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Speech Aerodynamics and Phonological Universals

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I. Introduction

A. Explanations in Phonology

One of the most important current questions in linguistics is that of explanation; that is, what constitutes an explanation of certain observed linguistic data. In the area of phonological universals, there seem to be two types of methodologies: first, descriptions of phonological data which are intended as descriptions (for example, the work of Greenberg, Ferguson, and Hockett), and second, descriptions of phonological data which are intended as explanations (for example, the strength hierarchies and markedness conventions of Chomsky and Halle, Hooper, and Foley). These latter types of descriptions fail to be truly explanatory in that their primitives are defined in terms of the theory itself, rather than making reference to empirically verifiable principles outside the theory.

Recently some linguists, for example John Ohala (see Ohala 1977), have argued that those phonological processes which tend to be universal probably are so because they are caused by, and can therefore be explained with reference to, that which all speakers have in common: the human speech production and speech perception mechanisms. Most phonological patterns or sound changes which can be explained in terms of sociolinguistics, for example borrowings or fashion, will tend not to be universal. Since many aspects of human speech production and perception can be empirically investigated, explanations of phonological patterns based on these phonetic data can be truly explanatory, with primitives defined in terms of principles outside the theory, for example, principles of mathematics or physics. Further, theories based on empirically gathered phonetic data should be able to make predictions about phonological universals which can then be verified with reference to phonological data gathered from the world's languages. In this paper I will describe such a theory, present explanations of and predictions about several phonological universals, and then discuss these universals in detail with support from real language data.

B. A mathematical model of speech aerodynamics.

A computer-implemented mathematical model of speech aerodynamics has been reported in Ohala 1975a, 1976. This model basically works as follows: the user specifies starting values for various aspects of the modeled air passages, specifically, the volumes of the oral and pulmonic cavities, air masses in these cavities, and time-varying values for oral and glottal resistances and pulmonic force. The model has built into it various well-known principles of aerodynamics, for example, formulas for predicting when air flow will become turbulent, given its velocity and the dimensions of the channel it is passing through. The model is calibrated with reference to well-documented, measurable data about human speech aerodynamics. The model then outputs time-varying values for oral and glottal air flow and for air pressure in the oral and pulmonic cavities. Some of the values which the model outputs are compared with measurements taken from human speakers, to verify by extension the validity of the predicted values which are not easily measurable, such as pulmonic force or glottal air flow during obstruents.

The two main phonetic factors about which this model can make explanations are 1) voicing maintenance, and 2) introduction of turbulence into the speech air stream.

Voicing is a function of the pressure drop across the glottis; voicing can only be maintained when the air pressure above the glottis is less than that below the glottis, so that air can flow from the lungs across the glottis into the oral cavity, causing the vocal cords to vibrate. When there is a blockage of airflow in the oral cavity, whether it be a complete blockage as in stops, or a partial blockage as in fricatives or the narrow constriction for high vowels, the pressure of the air in the oral cavity will increase. If oral pressure becomes equal to subglottal pressure, voicing stops. So voicing maintenance depends on air pressure and velocity, oral cavity size, and the resistance of the oral constrictions, which are all specified or derived by the aerodynamic model.

Turbulence can be described as follows: when air is passing slowly through a tube or constriction, it moves in a smooth, or laminar flow; however, if air is forced to move through the constriction at faster and faster rates, at some point laminar flow will become turbulent, developing eddies in the air flow. A narrower constriction will cause turbulence to begin sooner, as air velocity increases. Turbulence, then, depends on the area of the constriction and air velocity, which are also specified or derived by the aerodynamic model.

These two factors, voicing maintenance and turbulence, are the key factors in the several phonological universals to be discussed here.

C. Methodology of this study.

Three predictions made by this model about phonological patternings related to aerodynamic factors were researched in the Stanford Phonology Archive. This Archive is a collection of computer-readable descriptions of the phonological systems of 221 languages (at the time of my research). Since the languages in the Archive have been chosen to represent as widespread and characteristic a sample as possible, no data from further languages was included, so that my sample would not be biased. Data was gathered on all languages which exhibited the phenomena in question, and simple counts were made to see whether or not the model's predictions were generally upheld. Examples and counterexamples were further researched to see whether something other than aerodynamic factors might be coming into play in any important way. Finally, languages were looked at in geographical groups, to make sure no purely areal features were surfacing; geographical locations of the languages discussed below are listed in Appendix 1.

