The Role of Physiological and Acoustic Models in Explaining the Direction of Sound Change*

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The sounds of language change due to sociological, grammatical, physiological, and perceptual reasons. I will not be concerned in this paper with those changes due to sociological or grammatical factors, that is, those which are essentially unique to a given language at a given period in time. Rather, I will discuss those sound changes which have been observed in a wide variety of unrelated languages and which therefore undoubtedly reflect some universal tendencies of human sound systems—tendencies which must originate in the common articulatory and perceptual mechanisms used by human speakers and listeners.[1]

There seems to be no great difficulty in recognizing these common sound changes or their results, the present-day alternations in words, but there has always been in phonology a constant search for the best model with which to represent and explain these sound changes or alternations. This is evident in the number of revisions phonological notation has undergone in the past two decades. The notation system employed by some scientific fields may be no more than mnemonic devices to denote entities in the system studied, but in phonology and some other fields the notational devices are clearly much more than this. As with the notation systems in chemistry it is expected that a given representation of a phonological process will—by its very structure—somehow explain or capture known aspects of the process it represents. When it does not do this we feel compelled to change or otherwise improve the notational conventions.

I would like to point out some rather serious inadequacies in the model of the speech process implied by the current Chomsky and Halle (1968) feature system and at the same time urge that a drastically different but vastly more explanatory type of model be adopted. Let me put this into perspective by reviewing the factors which led another field, chemistry, to adopt various changes in its notational systems. The parallels with phonology are really quite striking.

Before the beginnings of modern chemistry those who worked with matter and its changes had only simple arbitrary labels with which to represent a particular change that substances might undergo. For example, it was common knowledge that if an iron object were left outside unattended for even a few days, it would soon acquire a reddish-brown coat of rust. If anyone then had thought to try to represent this change in a formal equation the best they could have achieved would have been a notation such as that in (l).

IRON + AIR > RUST (l)

* This is a revised version of a paper with the same title read at the 1st Annual All-California Linguistics Conference, Berkekey, 1-2 May 1971. This work was supported in part by the National Science Foundation. [This appeared in print in *Project on Linguistic Analysis [POLA] Reports,* (Berkeley) 15.25-40. This pdf version does not retain original pagination.]

[1] It is not obvious to me how these common sound changes which occur in widely separated languages are to be accounted for by those who consider sound changes to be almost exclusively a mentalistic phenomenon, that is, consisting of changes in the speaker's internalized grammar of his language and initiated by the same whims of fashion that lead to changes in dress and car styles (Postal 1968). Why should the fashion in phonological rules change in such similar ways in languages which are geographically, typologically, and temporally distant? As will be made evident in this paper the explanation for this lies in considering the physical aspects of speech.

This formula accurately accounts for the observed facts and it has predictive power. But there is no way of knowing from this particular representation of the facts whether this is a natural or expected process. We have no way of knowing whether some other combination of ingredients might also produce rust, or if the same two ingredients, iron and air, might produce something else besides rust. In short, we do not know why this change takes place.

The discoveries of Lavoisier, Dalton, Berzelius, and others led to a new understanding of chemical changes and thus to a new notational and terminological system which incorporated the new model. Now compounds were recognized as consisting of one or more elements which were themselves incapable of further decomposition. Further it was recognized that elements combine into compounds in fixed proportions which could usually be expressed by whole numbers. This was correctly assumed to be due to the fact that individual atoms of one element joined individual atoms of the other elements in fixed ways. Thus the same fact represented in (l) would now be expressed as in (2).

$$\mathbf{4Fe + 30_2 \longrightarrow 2Fe_20_3} \qquad (2)$$

Now we can see from this representation why these ingredients and only these ingredients would produce rust and it predicts other useful facts, too. Of course, this still leaves unanswered the question of why iron and oxygen should combine in precisely these proportions. The answer to that question could come only after further advances were made. One of these advances was made when it was discovered that certain substances, isomers, consisted of identical mixtures of elements in identical proportions, but still had different properties. It was then correctly proposed that what mattered was not only the composition of the compound but also the particular arrangement of the atoms in the compound. Thus ethyl alcohol, a familiar substance, and dimethyl ether have the same empirical formula, C_2H_6O, but have a different arrangement of their constituent atoms as symbolized by the different structural formulas in figure 1. With notations such as these chemists could incorporate structural details which explained many of the

