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QUANTIFYING THE SONORITY HIERARCHY

A Dissertation Presented

by

STEPHEN G. PARKER

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2002

Linguistics

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DEDICATION

To my beloved wife, Mónica.

ACKNOWLEDGEMENTS

This is the section of the dissertation where you're supposed to tell everyone you know how grateful you are for everything they've done for you. Flattery and exaggeration are typical devices, and even seem to be somewhat expected. Since most of these acknowledgement sections begin with the doctoral committee, I guess that's where I have to start. My chair, John Kingston, spent countless hours with me in the phonetics lab. Without his constant technical support, my experiment never would have gotten off the ground. I had so many meetings with him that I can actually say I learned as much from him outside the classroom as inside (not that he's a bad teacher). During the course of my six years here at UMass, I've come to appreciate him not only as a mentor and colleague, but also as a friend. John McCarthy has been a true role model and has taught me more about phonology than I could sometimes absorb. He patiently answered every question I could dream up, some of which were devious, dastardly, and duplicitous. He also holds the distinction of reading and commenting on virtually everything I've written while here at UMass, leading to much-needed improvements in my work. For this I will always be thankful. Lisa Selkirk has always challenged me to look at things in new ways that I had not previously considered. While this is not always easy to do, it is really the best way to discover new insights that will take your work to the next level of proficiency. In addition, her support as chair of the department was completely instrumental(!) in allowing us to acquire the equipment we needed to run my

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This dissertation is offered as a sacrifice to Him who is the way, and the truth, and the life:

> "Jesus then said to those Jewish people who had believed in him, 'If you abide in my word, then you are really my disciples, and you shall know the truth, and the truth shall make you free.'"
> (John 8:31-32)

ABSTRACT

QUANTIFYING THE SONORITY HIERARCHY

MAY 2002

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A long-standing controversy in the interface between phonetics and phonology involves the nature of sonority. This dissertation seeks to help resolve this problem by showing that the sonority hierarchy is both physically and psychologically real. This is accomplished by reporting the results of two rigorous and in-depth experiments. The first of these involves phonetic (instrumental) measurements of five acoustic and aerodynamic correlates of sonority in English and Spanish: intensity, frequency of the first formant, total segmental duration, peak intraoral air pressure, and combined oral plus nasal air flow. Intensity values are found to consistently yield a correlation of at least .97 with typical sonority indices. Consequently, sonority is best defined in terms of a linear regression equation derived from the observed intensity results.

The second major experiment — this one psycholinguistic in nature — involves a common process of playful reduplication in English. A list of 99 hypothetical rhyming pairs such as *roshy-toshy* was evaluated by 332 native speakers. Their task was to judge which order sounds more natural, e.g., *roshy-*

toshy or *toshy-roshy.* The data again confirm the crucial importance of sonority in accounting for the observed results. Specifically, the unmarked (preferred) pattern is for the morpheme beginning with the more sonorous segment in each pair to occur in absolute word-initial position. A generalized version of the Syllable Contact Law is utilized in the formal analysis of this phenomenon in terms of Optimality Theory. Finally, a complete and universal sonority hierarchy is posited by building on the findings of the two experiments as a whole.

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LIST OF ABBREVIATIONS

2	second person
3	third person
ASL	American Sign Language
BR	Base-Reduplicant
c.	circa
cc	cubic centimeters
cm	centimeters
CON	the universal constraint component of Optimality Theory
cont.	continued
cps	cycles per second
D	(sonority) dispersion
dat.	dative
dB	decibel(s)
df	degrees of freedom
esp.	especially
EVAL	the evaluation component of Optimality Theory
f.	feminine
F_0	fundamental frequency
F_1	first formant
F_2	second formant
fem.	feminine
FFT	Fast Fourier Transform
GSCL	Generalized Syllable Contact Law
Hz	hertz
ITB	Imdlawn Tashlhiyt Berber
kHz	kilohertz
LPC	linear predictive coding
m.	masculine
ml	milliliters
mm	millimeters
ms	manuscript
ms	milliseconds
MSD	minimum sonority distance
mv	millivolts
n.d.	no date
no.	number
OCP	Obligatory Contour Principle
OT	Optimality Theory
P_o	intraoral air pressure
p.c.	personal communication
perf.	perfective
RED	reduplicant