II. Universals of Speech Aerodynamics: Three Examples

A. Voiceless vowels and vowel height.

The first prediction is also a well-known observed universal: in vowel systems in which only some vowels devoice, high vowels will devoice before non-high vowels. This universal was noted by Greenberg (1969) among others. The explanation is fairly simple: the narrower constriction for high vowels causes air pressure in the oral cavity to be greater than that during low vowels, so that devoicing due to supra and subglottal pressure equalization can occur sooner, as described above.

The data from the Archive supports this prediction, and reinforces earlier observations, as can be seen in Table 1. Out of 44 languages with voiceless vowels, 24 devoice only part of their vowel systems; of these 24, 20 either devoice only high vowels, as in Dafla, Greenlandic, and Guarani for example, or preferentially devoice high vowels, as in Japanese and Nyangumata. (Greenberg 1969 cites 10 additional languages not included in the Stanford Phonology Archive as having only high voiceless vowels. These languages are listed in Table 2.) Of the five languages which are exceptions (see Table 3), two, Morroccan Arabic and Paez, devoice only schwa. [1] In both of these languages, schwa is described as an overly short transitional sound; in the case of Paez, it is optionally inserted in certain environments, and is not phonemic. In both languages it

TABLE 1
Languages which only or preferentially devoice high vowels

Language	Devoices
1. Portuguese	i,u [-stress], in the environment of voiceless consonants.
2. Malayalam	i,y /e,a,o___#,C
3. Japanese	all, but high more often
4. Mandarin	following syllable in high-falling tone, syllable final high vowels under weak stress are voiceless following voiceless fricatives or aspirated fricatives.
5. Dafla	i,u / C̥___C̥
6. Akha	i / X___
7. Garo	i / s___n,r
8. Korean	y / medially, after fricatives, affricates, or aspir. cons.
9. Azerbaijani	I,ø,U,ɤ when short in unstressed open syllables
10. Gadsup	i / ___##
11. Western Desert	U in one morphological env.
12. Nengone	i,e,u,o (not ɛ,a,ɔ) / ___#
13. Nyangumata	all, but high more often, /__#
14. Greenlandic	i,u / C̥___C̥
15. Chipewayan	i, when second element of diphthong
16. Tunica	u, phrase-final preceeded by [k,hk] with penult. stress
17. Alabaman	i / #___s (free variation)
18. Mixtec	i / C___##
19. Campa	i / ___#
20. Guarani	i,ɨ,u / ___#

TABLE 2
Additional languages with only voiceless high vowels listed in Greenberg 1969

Language	Devoices
1. Serbo-Croatian	i, u
2. Tadjik	i, u, a
3. Awadhi	i, e, u
4. Uzbek	i, u
5. Dagur	i, e, u
6. Papago	all, high more extensively
7. Comanche	all but /a/
8. Shawnee	i̥ forces vowels in preceding syllable to devoice
9. Huichol	i, ʌ (+high), e
10. Chatino	i, u

TABLE 3
Languages whose only voiceless vowels are not high

Language	Devoices
1. Morocco Arabic	schwa / C̥___C̥
2. Paez	schwa / C̥___C̥
3. Hupa	[e,a,o] but not [i,u]; the second half of long vowels devoice; only [e,a,o] occur long.
4. Tarascan	[i,e,ɨ,a,u] not [o]; before pause when single, unstressed. /o/ is defective phoneme in this system.

devoices between voiceless consonants in unstressed syllables. Because it is a particularly short vowel and non-phonemic, its devoicing in this environment is not surprising; it is clear, however, that it is not a function of aerodynamic factors, but of some other phonetic factors.

The other two languages which devoice something other than high vowels also seem to do so for non-aerodynamic reasons. Hupa devoices /e,a,o/, but not its high vowels, which are described phonetically as: [i, I, Ɨ, ɤ, ɯ]. However, vowel devoicing is an attribute of long vowels in this system, that is, the second half of long vowels devoice before pauses, and only /e,a/ and /o/ occur long. In fact, the high vowels in Hupa are sometimes analyzed as "lax" (short, unstressed) allophones of the phoneme /e/, so that they are phonemically never in a position to devoice.