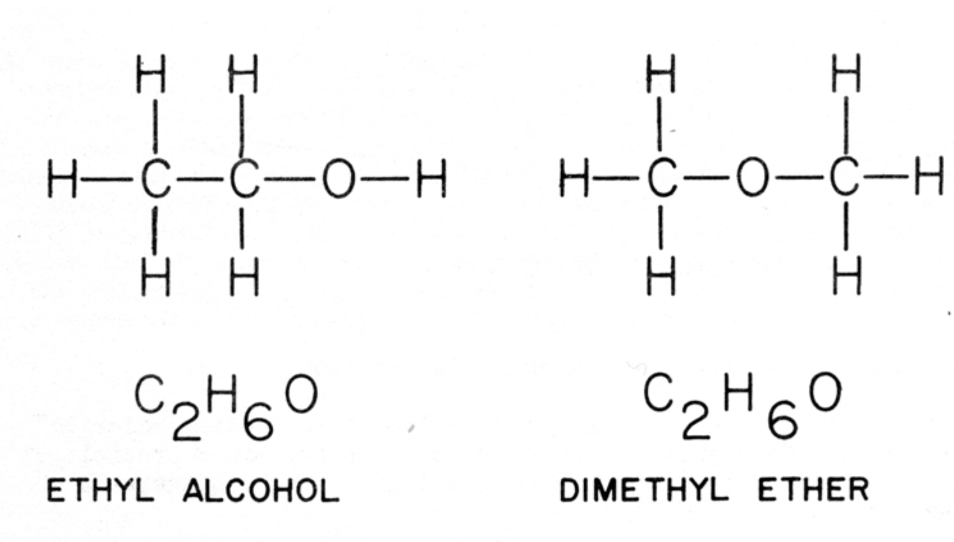

Figure 1.

properties of compounds. These two-dimensional letter-and-line structural formulas were adequate for the field until someone discovered optical isomers, that is, certain substances having identical structural formulas but which in certain forms had different optical properties. Specifically, in one form polarized light passing through it would be rotated to the right and in the other light would be rotated to the left. Common examples of such optical isomers are dextrose and levulose, both of which would taste the same in one's coffee, but which rotate polarized light in opposite directions, whence their names. It was suggested by van t'Hoff that this could be accounted for by considering the three-dimensional arrangement of the bonds between the constituent atoms of a molecule, for example, as shown in figure 2. Both substances, lactic acid molecules, have the same empirical and structural formulas but in their three-dimensional aspect are exact mirror images of each other, and this accounts for their different optical properties.

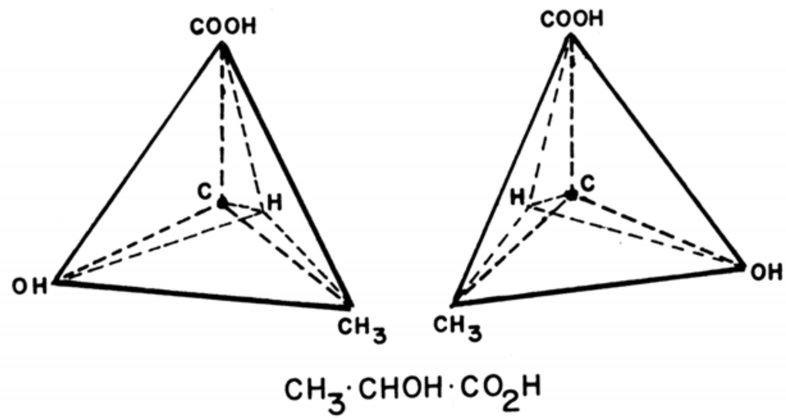

Figure 2. Two mirror-image molecules of lactic acid.

By no means does this represent the end point in the developing of new models to explain the properties of matter nor does this mean that the earlier models or notations are unused. Any of the previous notations are employed for a particular purpose as long as they are useful for the purpose, i.e., when no ambiguity results. If one simply wishes to denote a particular common chemical substance one might simply call it "table salt" or "lime" rather than "sodium chloride" or "calcium oxide." Only when the notation fails to explain a crucial fact should one escalate to a model incorporating the relevant details of the system one is studying.

Let us turn to phonology and examine how its notation system represents and models a common phonetic process. Consider the well known variation in the place of articulation of dorsal obstruents depending on the articulation of the neighboring vowels. The change of [ki] to [t͡ʃi] figures prominently in English phonology and is due in part to this assimilatory effect. Figure 3 presents some cine-x-ray tracings made by Wada and his colleagues (1970) at Osaka shoving this effect. On the left are the tongue positions for the five Japanese vowels /a o u e i/. The main constriction in the vocal tract is progressively further forward for the vowels in this order. On the right are the various tongue positions for the articulation of the /k/ in Japanese depending on which of the five vowels follows: a considerably fronted articulation before /i/ and a back articulation before /a/, with the other articulations in between. Some linguists (Bach 1968) seem to write as if there were only two positional variants for the /k/, front and back.

Of course, this is wrong: there are as many positional variants of the /k/ as there are vowels that can appear around it. Both /i/ and /æ/ induce a "fronted" articulation in the /k/ but that for /i/ is more fronted, and thus so-called velar "softening" is observed to occur more frequently before /i/ than before /æ/. And if, in any language, it occurs before /æ/ it will also occur before /i/ but not necessarily vice-versa. These facts can only be explained by considering the variations in articulation that occur <u>within</u> the class of the so-called "fronted" /k/'s.