SCL	Syllable Contact Law
sd	standard deviation
SDP	Sonority Dispersion Principle
sec	second(s)
sg.	singular
SPE	*The Sound Pattern of English*
SSG	Sonority Sequencing Generalization
SSP	Sonority Sequencing Principle
TETU	the emergence of the unmarked
U	air flow
U_g	glottal air flow
U_n	nasal air flow
U_o	oral air flow
U_t	total air flow
UG	Universal Grammar
VOT	voice onset time

INTRODUCTION

The general topic of this dissertation is ***sonority***. Specifically, the primary objective of my research is to pursue the hypothesis that inherent segmental sonority (in the phonological sense) has concrete, measurable, physical correlates which can be quantified into a precise and nonarbitrary definition. To achieve this goal I report the findings of an extensive instrumental experiment designed to quantify the universal sonority hierarchy in a phonetically reliable and unambiguous way. The results of this project are then used to provide some fresh answers to several important and long-standing theoretical controversies in the interface between phonetics and phonology: (1) What is sonority? That is, is there any coherent notion of sonority that can be shown to be grounded in evidence external to the sequencing facts that sonority is assumed to account for? (2) What is the articulatory and/or acoustic basis of sonority? (3) Can and should the sonority hierarchy be quantified in some way? If so, how should the increments be expressed — in phonetic (articulatory, acoustic) or phonological terms? In other words, what is the best and most appropriate characterization of the sonority hierarchy?, and (4) Is the sonority scale universal or language-specific?

As a preview of what is to come, I offer the following terse replies to the queries just raised: (1-2) Sonority is a nonbinary (*n*-ary) phonological feature which derives from a hierarchical phonetic scale that is strongly correlated with intensity of the voice (in decibels) in a positive direction and with peak intraoral air pressure (in cm H_2O) in a negative direction. In other words, the more sonorous a sound is, the louder it will tend to be, and conversely, less sonorous sounds involve greater air pressure (and concomitant rate of air flow). (3) For example, in chapter 5 I posit that sonority can be defined by means of a linear regression equation such as the following: $sonority = a + b \times dB$, where the slope b is positive. The main reason for expressing sonority in this way is to show that it is phonetically grounded in specific physical events. In other words, characterizing sonority as a function of this type fits the obtained experimental data quite well and thus demonstrates that the relationship between sonority and intensity is both simple and direct. (4) As implied by the use of the word *inherent* above, the sonority scale need only be established once since it is universal. However, in keeping with a fundamental premise of Optimality Theory (OT: Prince and Smolensky 1993), cross-linguistic phonotactic variation reflects not a difference in sonority *per se*, but rather the free permutation and factorial typology resulting from language-specific rankings of universal constraints which are based in sonority.

In conjunction with the goals stated above, I now list a number of more specific research issues which this work helps to resolve. In the first place, there is widespread disagreement among linguists concerning which natural classes need to be distinguished in terms of the sonority hierarchy. For example, the following sonority contrasts are often disputed:

- high vowels vs. glides

- laterals vs. rhotics
- fricatives vs. stops
- voiced vs. voiceless obstruents
- voiced stops vs. voiceless fricatives
- affricates vs. stops and affricates vs. fricatives

For each of these pairs several questions have never been conclusively answered:

- Does the physical evidence support a difference in sonority between these two groups of segments?
- If so, is such a distinction confirmed by the cross-linguistic behavior of these natural classes?
- In other words, does the phonological evidence indicate that there is any empirical reason to separate group A from group B in terms of relative sonority?