Tarascan has a very odd system in that it devoices /i, e, ɨ, a/ and /u/, but not /o/. Vowels in this language devoice before pause juncture when occurring singly under weak stress, and /o/ does occur in this position, for example in the word <u>čénembo</u> 'his house'. However, /o/ is reported to be a defective phoneme in Tarascan, of infrequent occurrence, which is never found in a number of environments, namely, after /w, th, t, tsh/ or /s/. One possible explanation for this imbalance is that /o/ may be a more recent addition to the vowel system than the others, and that the devoicing developed in the rest of the system before /o/ became part of the system; however, this is just a speculation. But it appears that none of these counterexamples seriously detracts from the original prediction, that high vowels are more likely to devoice than low vowels.

<u>B</u>. <u>Effect</u> <u>of</u> <u>vowel</u> <u>height</u> <u>on</u> <u>obstruents</u>.

The second prediction is that if a language has rules which either devoice, aspirate, fricate or affricate consonants before only some vowels but not others, it will be before high rather than low vowels. The reason is rather complex. As I have pointed out, the narrow constriction for high vowels causes increased oral pressure; this can delay voice onset time, as reported by Smith (1975). [2] The lag in VOT can be heard as being part of the preceding consonant, so that a voiced obstruent can be heard as voiceless, or a voiceless obstruent as aspirated. Further, high vowels are more likely to create turbulence than low vowels, because they offer a narrower channel for the air flow. This can affect the preceding obstruent in two ways: first, it can actually add frication to it; secondly, it is generally true that the frication on voiceless obstruent segments is noisier and of higher amplitude than the frication on voiced segments, as noted in Stevens 1971; therefore it is possible that the presence of turbulence itself may favor a reinterpretation of preceding consonants as voiceless, aspirated or fricated.

Before I describe the Archive data I should point out that I did not include in my count cases described as 'palatalization' unless there was actual affrication involved; this is because palatalization is more a function of front-back assimilation (i.e. of tongue body) rather than an aerodynamic feature.

Languages seem to exhibit this phenomenon in two different ways, as shown in Table 4. Some have skewed phonological systems in which only the affricated allophone of an obstruent phoneme occurs before high vowels. Japanese is a well-known example of this situation, in that its alveolar stops and fricatives affricate before /i/ and /ɯ/. The Akan family shows a similar system, in which all alveolar and velar consonants affricate before high front vowels. Other languages have allophonic rules which devoice, affricate, aspirate or fricate single segments only in particular environments; the Gadsup language has three such rules, which are also listed in Table 4. Of the 23 languages, then, that exhibit the phenomenon in question, 20 do so before high vowels, and three before low vowels.

The counterexamples to this claim, listed in Table 5, are particularly interesting. In Yakut, a Turkic language of the USSR, voiceless velar stops are affricated before only low back vowels, and voiced velar stops are fricated before only low vowels, both front and back; the velar stops are also backed to uvulars. My only explanation for this is that in Yakut, as in various Turkic languages, there are front/back allophones of each obstruent (a function of 'palatalization' and vowel harmony), and that the back version of the velar phonemes are fricated, possibly due to the lesser agility of the tongue toward its root. However, this does not explain why even low <u>front</u> vowels cause frication of the voiced stop; I can think of no obvious phonetic explanation for this situation. On the surface, this is a counterexample to the predictions.

In Hupa the frication is used for emphasis, (i.e. t → tX in emphatic speech), which is clearly a function of perceptual rather than aerodynamic influences.

Lakhota, or Teton Dakota, has a very odd system in that it not only preferably affricates its aspirated stop phonemes before <u>low</u> vowels, but prefers to affricate them in the environment of <u>nasalized</u> vowels as well. The reason I find this strange is that there seems to be accumulating evidence that in general, nasals have a tendency to <u>block</u> aspiration, devoicing,

TABLE 4

Languages in which consonants devoice, aspirate, fricate or affricate in the environment of high vowels only