This process could be symbolized in part using IPA notation as in (3)

$$k \longrightarrow \left\{ \begin{array}{l} \underset{+}{k} / \_\_ i \\ k / \_\_ u \\ q / \_\_ o \end{array} \right\} \qquad (3)$$

(3) says that /k/ "becomes fronted "before /i/, a velar stop before /u/, and an uvular stop before /o/. This representation adequately describes the phenomenon and incorporates nicely the fact that it is the first part of the sequence /ki/ that is affected by the last part, and not vice-versa. This may seem trivial, but consider that had the IPA adopted a phonetic syllabary instead of the phonetic alphabet, this fact would not be so easily represented. However we know this phenomenon is an assimilatory one but the representation does not reveal it. In fact there is nothing in the rule itself to indicate that this manner of change is any more or less expected than a change to a palatal stop before /ɔ/ or to an uvular stop or even a bilabial stop

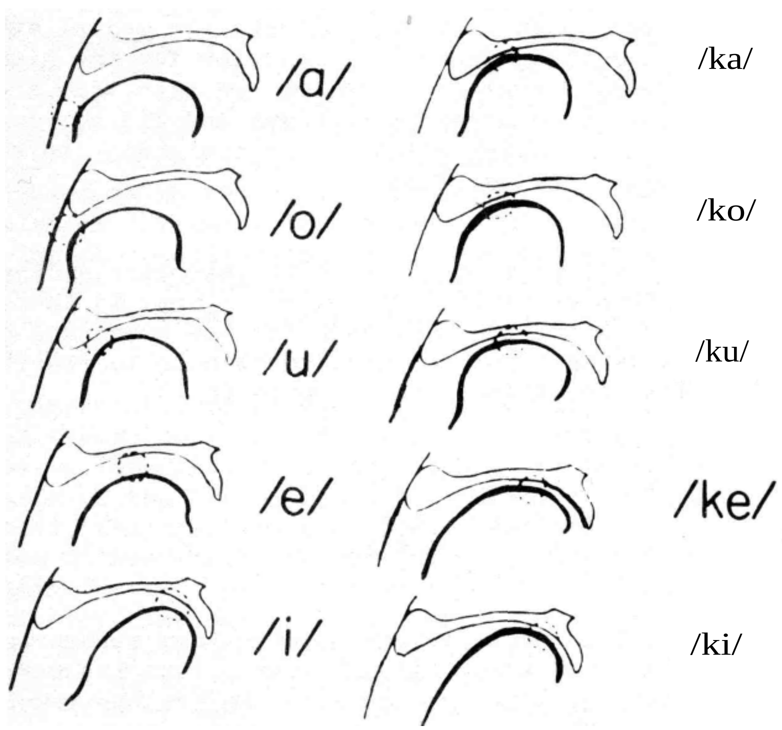

Figure 3 (from Wada *et al/).*

before /i/. Arguments such as these led to the representation of such phonological processes in terms of features, as in (4).

$$\begin{bmatrix} \text{C} \\ \text{-ant} \\ \text{-cor} \end{bmatrix} \dashrightarrow \left\{ \begin{matrix} \begin{bmatrix} \text{+high} \\ \text{-low} \\ \text{-back} \end{bmatrix} / \_\_ \begin{bmatrix} \text{V} \\ \text{+high} \\ \text{-low} \\ \text{-back} \end{bmatrix} \\ \begin{bmatrix} \text{+high} \\ \text{-low} \\ \text{+back} \end{bmatrix} / \_\_ \begin{bmatrix} \text{V} \\ \text{+high} \\ \text{-low} \\ \text{+back} \end{bmatrix} \\ \begin{bmatrix} \text{-high} \\ \text{-low} \\ \text{+back} \end{bmatrix} / \_\_ \begin{bmatrix} \text{V} \\ \text{-high} \\ \text{-low} \\ \text{+back} \end{bmatrix} \end{matrix} \right\} \qquad (4)$$

This shows the same process represented in (3) now in terms of the features used in Chomsky and Halle's (1968) Sound Pattern of English. Now the assimilatory nature of the change is clear: before /i/, which has the feature composition: high, nonlow, nonback, the dorsal stop acquires the same values for those features. Likewise for the high back vowel /u/ and for the mid-back vowel /ɔ/. Now we are also able to see quite naturally why the change occurred in this way and did not involve a stop becoming high before a nonhigh vowel. Thus the change to this more detailed notation system is justified.