Several other controversies which recur in discussions of sonority are the following:

- Where do /ʔ/ and /h/ fit in the hierarchy? Or, why do they seem to behave at times like sonorants yet other times like obstruents? (Many treatments of sonority ignore problems such as these because of their inherent difficulty.)
- Do /s/ (and perhaps other sibilants) merit a special position separate from all other obstruents?

- Which relationships in the sonority hierarchy are universally fixed, and which are open to language-specific permutation?

In short, this dissertation probes (among other things) the potential difference in sonority between several natural classes of speech sounds. In the final analysis, most of these questions are probably best resolved by phonological evidence such as phonotactic restrictions and dynamic segmental alternations. However, an important related issue is whether the phonetic characterization of sonority which emerges from my experiment lines up with the hierarchy given by the phonology. This latter point is a focus of chapter 5.

The remainder of this dissertation is organized as follows. In the first major part (chapters 1-3) I summarize the extant literature on sonority in order to lay a foundation for part 2. My goal in part 1 is to critically review the major issues, controversies, and insights which have resulted from treatments of sonority in the past. First, in chapter 1 I briefly discuss a number of universal as well as language-specific phonological phenomena which indicate that sonority is a valid and useful theoretical construct. Next, in chapter 2 I show that previous attempts to define sonority have led to a noticeable lack of consensus among linguists. Finally, in chapter 3 I trace the historical development of the sonority hierarchy in linguistic theory and description, focusing especially on the numerous scales or indices which have been posited to capture systematic relationships between speech sounds. Readers who are already well-versed in the literature on sonority may wish to initially just skim through chapters 1-3 or jump over them entirely.

Part 2 (chapters 4-6) reports the results of a series of experiments which explore the physical and psychological bases of sonority in human language. First, in chapter 4 I analyze an extensive corpus of instrumental data that documents the correlation between sonority and five phonetic parameters in both English and Spanish. Three of these are acoustic in nature — intensity, F_1, and segmental duration — while two are aerodynamic — intraoral air pressure and oral plus nasal air flow. Of these, intensity clearly and consistently emerges as the best "substance" for quantifying sonority. Consequently, in chapter 5 I apply the obtained measurements of intensity to the elaboration of a precise and potentially universal definition of sonority. Finally, in chapter 6 I discuss a psycholinguistic experiment that manipulates reduplicative rhyming pairs (such as *roly-poly*) in which sonority also plays a crucial role in explaining the attested patterns.

PART 1

BACKGROUND: A REVIEW OF THE LITERATURE ON SONORITY

CHAPTER 1

PHONOLOGICAL EVIDENCE FOR THE SONORITY HIERARCHY

1.1 Introduction

In this chapter I discuss a series of phonological rules, constraints, and principles which demonstrate the need for some notion of sonority as a theoretical primitive of Universal Grammar (UG). First I examine five phenomena which are observed in many or most languages of the world, such as the Sonority Sequencing Principle (SSP). Then I consider four processes involving sonority which appear to be language-specific.

1.2 Universal patterns of sonority

1.2.1 The Sonority Sequencing Principle

The *syllable* is often defined as a sequence of one or more adjacent segments which comprise a single wave or pulse of acoustic energy. This conceptualization of the syllable dates back at least as far as the work of Sievers (1885/1901). The physical force which is minimized at the margins of syllables and rises to a peak in the nucleus was eventually termed *sonority* (e.g., Pike 1943). With the development of formal models of linguistics in the 20th century, the tendency of speech sounds to be arranged in an alternating pattern of sonority crests and troughs came to be known as the Sonority Sequencing Principle (SSP) or Sonority Sequencing Generalization (SSG). There are too many works dealing with the SSP to list each one, but some of the more important references include Hooper (1976), Harris (1983), Selkirk (1984), Clements (1990), and Blevins (1995). The SSP can be expressed in several different yet basically equivalent ways; as working definitions let us posit the following statements:

(1.1) Sonority Sequencing Principle

(a) In every syllable there is exactly one peak of sonority, contained in the nucleus.

