.

Another way to circumvent the AVC is to vent the oral air pressure via the nasal passage, i.e., by opening the velopharyngeal port. This is still compatible with the production of voiced stops as long as complete velopharyngeal closure is made in the last 20 msec or so of the stop closure (Ohala and Ohala 1991). In effect, this would be phonetically a prenasalized stop but in fact this is a not uncommon allophonic manifestation of voiced stops, including those in English in words such as *amble* (Suen and Beddoes 1974).

With regard to factors involving aerodynamics, then, Table 1 lists the ways voicing can be facilitated or inhibited.

Table 1. Factors affecting voicing in stops by influencing glottal flow.

Facilitating Voicing	Inhibiting Voicing
short closure duration	long closure duration
lax vocal tract walls	tense vocal tract walls
forward place of articulation	back place of articulation
nasal leakage	
active oral cavity expansion	

1.2. The AVC and fricatives

One might suppose that fricatives would be less affected by the AVC since at least some of the air accumulating in the oral cavity escapes, thus tending to keep the oral pressure low. However, this is not the case. As it happens there is statistically an even greater tendency for fricatives to favor voicelessness than stops (Ohala 1983, 1994): whereas an estimated 24% of the world's languages have only voiceless stops, some 38% have only voiceless fricatives. The reasons for this are as follows:

For optimal voicing,

(1) $\Delta P_{glot} = P_{sub\text{-}glot} - P_{oral} = \text{max}$

That is, one must try to maximize the pressure differential across the glottis. It is not really practical to do this by raising subglottal pressure, given the massiveness and consequent inertial properties of the respiratory system and because it would be only a short-term solution in any case since an increase in $P_{sub\text{-}glot}$ would instantly lead to increased P_{oral}. Thus the way to maximize ΔP_{glot} is to try to keep P_{oral} as low as possible.

But fricatives have another aerodynamic requirement: to produce frication. For optimal frication,

(2) $\Delta P_{oral} = P_{oral} - P_{atmospheric} = \text{max}$

Here one must try to make the pressure drop across the oral constriction as large as possible because that is one of the principal determinants of the air velocity through the narrow constriction which leads to fricative noise. One has no control over the atmospheric pressure, so one must try to keep P_{oral} as large as possible.

Now it is evident why voiced fricatives face an inherent problem: for voicing the P_{oral} should be as low as possible, whereas for frication, it should be as high as possible. Obviously, one can't satisfy both demands optimally. Some middle ground is possible, of course, but to the extent that a voiced fricative has good voicing, its fricative energy is less and to the extent it has good frication, its voicing may be threatened. It has been widely noted in the phonetic literature that in voiced - voiceless fricative pairs, the fricative energy is invariably less for the voiced member (Pickett 1980: 155).

2. Some phonological generalizations owing in part to the AVC

We are now in a position to consider some of the phonological consequences of the AVC. In each of the generalizations, other principles are also involved, as was the case in explaining why fricatives favor voicelessness more than stops, namely, the aerodynamic principles governing the production of fricative noise.

1. ***Obstruents favor voicelessness***.

The reasons for this were discussed in detail above.

2. ***Voiceless unaspirated stops are more common than fully voiced or voiceless aspirated stops.***

The simplest -- the default -- manner of producing stops is to just make an oral closure and then release it. For the reasons detailed above – those underlying phonological generalization No. 1 – such a stop will typically be voiceless, not voiced. Producing an aspirated stop requires that glottal abduction be coordinated with oral closure and release. There is some extra cost both to the fact of having glottal abduction and in having to carefully time it with respect to the supraglottal action. (There may be additional perceptual reasons militating against voiceless aspirated stops.)

3. ***Long (geminate) stops favor voicelessness (more than singletons).***

The longer the stop closure is held, the more air accumulates in the oral cavity and the less is the capacity for additional expansion, whether by passive or active means (Chao 1936).

4. ***Back-articulated stops favor voicelessness (more than front-articulated ones).***

The reasons for this were discussed in detail above. Again: the further back a stop is articulated, the less surface area there is to expand the oral cavity containing the pressure build up.

5. ***Voiced implosives can develop historically geminate voiced stops.***

In Sindhi, an Indo-Aryan language, voiced implosives are the reflexes of earlier voiced geminates, e.g., Prakrit **pabba* > Sindhi /paɓuni/ 'lotus plant fruit'. Presumably, maintenance of voicing in the geminate stops was achieved by lowering the larynx and this glottalic feature was re-interpreted as being the primary distinctive feature of these stops. This is, however, the only example I know of of this type of sound change.

6. ***Fricatives favor voicelessness (more than comparable stops).***

The reasons for this were discussed in detail above.