This representation would seem to allow us to introduce another notational change with still greater explanatory power. Since, in these examples, the values for the features high, low, and back for the consonant become the same as those for the following vowel we ought to be able to rewrite the rule by using the now familiar variable notation as in (5).

$$\begin{bmatrix} \text{C} \\ \text{-ant} \\ \text{-cor} \end{bmatrix} \dashrightarrow \begin{bmatrix} \alpha\ \text{high} \\ \beta\ \text{low} \\ \gamma\ \text{back} \end{bmatrix} / \_\_ \begin{bmatrix} \text{V} \\ \alpha\ \text{high} \\ \beta\ \text{low} \\ \gamma\ \text{back} \end{bmatrix} \qquad (5)$$

Now the rule reveals the common assimilatory pattern that occurs in all three cases. But note that this rule will not work, given the current definitions of the Sound Pattern of English features: Before the vowel /a/, which is nonhigh, low, and back, this rule would predict that the consonant would be pharyngeal. The /k/ before /a/ is the farthest back of the /k/'s but it is not that far back. Even worse, when the stop appears before either a mid-front or low front vowel, that is, having the feature composition nonhigh, nonlow, nonback or nonhigh, low, nonback, respectively, we find that the consonant would assume feature values that consonants are not permitted to have in the Chomsky-Halle system. It is reasonable that no consonant should have these feature values since otherwise it would imply that there was no point of articulation for it, nevertheless the place of articulation of these stops is influenced by these vowels as well.

We can either give up our try to represent all these assimilatory changes by one general rule or we can adopt a new system for representing these processes. Let us abandon the Chomsky-Halle feature system for the representation of this process—in fact, let us simply abandon features. Öhman (1967) has offered a mathematical model of coarticulation which suggests how one might handle all the varieties of /k/. Using equations of the form in (6) it is possible to predict—with tolerable error, for

$$P(x) = V(x) + a\,[C(x) - V(x)]\,b_c \qquad (6)$$

the present—how the consonant is influenced by the vowel. In fact equations of this type ideally could apply to all combinations of consonants and vowels. Dorsal consonants are certainly not alone in being influenced by surrounding vowels as Öhman and others have shown. This particular equation holds for VCV words in which the first and second vowels are identical. It says that the position of any given point on the tongue, P(x), will be determined by the target position of that point for the vowel, V(x), plus another factor, in which $\underline{a}$ is a variable that ranges continuously between 0 and 1, and represents the progression in time of the utterance. Thus it is 0 at the target time of the vowel and is 1 at the target time of the consonant. C(x) is the target position of the point on the tongue for the consonant, and $\underline{b_c}$ is a constant that is unique to each consonant and whose value may range from 0 to 1. It determines the amount of coarticulatory influence from vowels a given consonant may show. A consonant showing no coarticulatory influence would have the value 1 for $\underline{b_c}$; a consonant that permits a great amount of coarticulatory influence from vowels would have a value closer to 0. Obviously /k/ will have a smaller value than /*s*/.

Therefore, if we want to express all these assimilatory phenomena in sound change or in sound alternation with a single statement we shall have to use a formulation resembling that of Öhman's—for a first approximation— instead of the IPA or feature notations. In that such representations can do this, they reflect a simpler model than those implied by either the IPA or the Chomsky-Halle feature system. Of course Öhman's model does not explain why this assimilation takes place (indeed, the need for the coarticulatory constant $\underline{b_c}$ is somewhat ad hoc) and the models that answer this question will undoubtedly have to take into consideration such factors as the inertial and elastic characteristics of the articulators, the acoustic result of such assimilations, and the character of the neural program controlling the articulators. We are some way away from this but actually more work has been done on these questions than one might gather by reading the current phonological literature.

Let us consider another example. Vowels become nasalized before nasal consonants. This is an important phonetic process in sound change since if the nasal consonant subsequently drops we are left with a vowel with auditorily distinctive nasalization.[2] This has occurred, for example, in English and is reflected in such contrasts as those between "cat" and "can't" (kæt vs. kæ̃t) and "let" and "lent" (lɛt vs. lɛ̃t). There is no particular difficulty in representing this in feature notation in a way that handles all cases of nasalization before nasal consonants and captures the assimilatory nature of the process as well.[3] The problem comes when we want to know why this happens. Why is this more likely than vowels assimilating the feature <u>high</u> of a following velar consonant?

[2] This common process is well documented by Lightner (1970).

[3] Nasalization also occurs in the environment of low vowels and glottal or pharyngeal consonants and the traditional feature systems cannot explain this. There is, however, a perfectly natural physical cause for this. See Ohala (1971).