(b) Syllable margins exhibit a unidirectional sonority slope, rising toward the nucleus.

Due to the effects of the SSP, for example, monosyllabic words such as *snug* are well-formed since the sonority slope rises progressively from /s/ to /n/ to the nucleus /ʌ/ before dropping to the coda /g/. On the other hand, hypothetical syllables such as *[nsʌg]$_\sigma$ violate the SSP due to the reversed onset cluster /ns/ in which /n/ constitutes a second peak since it is more sonorous than /s/. In most languages syllables like */nsʌg/ are ungrammatical because they disobey the SSP. The robust tendency of most languages to systematically enforce the SSP in their inventory of possible syllable types constitutes evidence that some notion of sonority must be encoded in the universal constraint component CON.

However, as critics of sonority often point out, many languages do in fact permit some syllables to violate the SSP (Ohala 1990a). A very common type of example would be English words such as *school*, *stick*, etc., provided that fricatives are higher in sonority than stops, a fairly standard (but not universally accepted) assumption. Other languages exhibiting highly complex clusters are Russian (Halle 1971, Itô 1982) and Klamath (Barker 1964, Clements and Keyser 1983). A number of formal devices, some of which are painfully ad hoc, have been posited to explain away exceptional "sonority reversals" like these: extrasyllabicity, syllable appendices and "affixes", adjunction, non-exhaustive parsing, degenerate syllables, null or empty nuclei, language-particular stipulation, complex phonemic units (e.g., inverted affricates), etc. (See Churma and Shi (1996) and Cho and King (2000) for a useful discussion of this issue.) However, /s/ (or perhaps sibilants in general) may be a special case, due to their high stridency; see §3.2.3 and 6.5. Thus it may not be necessary to admit reversals for other fricatives. If this is right, then the number of ad hoc statements and patches we need to invoke may indeed be few. That is, "true" sonority reversals of the type /lk/ are quite rare. Furthermore, there is still a strong implicational universal which is exceptionless, as far as I am aware: any language which has a reversed onset cluster such as *liquid* + *obstruent* will always have the less marked sequence *obstruent* + *liquid* as well (Greenberg 1978).

Another problem for the SSP is that sonority peaks do not always coincide with the syllable nucleus; for example, in the word *yearn* the /y/ is an onset, as noted by Clements (1990), Butt (1992), and Kenstowicz (1994). A similar complication is the existence of minimal pairs in which the same sequence of segmental melodies is syllabified in contrasting ways, such as in the phrases *hid names* vs. *hidden aims*, pointed out by Ladefoged (1975, 1993) and Nathan (1989). However, in this case the problem disappears when we take into account the prosodic bracketing, i.e., when *hidden* is pronounced in isolation, the /n/ is already syllabic. A more difficult challenge is the contrast between *cauldron* (with a syllabic /n/) and *lantern* (with a syllabic /r/). For this pair it is impossible to predict which consonant in the /rn/ sequence will be syllabic. Clements (1990) also mentions the pair *pedlar* (two syllables) vs. *pedaller* (three syllables).