Language	Rules
1. Gbari	tʃ and dʒ occur only before /i,e/
2. Akan	d --> dz t --> ts g --> dǰ /___/i,e/ k --> tç h --> ç
3. Tigre	alveolar stops become fric. before /e/
4. Japanese	(see below)
5. Ryukyuan	t --> ts, th --> tʃh, d --> dʒ /___j
6. Lahu	p,ph,b,m affric. before u u --->ɯ in this environment
7. Sa'ban	labials fricate / #__w
8. Selepet	ph --> ɸ,f / #___i, u
8. Gadsup	a) aspiration tends to be more frequent and pronounced before high vowels. b) β has less frication before low vowels. c) j → ǰ before high vowels.
10. Sentani	j --> dʒ / i, w, j ___
11. Kunimaipa	l --> dɬ / high vowels
12. Nasioi	t --> ts / ʔ___i; t --> s / n,V___i
13. Nuangumata	p --> ɸ, pɸ / #___U
14. Greenlandic	t --> ts/ __i
15. Oneida	tʃ, dʒ occur only before [j,i]
16. Totonac	l --> ɬ / i___
17. Amahuaca	w -->β / env. of I
18. Carib	r --> dʒ / i,j ___V
19. Ticuna	dʒ --> j/ ___ a
20. Jivaro	w -->β / ___i

4. Japanese:

	t	d	s	z	h
i	tʃ	dʒ	ʃ	dʒ~ʒ	ç
u	ts	dz	s	dz	ɸ
e,a,o	t	d	s	z	h

TABLE 5

Languages in which consonants devoice, aspirate, fricate or affricate in the environment of non-high vowels only

1. Yakut: /k/ --> [qX] / ___ [a,o]
   /g/ --> [ɣ] / ___ [a,e,o,ɤ]

2. Hupa : /th/ --> [tX] in emphatic speech before /a/.

3. Lakhota: (Data from K. Whistler and R. Van Valin)

	/ph/	/th/	/kh/
i	h	h	h
e	h~X	h	h
u	h	h~X	h
o	X	X	h~X
a	X	X	X
ĩ	h	h	X
ũ	X	X	X
ã	X	X	X

thipi	[t^hipi]	'house'
ophethũ	[op^hetXũ or opXetXũ]	'to buy'
thãka	[tXãka]	'big'

or affrication of preceding segments [3], so that it seems that a language which preferentially affricates its obstruent phonemes in <u>nasal</u> environments is unusual, if not aberrant. However, the explanation for this phenomenon may in fact lie in its very strangeness. Consider the following speculation: Lakhota has both a voiceless aspirated and a voiceless unaspirated stop series. In certain environments, however, the aspiration tends to be lessened or damped, specifically around low vowels for aerodynamic reasons, and around nasals, probably for perceptual and aerodynamic reasons, since air escaping from the nose has less turbulence and therefore less perceptible noise than air escaping from the mouth. Therefore, in order to preserve the perceptual distinction between aspirated and unaspirated voiceless stops, frication is added to the segments <u>in just those environments where it does not occur naturally</u>. Because this frication occurs in the environment of <u>low</u> and back vowels, it takes on the same tongue position and occurs as velar frication. While this solution is merely speculation, it seems to be plausible, and if it were true, it would in a sense reconfirm the prediction that the more likely place to find devoicing, aspiration, frication, or affrication of obstruents is before high rather than low vowels. [4]

<u>C. Geminates and Long Consonants</u>

The third prediction is as follows: If a language has both voiced and voiceless obstruents, but geminates ony part of its obstruent system, it will have long voiceless rather than long voiced obstruents.

The explanation is that a stop closure of long duration will allow air pressure in the oral cavity enough time to equalize with sub-glottal pressure and cause voicing to stop; this is also true of the narrow constriction for fricatives, but not true of nasals, which of course allow air to escape from the nose, disallowing oral pressure build-up. Voiced geminate obstruents are more unstable than voiceless; over time they should either devoice, or devise some means of prolonging voicing, for example, becoming prenasalized or imploded. While this is clearly a diachronic prediction, a synchronic manifestation would be languages with geminate systems skewed in a voiceless direction, or with geminate or long obstruents only among the voiceless series.

In making this survey I of course discounted languages which have <u>no</u> voiced obstruent segments as phonemes or allophones. However, I did include languages which lack phonemic voicing but do have voiced allophones contrasting with the geminate obstruents. Examples of this are Ojibwa and Delaware.