Some beginnings of an answer to this question have been obtained from two sources: physiological studies of soft palate movement in speech and acoustic studies. The physiological studies were done using a device called the nasograph (Ohala 1971). It consists of a light and light sensor encased in a transparent tube which is inserted into the subject's nose and pharynx such that the light is in the pharynx and the light sensor in the nasal cavity. Greater or lesser velar elevation allows less or more light to impinge on the light sensor and thus develop relatively a greater or lesser voltage which can be recorded and related to other speech events. Figure 4 shows some output of the nasograph which illustrates the effect of vowels becoming nasalized in the vicinity of a nasal consonant. The figure shows the nasograph signal and the simultaneous microphone signal for the two utterances "say mitt twice" and "say Tim twice." Time progresses from left to right and a lowered velum is represented by the nasograph signal being at the bottom of its range. As can be seen in both cases the vowels adjacent to the nasal consonants have a lowered velum and are thus nasalized. An alternative to nasalizing the vowel would be to keep the velum raised until the very end of the vowel and then lowering it once the nasal consonant begins. But preliminary evidence seems to indicate that the velum does not move fast compared to other articulators. Thus it may be that the velum could not open quickly immediately after an oral vowel.[4] Second, and perhaps more importantly, acoustic studies, for example those of House and Stevens (1956), which I will refer to in more detail shortly, indicate that although opening the velopharyngeal port obviously does distort the spectrum of a vowel it does not seem to distort it so much that it loses its distinctiveness—I use "distinctiveness" in an impressionistic and as yet non-quantified sense. If this is true it suggests that the early lowering of the velum is allowed because it does not destroy the acoustic identity of the vowel. But if a vowel assimilated the high tongue position of a following /k/, for example, this would obviously greatly distort the quality of at least low vowels. This point needs further study, of course, but it illustrates quite well that explanations of why this or that sound change occurs must take into account physiological and acoustic facts such as these.[5]

[4] This opening could probably be done at the fastest in some 50-60 msec. This may be fast enough to eliminate the impression of nasality on the vowel. The question of how long a vowel must be nasalized before it is heard as nasalized requires further study.

[5] Lightner (1970) has approached the question of why and how vowels become distinctively nasalized and offers the following explanation. Final nasals, like all final consonants, are frequently dropped; therefore to avoid losing information (about the identity of the word) the nasalization on the vowel is retained. I do not deny that an examination of sound change seems to indicate the presence of a very basic "ground rule" in human vocal communication that a given word cannot suddenly change into a form that bears no auditory resemblance to the original form, however Lightner's explanation, like all teleological explanations, raises more questions than it answers. If there is supposed to be some "force" which tries to maintain the distinctiveness of words, then why did it allow these final nasal consonants to drop in the first place? Further, this explanation fails to account for a huge number of common sound changes in which segments are dropped without leaving a trace, e.g., English "last" [læst] —> [læs]. And even when vowels become distinctively nasalized after the loss of a final nasal consonant some information is lost: information on the place of articulation of that nasal, which presumably could be bilabial, dental, velar, etc. Finally, Lightner's explanation fails to tell why information on the lost nasal consonant is not, in some languages, signalled by some other phonetic feature instead of nasalization of the preceding vowel, i.e., why don't we find even a few languages doing this by adding distinctive tone to the vowel or by diphthongizing it, etc.? Why instead do we find such consistency among languages in their treatment of this change?

These difficulties can be avoided by simply considering what probable physiological and acoustic factors were at work in this situation. There were probably at least the following three steps in the process leading to distinctively nasalized vowels.