In the models of generative grammar typical of the 1970's and 1980's, these facts often led to conundrums such as, how can the SSP simultaneously be turned "on" and turned "off" in the same language?; Why do we need different types of formal mechanisms (principles, filters, constraints, rules) to deal with the same phenomenon (sonority)?; etc. The more recent model of Optimality Theory (OT: Prince and Smolensky 1993, McCarthy and Prince 1993) provides an insightful answer to these dilemmas: all linguistically-significant generalizations (of which the SSP is clearly one) are universal in the sense that they are present in every language, but they are encoded as a series of ranked and violable constraints which potentially conflict with one another. Lower-ranked constraints may be violated (albeit as minimally as possible) in order to increase satisfaction of higher-ranked constraints. A grammar is a language-specific hierarchy of the complete inventory of UG constraints, or CON. This conceptualization of human language illuminates the fact that phonological principles such as the SSP are only universal ***tendencies***: they exert pressure on the selection of output forms, but this pressure is not always absolute. In one language the SSP may be highly ranked and therefore visibly active (*ceteris paribus*), while still yielding to more important constraints in the right circumstances. And in another language the SSP may be ranked quite low and thus appear to be "turned off" in general, yet still exert its force in just those cases in which all dominating constraints fail to determine the outcome. This is emergence of the unmarked or TETU (McCarthy and Prince 1994). If a necessary criterion for including a generalization in CON is that it have no exceptions, i.e., never be violated, in any language of the world, our inventory of phonotactic constraints would be quite meager indeed. I therefore conclude that the SSP is a soft but nevertheless valid universal principle which must be captured in phonological theory by means of one or more constraints.

A striking and well-known instantiation of the SSP is provided by Berber. Important references include Dell and Elmedlaoui (1985, 1988, 1992), Prince and Smolensky (1993), and Clements (1997). In the Imdlawn Tashlhiyt dialect of Berber (hereafter ITB), long clusters of consonants without any vowels are possible, and even somewhat common: /tftktstt/ 'you sprained it (fem.)' (Dell and Elmedlaoui 1988:1). In ITB, syllabification is completely predictable, being straightforwardly driven in the vast majority of cases by the interaction of only two constraints: (1) the SSP; and (2) ONSET, the requirement that all syllables begin with a consonant. In ITB, ONSET can be violated only in phrase-initial position; in all other situations it is obeyed without exception. Given this pressure, all phonemic segments of the language, vowels and consonants alike, may be recruited to serve as a syllable nucleus, including voiceless stops. Thus, for example, the word cited above is parsed as [tf.tk.tstt], where periods mark syllable boundaries and syllabic consonants are underlined. In cases of potential ambiguity, i.e., when the violation of ONSET is not at stake, any two adjacent segments are parsed in such a way that the more sonorous one constitutes a nucleus, as demanded by the SSP. This requirement leads to alternations in syllabicity, as illustrated by the following paradigm from Dell and Elmedlaoui (1985:106). In these verbs the form on the left is the 2 sg. perfective and the one on the right is 3 f. sg. perfective. (The 2 sg. is marked by /t-...-t/; 3 f. sg. by /t-/; /-a-s/ indicates a dat. 3 m. sg. object; /X/ is a voiceless uvular fricative; and underlining denotes consonants which are parsed as syllable nuclei.):

(1.2)	2 sg. perf.	3 f. sg. perf.	gloss
	[trglt]	[trglas]	'lock'
	[tskrt]	[tskras]	'do'
	[tXznt]	[tXznas]	'store'
	[tzdmt]	[tzdmas]	'gather wood'
	[trkst]	[trksas]	'hide'

To anticipate the discussion in §3.2.5.2, the contrast between [tXznt] and [tXznas] shows that it is important to recognize voicing as a feature which can distinguish among obstruents in terms of relative sonority. This is because the SSP favors /z/ over /X/ as a nucleus. In this case the fact that *[tXznas] is ungrammatical demonstrates that the preference for a voiced fricative over a voiceless one in nuclear position (enforced by the SSP) overrides the pressure to parse every two adjacent consonants (e.g., /tX/) such that the more sonorous one (/X/) is syllabic. As noted by Prince and Smolensky (1993), the syllabification facts of ITB are confirmed by native speaker intuition, emphasis spread, consonant gemination, intonation, and poetic versification (Dell and Elmedlaoui 1985, 1988, 1992).