7. ***A voiced vs. voiceless contrast on obstruents may give rise to a contrast of low tone vs. high tone on following vowels.***

As is well known, the daughter languages of Middle Chinese show each of the original four tones split into a higher and lower variant dependent on the voicing of the initial consonant (Karlgren 1926). Many other languages around the world show a similar consonantal influence on tone. Recently Löfqvist et al. (1989) found increased activity in the cricothyroid muscle, the principal tensor muscle of the larynx and thus the principal regulator of voice F0, during the production of voiceless stops. Presumably this increased vocal cord tension was present to help to insure complete voicelessness during the stop closure, given that with un-abducted vocal cords voicing would be possible at least in the first few 10's of msec of the stop closure because of continuing glottal airflow. This increased cricothyroid activity persists for some time into the following vowel thus producing the well known consonantal perturbation of the F0 of the following vowel (Hombert et al. 1979)

8. ***Glides and high vowels have a greater tendency to devoice than comparable lower vowels.***

The devoicing of predominantly high vowels in Japanese is well known and this pattern has been documented for languages around the world by Greenberg (1969) and Jaeger (1978). The reason for this is that these segments, by virtue of their high close constriction, impede the flow of air more and thus constitute "almost" obstruents. In conjunction with other factors, they can help to reduce ΔP_{glot} enough to extinguish voicing. A corollary of this is:

9. ***High vowels that are nasalized do not contribute to devoicing.***

Although the data are not extensive, Ohala 1983 presents some evidence apparently showing that in a language where high vowels are sometimes voiceless, they do not devoice when nasalized. In any case, this relation would be predicted since by venting any oral air pressure build up via the nasal passage there would be no decrease in the ΔP_{glot} necessary for voicing.

10. ***Distinctive aspiration may develop on stops before high, close, vowels.***

Mathangwane (1996) showed that in Ikalanga, a Bantu language of the Shona group, distinctive aspiration has developed before the reflexes of the Proto-Bantu "super-close" vowels (which have now merged with the next lowest vowel). Some relevant data are presented in Table 2.

Table 2. Data from Ikalanga showing that distinctive aspiration has developed on stops that appeared before the Proto-Bantu super-close vowels but not before the next lower vowels (from Mathangwane 1996)

Proto Bantu	**Ikalanga**	**Translation**
tima	t͡sʰima	'well'
tudi	tʰud͡zi	'shoulder'
BUT:		
tɪma	tima	'heart'
tʊndʊ	tundu	'basket'

11. ***Voiced stops are more commonly associated with pre-nasalization than voiceless stops.***

The reasons for this were discussed in detail above. Again, nasal venting allows voiced stops to preserve voicing by avoiding the AVC. M Ohala and J. Ohala (1991) presented the historical data in Table 3 from Hindi showing that nasal consonants are likely to emerge between a nasalized vowel and a voiced (but not a voiceless) stop.

Table 3. Historical data from Hindi showing the emergence of a nasal consonant between a nasalized vowel and following voiced (but not voiceless) stop (from M. Ohala and J. Ohala 1991).

Old Hindi	**Modern Hindi**	**Translation**
ãːgana	[ãŋgə̃n]	'courtyard'
t͡ʃãːda	[t͡ʃãnd]	'moon'
BUT:		
dãːta	[dãt]	'tooth'

12. ***Intervocalic voiced stops have a greater tendency than voiceless ones to spirantize (become approximants).***

As mentioned earlier, one way to avoid devoicing of stops as a result of the AVC is to keep the closure duration short. However, excessive shortening could lead a stop to have an imperfect closure and thus become a spirant or approximant such as [β] or [ð]. In contrast, there is no similar motivation to shorten the closure duration of voiceless stops; on the contrary, a longer closure duration tends to ensure voiceless by the time of the stop release. As is well known, voiced stops are typically shorter than cognate voiceless stops (Suen and Beddoes 1974). Thus voiced stops show a greater tendency to spirantize intervocalically than do voiceless stops.

3. Conclusion

There are many more physical phonetic principles governing the operation of speech processes, both in production and perception. Some we know and some have still to be discovered. For example, there are addition aerodynamic principles governing the generation of turbulence and of the aerodynamically-driven oscillations in trills. But the important point is that the phonetic primitives are *fewer* than the phonological generalizations that are derived from them. Thus some of the principles underlying the production of trills also apply to the oscillation of the vocal cords in voicing. The 12 phonological generalizations in **2**., above, all have the AVC as one of their explanatory primitives. Another important aspect of the above explanations for sound patterns is that the explanatory principles are *real-world* and *independently motivated*, that is, they are part of the everyday world in which we live and are not limited to the specific domain that we apply them to in phonology. The aerodynamic principles that govern the generation of air pressures and airflows in speech are the same that apply in bicycle pumps, the inflation of party balloons, the action of automobile pistons and carburetors, etc., etc. Finally, these principles have been established through *empirical studies*; they have not been generated *ad hoc* just for the sake of the phonological problems at hand.

Mainstream phonology, practiced as an autonomous discipline, has yet to produce any explanatory principles comparable to the type of deductive system sketched above. Typically, a sound pattern is explained or accounted for by a shorthand re-statement of the sound pattern itself. Moreover the primitives invoked are abstract, applicable only within phonology, and lacking in empirical support.

I believe that only by fully integrating phonetics (as well as relevant contributions from psychology and socio-cultural studies) into its practice can mainstream phonology escape from its present circularity and sterility.

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