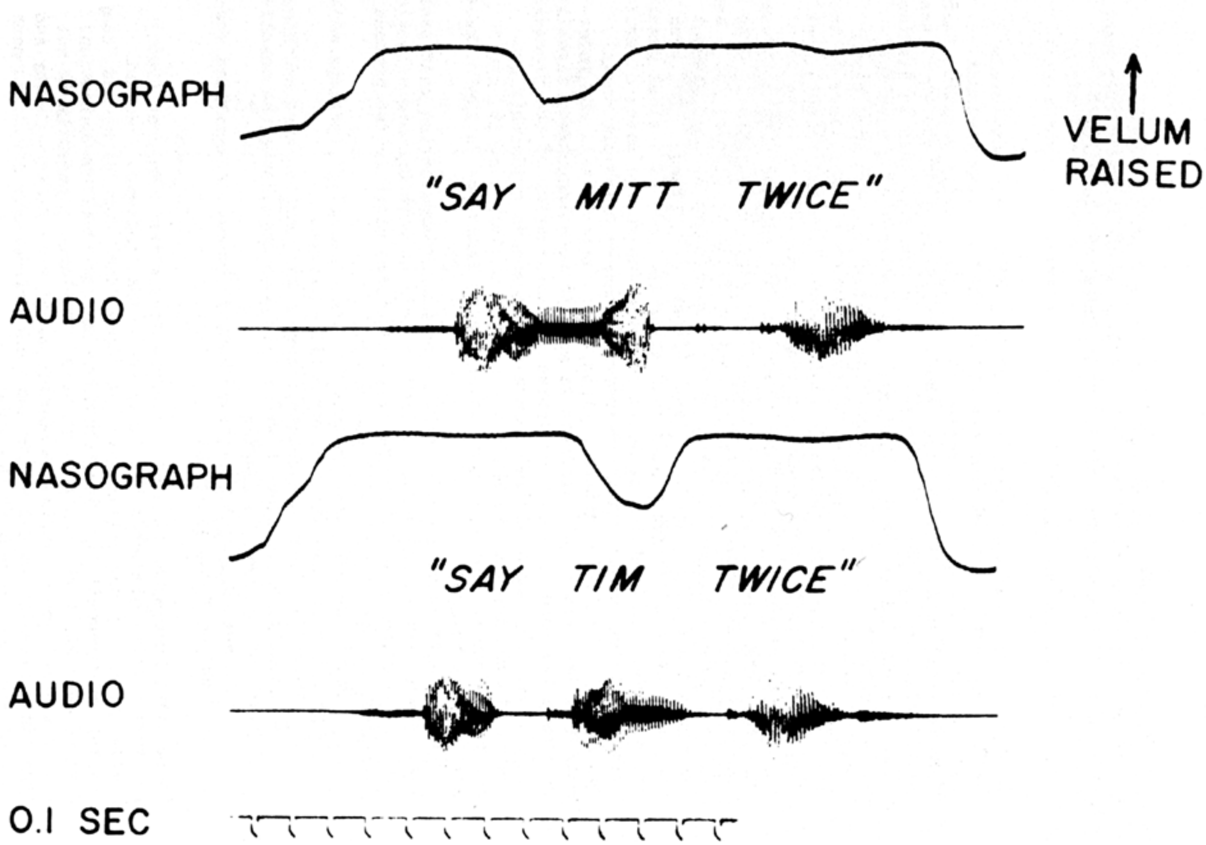

Figure 4.

Another example: It has been observed both in French and in Chinese (in the latter case by Matthew Chen (1971)) that once high vowels become distinctively nasalized they then tend to lower. This effect is revealed in the French Pairs "fin" [fɛ̃] and "finir" [finiʁ]. Again, the fact of this change can be represented adequately by feature notation, as in (7), but it provides no insight as to why the change occurs. Some studies by House and Stevens (1956) with an electronic analogue of the vocal tract suggest an explanation for this. They studied the effect

$$[+\text{high}] \dashrightarrow [-\text{high}] \,/\, \begin{bmatrix} \overline{} \\ \text{V} \\ +\text{nasal} \end{bmatrix} \quad (7)$$

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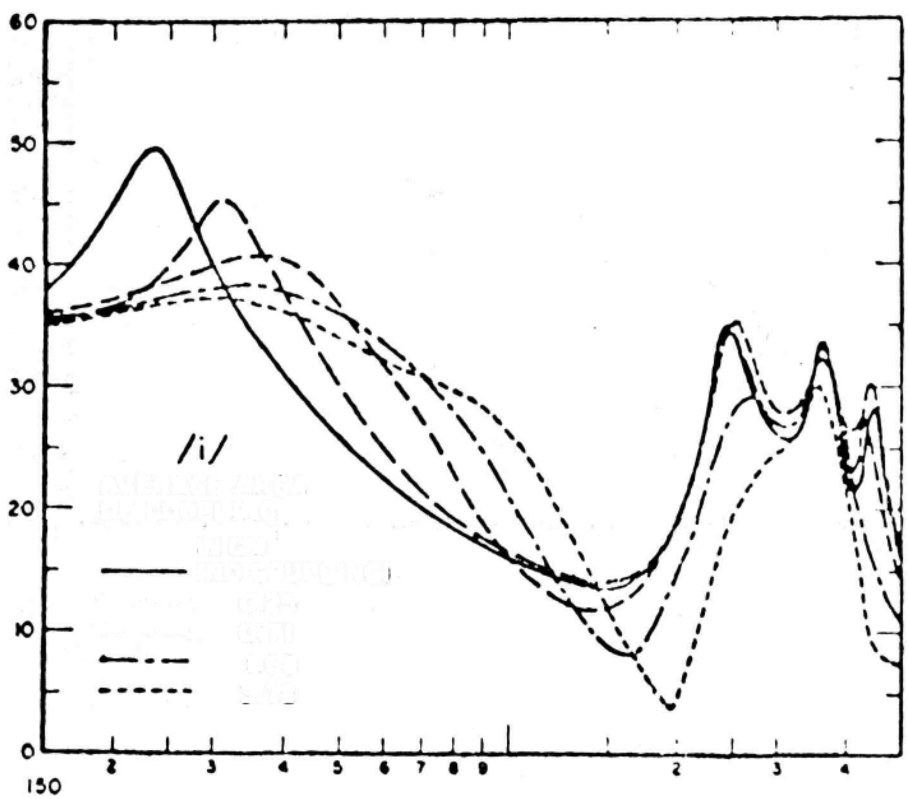
1. Vowels before nasal consonants become nasalized (perhaps non-distinctively) for the reasons outlined above.

2. The final nasal consonants become weakly articulated and hence perceptually indistinct, however this does not change the nasalization of the vowel preceding.