The data from the Archive, displayed in Table 6 again supports our prediction: of 20 languages with skewed geminate systems, 18 either have only long voiceless obstruents or have systems skewed in a voiceless direction, not counting nasals. Japanese is again the classic case which exhibits this phenomenon in its phonological system, as it has both voiced and voiceless obstruents, but only geminate voiceless. Lak, a Caucasian language, is a further example. Awiya, an African language spoken in Ethiopia, demonstrates a voiceless skew, with two voiced and two voiceless geminate stops, but only voiceless geminate fricatives and affricates.

One of the counterexamples (see Table 7) appears to be in fact a verification of the claim that voiced geminates are diachronically unstable. Armstrong (1934) analyses Somali as having voiceless obstruent phonemes of rather limited occurrence, and voiced obstruent phonemes with a number of allophonic variations. Intervocalically, voiced obstruent phonemes can occur either <u>short</u>, in which case they are fully voiced and somewhat spirantized, or <u>long</u>, in which case they are described as "[not] sound[ing] fully voiced", or having "weak voicing", or none at all. What seems to be happening is that these long voiced segments are in the process of devoicing, as our model predicts they are likely to do.

The second counterexample, that of Island Carib, seems to be an example of a skew due at least in part to systemic reasons; that is, the voiceless segments /p/ and /k/ only occur initially, and long consonants only occur finally, so that /p/ and /k/ are never in a position to occur long. (p/b and k/g neutralize medially, so that the phonemicization of this languge is problematic.) However, of the two voiceless stops which do occur finally, /t/ does occur long, but /c/ does not, and all the voiced obstruent phonemes do occur long. So while in one sense this stands as a counterexample, it appears that whatever is causing the skewing toward voiced geminates is systemic, a function of the somewhat asymmetrical phonological pattern, rather than due to aerodynamic factors. That is, non-phonetic factors have overridden the phonetic factors in determining the behavior of the sounds in this case.

It is interesting to note in passing that the most frequent type of geminate or long consonant in the world's languages is clearly the nasal geminate. This fact was briefly mentioned by Ferguson (1975), but no explanation was offered. As indicated in Table 8, the Archive shows 72 languages with some type of long or geminate consonants, 67 of which have long nasals. This leaves only five languages which have only non-nasal long consonants. There are sixteen languages whose only

TABLE 6

Languages which either have only long voiceless obstruents, or geminate systems skewed in a voiceless direction.

Language	Language
1. Finnish	10. Lak
2. Icelandic	11. Yurak
3. Walamo	12. Evenki
4. Awiya	13. Greenlandic
5. Kanuri	14. Alask. Eskimo
6. Malayalam	15. Ojibwa
7. Kurux	16. Delaware
8. Japanese	17. Karok
9. Maranungku	18. Alabaman

EXAMPLES

Japanese

p	d	g	z
p	t	k	s
p:	t:	k:	s:

Lak

b	d			g	
p	t	ts	č	k	q
p:	t:	ts:	č:	k:	q:
p'	t'	ts'	č'	k'	a'

Awiya (skewed system)

b		ɖ	g	dz	dʒ	z	ʒ
p	t		k	ts	tʃ	s	ʃ
p:	t:	ɖ:	g:	ts:	tʃ:	s:	ʃ:

TABLE 7

Languages which either have only long voiced obstruents, or have a skew towards voiced geminates.

1. Somali: all geminates are phonemically voiced, but are in the process of devoicing.

2. Island Carib:

b	d		g	f	s	h
b:	d:		g:	f:	s:	
p	t	c	k			
	t:					

/p/ and /k/ only occur initially; long variants only occur finally.

TABLE 8
Geminate Nasals

Number of languages with geminate or long consonants of any type........................72

Number of languages with geminate or long nasals...................................67

Number of languages whose only long or geminate consonants are nasals................16

Number of languages whose only long or geminate consonants are nasals and liquids....9

Languages without long nasals, which have other long consonants:

Language	Has Long:
1. Atayal	t, l
2. Cheremis	r
3. Iraqw	s
4. Totonac	p,t,k,q,ɬ
5. Tarascan	k

long consonants are nasals, and another nine which have only long nasals and liquids; combined, these two categories comprise over a third of the languages in this count. The interesting question is this: why are long nasals more frequent than long voiceless oral obstruents; is this just a function of the greater stability of nasals over time, as noted by Ferguson 1975, and Ohala 1975b, or are there other factors, perhaps aerodynamic, involved? The answer will have to be the topic of some future research.