3. The next generation imitates what it hears: a nasalized vowel only and no final consonant.

These steps have apparently all occurred in English. Malécot (1960) has very neatly documented the first two steps, and such frequent misspellings by young children as "pik" and "cap" for "pink" and "camp," respectively, (Read 1971, Susan Ervin-Tripp, personal communication) seem to indicate that step 3 is at hand. Children apparently do not hear the nasal consonant in the words spelled with final -nC—why should they, since often it is not there?—and our orthography offers no means to indicate nasalization of the vowel.

on various vowels of varying amounts of nasal coupling. Figure 5 shows their results for the vowel /i/. The solid line shows the spectrum of /i/ with no coupling and the lines underneath show the effect on the spectrum of increasing amounts of coupling. As can be seen, the first formant flattens out and moves upward in frequency. The second formant shows relatively little change. Figure 6 shows this effect for all of the six vowels studied plotted on the familiar first formant vs. second formant graph. As has been recognized, vowels fit on this acoustic space in much the same way as they are said to occupy the traditional pseudo-articulatory vowel space (Ladefoged 1967). Plotted in this way it can be seen that increased nasal coupling tends to "lower"



Frequency in CPS

Figure 5.

vowels, high vowels more than low vowels. (The effect on the formants of increased nasal coupling is indicated by the arrows.) Thus to explain in part why high vowels, once nasalized, tend to lower, we can say that the acoustic result of opening the velum is to raise the first formant of a vowel and thus auditorily it seems to be lowered. Whether this may in fact lead to an actual shift in the articulation of the vowel is another question; it is not unlikely.[6]

[6] Delattre (n.d.) offers a different explanation for the lowering of nasalized vowels. He says that distinctive nasalization on vowels involves lowering the amplitude of the first formant (which is true, in part, as is evident in Fig. 5) and that this is best accomplished by making the volume of the pharyngeal cavity match that of the

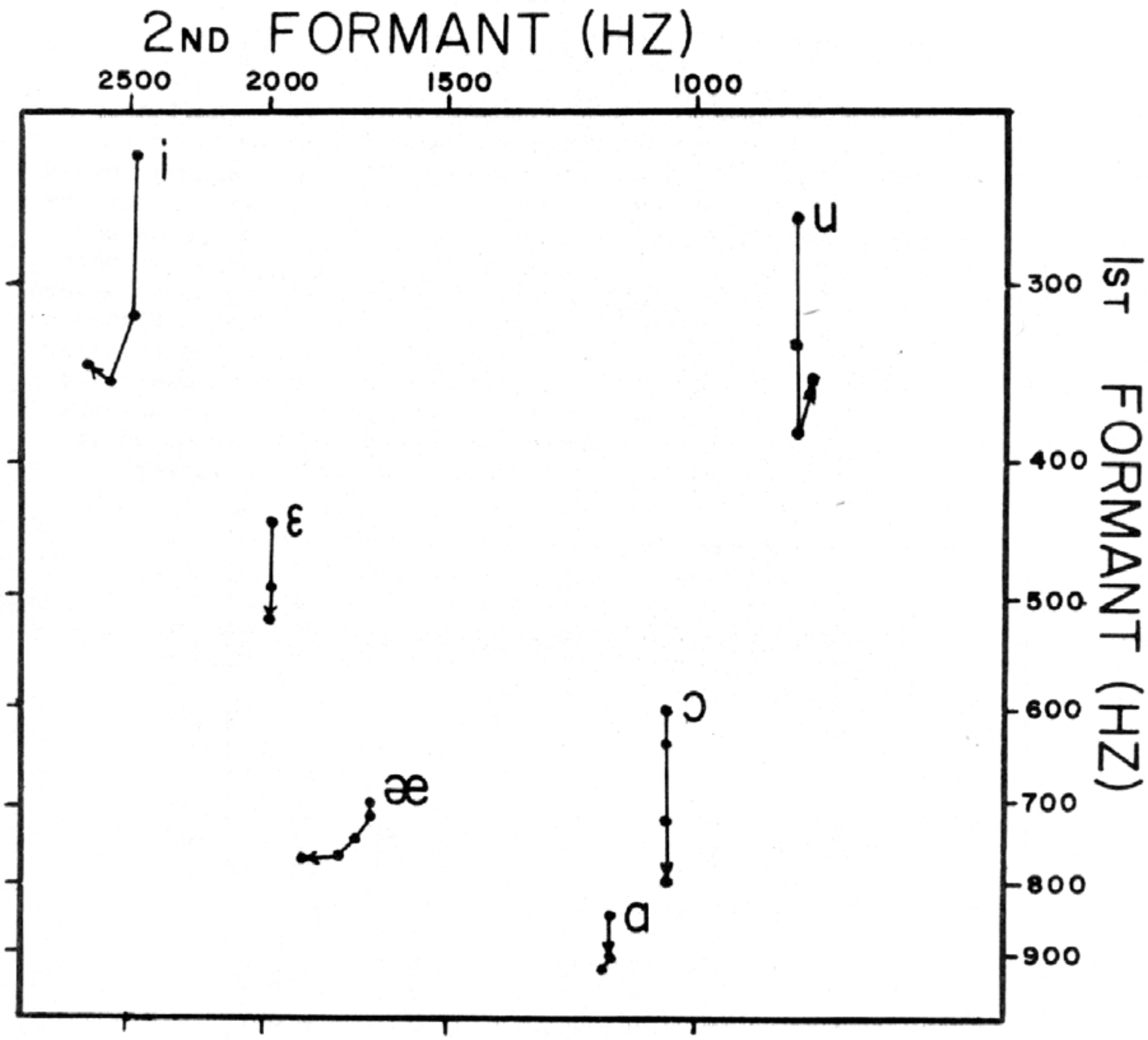


Figure 6.