III. Conclusion

In his recent dissertation Hector Javkin has argued that most sound changes of the universal sort can be explained with reference to either primarily articulatory, acoustic, or perceptual facts, and that each of these areas will be able to explain a different type of sound change. Because synchronic patterns are nothing more than the output of previous sound changes, as Greenberg 1966 argues, it follows that phonological universals should also be explainable in these terms. I have shown in this paper that certain facts about the aerodynamic aspects of speech production can be used to predict and explain a particular body of phonological data. The mathematical model of speech aerodynamics discussed here does not pretend to be a theory for explaining all possible speech patterns, but rather only those which are directly a function of aerodynamic facts. Because phonological universals obviously are caused by a wide range of phonetic factors, articulatory, acoustic and perceptual, any theory which hopes to be able to explain fully <u>all</u> phonological universals will have to include data from all of these areas; and since our knowledge in many facets of these fields is at this point sketchy at best, much more research will need to be done before such a comprehensive theory can be developed. However, it is clear that the basis for truly explanatory theories about phonological universals will have to be empirically gathered phonetic data, such as I have described in this paper.

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FOOTNOTES

1. I originally included Puget Sound Salish as a language with voiceless schwa, but have since had several Salishanists explain to me that this is incorrect.

2. Smith's results are somewhat complex in that he finds that fully voiced stops will have more pre-voicing before high than low vowels, while voiceless stops will have a much longer VOT before high than low vowels. This needs further investigation and explanation.

3. The incompatibility of nasalization with oral stops and fricatives is discussed in Ohala 1975a, and with frication on vowels and glides in Ohala 1977. The reason cited is the necessity of high oral pressure for noise bursts in the former case, and turbulence in the latter; the release of air through the nose makes high oral pressure difficult to accomplish. In going through the Archive data I came across a large number of languages with rules which, for example, devoice or aspirate obstruent phonemes everywhere except in the environment of nasals, where they are voiced or unaspirated. However, there is some evidence for an affinity between /h, ʔ/ and nasality (see Matisoff 1975), and 'spontaneous nasalization' is attested around /s/ and /h/ (See Ohala 1975b). This entire area is very unclear and awaits further investigation.

4. This is not a totally unprecedented type of argumentation. Jakobson (1962) has used a similar argument to explain why Ukranian has palatal consonants only before low back vowels.

APPENDIX 1
Geographical location of languages discussed

Language	Area	Language	Area
Finnish	Europe	Gbari	Africa
Portuguese	"	Akan	"
Icelandic	"	Tigre	"
Serbo Croatian	"	Walamo	"
Moroccan Arabic	Morocco	Awiya	"
Awadhi	India	Kanuri	"
Malayalam	"	Somali	"
Kurux	"	Iraqw	"
Tadjik	USSR	Greenlandic	N. America
Uzbek	"	Alask. Eskimo	"
Yakut	"	Chipewayan	"
Lak	"	Tunica	"
Cheremis	"	Alabaman	"
Azerbaijani	"	Papago	"
Yurak	"	Comanche	"
Evenki	"	Shawnee	"
Dagur	East Asia	Hupa	"
Mandarin	(Peking)	Oneida	"
Atayal	"	Lakhota	"
Japanese	"	Ojibwa	"
Ryukyuan	"	Delaware	"
Lahu	S.E. Asia	Karok	"
Dafla	"	Mixtec	Mexico
Akha	"	Huichol	"
Garo	"	Chatino	"
Korean	"	Tarascan	"
Gadsup	Pacific	Totonac	"
Sa'ban	"	Campa	S. America
Selepet	"	Guarani	"
Sentani	"	Paez	"
Kunimaipa	"	Amahuaca	"
Nasioi	"	Carib	"
Nyangumata	Australia	Ticuna	"
West. Desert	"	Jivaro	"
Nengone	"	Island Carib	"
Naranungku	"		

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IJAL = International Journal of American Linguistics
JASA = Journal of the Acoustical Society of America
UCPL = University of California Publications in Linguistics

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