In phonology solutions to problems such as these are of interest since considerable attention has recently been focussed on trying to explain and understand the naturalness of common phonological processes. Chomsky and Halle and others have, in fact, recognized that their feature system fails to reflect the naturalness of certain sound patterns. They admit that this is due to the system's failure to incorporate the "intrinsic content" of the features. This, as I have

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rhinopharynx, thus permitting vibrations to develop in both of these cavities which are equal in amplitude and frequency but opposite in phase, thus mutually cancelling each other out. Thus, according to him, [ĩ ỹ ũ], since they did not have the favorable pharyngeal dimensions for this process, changed their tongue positions until they did have the right dimensions and ended up as [ɛ̃ œ̃ õ], respectively. Delattre's explanation is hard to justify. It assumes, counter to current acoustic theory that one can speak of individual cavities in the vocal tract contributing separate resonances. Fant (1960) notes that "all parts of the vocal tract contribute to the determination of all formants but with varying degrees depending on the actual configuration" (21). Second, House and Stevens' results indicate that a given amount of velopharyngeal opening is more effective in lowering the amplitude of the first formant of high vowels than it is in lowering that of low vowels.

tried to show, is an understatement. But the only remedy proposed by the generative phonologists is the theory of markedness. According to this theory the naturalness of certain sound patterns is accounted for simply by labelling them "expected" or "unexpected," i.e., "unmarked" or "marked." It should be clear that a mere relabelling— which is all that the marking conventions are—is no solution at all. It is tantamount to saying: "I recognize shortcomings in my model, but I refuse to revise it; I will take care of the inadequacies by tacking on a list of facts I know to be true but which are not accounted for by my model." Surely, in the history of linguistics, the "theory" of markedness will go down as the most ad hoc of all ad hoc measures proposed in the field. When one has to start listing facts not reflected in one's model, that is the time to look for a new one.

Let me anticipate a possible objection to the proposals presented here. It might be said that the kind of models mentioned in this paper cannot be incorporated in an account of the speaker's phonological competence. I quite agree. I do not offer these models as explanations of speakers' competence; I offer them as explanations for the naturalness of certain common phonological processes. It is unfortunate that, as Ladefoged (1971) has pointed out, most modern phonologists fail to recognize the difference between the two goals of phonology: (l) accounting for the linguistic competence of speakers and (2) describing and hopefully providing physical, sociological, or other non-psychological explanations for the patterns that occur in language. The techniques used in pursuing these two separate goals are quite distinct: both the models proposed and the methods of evaluation will be different.

Models of speakers' phonological competence might very well include binary features, variable features values, braces, and the like (although this is just sheer conjecture at present), and the testing of such models would have be done, first, by psychological tests that show whether or not speakers are productive in forming the derivations predicted by the rules posited (Ladefoged and Fromkin 1968, Zimmer 1969, Hsieh 1970, Moskowitz 1971, Ohala, Sherman, Farley, and Thielmann (forthcoming), M. Ohala (forthcoming)), second, whether or not the rules used by the speaker are isomorphic with the rules proposed (cf. Ohala 1970: 5ff.) , and third, whether or not the rules proposed in the grammar are such that could reasonably be accommodated in and utilized by the human brain. It is obvious that very few phonologists seem to be concerned with the evaluation of the grammars they propose.

The models I have proposed in this paper, since they are offered as providing some explanation for the naturalness of common sound patterns due to physical causes are not constrained by the same principles that operate in a competence model. They need not be restricted to the use of binary features and such. Rather, they are free to use whatever physical concepts and principles are relevant and useful in accounting for given sound patterns. Of course, their evaluation will be accomplished in the same way as any hypothesis in natural science: by testing, but it will not be necessary in this case to show that the speaker "knows," tacitly or otherwise, the physical principles posited to account for the sound patterns. (Surely there are things linguists and phoneticians know, explicitly, about language and speech which the average language user does not know, even implicitly.)

Although relatively simple physical models have long been used in attempting to account for sound patterns (Whitney 1867), it is only recently that the complexity—and success—of the models used have increased greatly (Lindblom 1971). Is it therefore necessary that today's phonologists be part physiologist and physicist in order to account for certain common sound changes? The answer to this question depends on what the phonologist accepts as his goal. All that can be said is that whoever asks why certain sound changes and alternations are natural and others are not is obliged to make use of those models which do the job of explanation best.

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