1.2.2 Minimum sonority distance

While the SSP goes a long way in accounting for universally unmarked aspects of syllable structure, it clearly does not complete the story. Most languages which permit onset clusters consider syllables such as /pla/ and /pra/ to be well-formed, whereas syllables such as /pna/ and /psa/ are much less common cross-linguistically. All four of these syllables fulfill the SSP since the onset sonority slopes all rise; the difference between them lies in the relative sonority difference separating the two onset consonants in each case. Most languages thus invoke constraints on ***minimum sonority distance*** among tautosyllabic consonant clusters as a supplement to the SSP in arriving at their inventory of possible syllable types (Steriade 1982, Selkirk 1984). For example, in Spanish the difference in sonority between a voiceless stop and a liquid is sufficiently large, as attested by forms such as /playa/ 'beach' and /prado/ 'field; meadow'. However, syllables beginning with a stop followed by a nasal, such as */pna/, do not occur in Spanish. On the other hand, in Chamicuro, an extinct Maipuran Arawakan language of Peru, well-formed examples such as /pnahmule/ 'swamp' and /knani/ 'stomach' are abundant (Parker 1987). For a detailed treatment of the Spanish facts in a Principles and Parameters approach, Harris (1983) and Selkirk (1984) are standard references. OT analyses of onset sonority patterns include Baertsch (1998, in preparation) and Morelli (1998, 1999). Later in this chapter I note that families of sonority distance constraints may not in fact be necessary since they might be derived from Clements' (1990) Sonority Dispersion Principle, to be discussed shortly.

Before moving on, I note that sonority skeptics such as Ohala and Kawasaki (1984) and Ohala (1990a-b) reject sonority-based generalizations concerning syllable phonotactics since these do not work in all situations. For example, in English, /pl/ and /kl/ make good onsets but */tl/ does not, despite the fact that all three clusters presumably involve the same sonority distance. Ohala's objection is actually more complex than this oversimplified argument implies. For him, manner, place, phonation, etc., are all dimensions along which segments contrast, and languages tend to prefer that successive segments differ by some minimal amount on each of these parameters (and others as well). For example, labial consonants tend to combine more easily with unrounded vowels than with rounded ones (to maintain a sharper contrast in perceptibility). Ohala's story then is a more inclusive one, in which all phonetic features must be modulated sufficiently between one segment and the next. However, there is a presupposition behind this claim which I do not find convincing, namely, that if we cannot find a single physical correlate for sonority, then sonority must not exist. If this were true, we would also have to deny the existence of stress, tenseness, and many other distinctive features. While an appeal to simplicity in describing phonological phenomena is desirable, this does not invalidate the more complicated analyses which sometimes are required. Independently-required mechanisms such as the OCP (Obligatory Contour Principle) can pick up where sonority leaves off to deal with prohibitions based on, for example, homorganicity (cf. Basbøll 1994, Oostendorp 1999). In Ohala's view, of course, there is no principled distinction between the OCP and the SSP since both require some minimum modulation of the string.

In my opinion, the above arguments do not undermine the reality of sonority. A grammar consists of hundreds of interacting constraints, and it is unreasonable to demand that any single one of them account for 100% of the data without the aid of other constraints to clean up systematic exceptions which can be explained on other grounds. As an analogy I note that the perceptual principle of maximizing the distance between phonemes in the conceptual vowel space (resulting in a preference for the three segments /i a u/) should not be discarded as invalid just because some languages have an /i/ but no /u/. Since /i/ and /u/ are basically equidistant from /a/, the markedness of /u/ relative to /i/ must be explained by some other mechanism. This does not entail, however, that we should throw out the maximum distance principle for vowels; rather, we should obviously keep it since it clearly is a universal tendency. The following comments on constraint interaction echo these sentiments exactly. They read like they are taken from a classic OT work such as Prince and Smolensky (1993). Nevertheless, they were written in 1988!:

> "The preference laws express partially conflicting tendencies.... I do not consider this a defect of the theory. I mentioned at the beginning that improvement on one parameter can entail deterioration on another. It is impossible to optimize a language system on all parameters at once; there can exist no 'optimal' language system as such, but only systems that are optimized on some parameters.... [A]ll sound changes are local improvements, i.e. improvements on certain parameters, and the relative quality of structures is characterized by the relevant preference laws. It follows that when syllable structure is altered without any resulting syllable structure improvement, or even with a deterioration of syllable structure, the change is not a syllable structure change in the technical sense but a change motivated by some other factor, only incidentally affecting syllable structure." (Vennemann 1988:65-66)

1.2.3 The Syllable Contact Law

Another sonority-based constraint active in many languages is the Syllable Contact Law (SCL). Pre-OT works discussing the SCL include Hooper (1976), Murray and Vennemann (1983), Vennemann (1988), Dogil (1988), and Clements (1990). The following formulation of the SCL is due to Murray and Vennemann (1983:520):

(1.3) Syllable Contact Law

> "The preference for a syllabic structure *A$B*, where *A* and *B* are marginal segments and *a* and *b* are the Consonantal Strength values of *A* and *B* respectively, increases with the value of *b* minus *a*."

As far as I am aware, this was the first published work to use the name *Syllable Contact Law* and give it a precise definition. At that time the cover term *strength* was often used as an antonym for *sonority*. For our purposes here the two labels can be taken to be functionally equivalent inverses of one another, i.e., the scales run in opposite directions. Nevertheless, other subtle differences between strength and sonority are sometimes posited, a detail we can ignore for the moment (but cf. §3.2.5.4 for further discussion).

Vennemann (1988:50) posits an exhaustive list of repair strategies which languages employ to improve satisfaction of the SCL. These are summarized below, as annotated by Davis (1998:183):

Table 1.1: Illustrations of the Syllable Contact Law

process	example	language
coda weakening	b.r → w.r	Hausa
onset strengthening	k.l → k.t	Kazakh
tautosyllabification	k.l → .kl	Germanic
gemination	b.r → b.br	Latin > Italian
epenthesis	n.r → n.dr	Spanish
regressive assimilation	k.m → ŋ.m	Korean
progressive assimilation	g.n → g.g	Pali
anaptyxis	p.r → pV.r	Winnebago
metathesis	d.n → n.d	Sidamo

More recent treatments of the SCL as an OT constraint include Alderete (1995), Bat-El (1996), Urbanczyk (1996), Green (1997), Landau (1997), Shin (1997), Beckman (1998), Davis (1998), Davis and Shin (1999), Gouskova (1999, 2001), Morelli (1999), Struijke (1999), Krämer (2000), and Rose (2000). In many of these analyses two distinct constraints are required. One is the SCL proper, expressed somewhat along the lines of (1.3), but substituting *sonority* for *strength*. The second, related constraint, which is called SYLLABLE CONTACT SLOPE (Bat-El 1996, Shin 1997, Davis 1998) or SONORITY CONTOUR SLOPE (Rose 2000), mediates the relative degree of syllable contact violation permitted in each language, normally in a gradient fashion. As Clements (1990) notes, both the SCL itself as well as the SLOPE constraint are ultimately related to the Sonority Dispersion Principle, to which I now turn.

1.2.4 The Sonority Dispersion Principle

The next, and potentially most important, of the universal mechanisms based on sonority relationships is Clements' (1990, 1992) Sonority Dispersion Principle (SDP). The SDP can be tersely stated as follows: maximize the onset-to-nucleus sonority slope and minimize the nucleus-to-coda sonority slope. Borrowing from Fujimura and Lovins (1978), Clements (1990) adopts the proposal that the syllable consists of two parts or *demisyllables*, the first encompassing the onset plus nucleus and the second the nucleus plus coda. Thus in the syllable /kran/, for example, the initial demisyllable is composed of /kra/, and the final demisyllable of /an/. In this approach the nucleus crucially forms part of both demisyllables simultaneously. The SDP can then be expressed quite precisely as follows: among demisyllables of the same length (i.e., the same number of consonants), an initial demisyllable is more harmonic to the degree that it minimizes *D* in (1.4) below; a final demisyllable is more harmonic to the degree that it maximizes *D*, where *D* is defined by a formula taken from physics and geometry:

(1.4) $$D = \sum_{i=1}^{m} \frac{1}{d_i^2}$$ (Clements 1990:304)

d = distance between the sonority indices of each pair of segments
m = number of pairs of segments (including nonadjacent ones), where
$m = n\,(n-1)\,/\,2$, and where n = number of segments

Clements (1990:304) paraphrases (1.4) as follows: "D ... varies according to the sum of the inverse of the squared values of the sonority distances between the members of each pair of segments within" a demisyllable. *D*, then, is the reciprocal of dispersion. The linguistic use of equation (1.4) originates with the work of Liljencrants and Lindblom (1972) on perceptual distance between segments in a vowel space. Its application to sonority and syllable structure is anticipated in Hooper (1976) and in Vennemann's (1988:13-14) Head (Onset) Law.

To illustrate the application of (1.4), let us assume for the moment the sonority scale which Clements (1990) posits:

(1.5)

		sonority index
vowels	(V)	5
glides	(G)	4
liquids	(L)	3
nasals	(N)	2
obstruents	(O)	1

When *D* is computed for demisyllables containing one or two consonants, it results in the following values:

(1.6)

OV, VO	=	.06	(Clements 1990:304)
NV, VN	=	.11	
LV, VL	=	.25	
GV, VG	=	1.00	

OLV, VLO = .56
OGV, VGO = 1.17
ONV, VNO = 1.17
NGV, VGN = 1.36
NLV, VLN = 1.36
LGV, VGL = 2.25

The SDP correctly predicts that the universally-preferred syllable of type *CV* should have an onset consonant which is as low in sonority as possible. In OT the spirit of the SDP has been captured by Prince and Smolensky's (1993) Peak and Margin hierarchies, which are used in the analysis of Imdlawn Tashlhiyt Berber:

(1.7) (a) *M(ARGIN)/*a* ⟩⟩ *M/*i* ⟩⟩ ... ⟩⟩ *M/*d* ⟩⟩ *M/*t*

(b) *P(EAK)/*t* ⟩⟩ *P/*d* ⟩⟩ ... ⟩⟩ *P/*i* ⟩⟩ *P/*a*

where *MARGIN/*a* = *a* must not be parsed as a margin, etc.

A problem with the Margin hierarchy in (1.7a) is that it holds true only for onsets; in codas it needs to be reversed, in accordance with the SDP. As Clements (1992) and Smolensky (1995) point out, incorporating the SDP as a formal OT constraint may allow us to replace the list in (1.7a), simplifying CON. The following data illustrate the operation of the SDP. Gnanadesikan (1995b) provides a few sample forms from a 2;9 girl acquiring English in which all adult onset clusters reduce to a single consonant, invariably the least sonorous one (TETU):

(1.8)

clean	[kin]
please	[piz]

sleep	[sip]
snow	[so]
friend	[fɛn]
sky	[kay]
spill	[pɪw]

In this girl's grammar, complex onsets are not allowed. The determination of which consonant surfaces intact in each case is predictable, but not fixed. Thus in *sky* and *spill* the initial /s/ deletes since it is more sonorous than /k/ and /p/. On the other hand, in *sleep* and *snow* the /s/ survives since it is less sonorous than /l/ and /n/. (In her pronunciation of the word *straw*, both the /s/ and the /r/ are deleted.) Neither the SSP, nor minimum sonority distance constraints, nor the SCL, nor ONSET by themselves can achieve this result for us, but the SDP can. I refer the reader to the formal analyses of these data in Gnanadesikan (1995b) and McCarthy (2002), who capture the effect of the SDP with the Margin constraint family in (1.7a). An analogous process in adult language is provided by Sanskrit reduplication, to be discussed in §1.3.3 below.

The pattern illustrated in the data in (1.8) sheds light on a shortcoming in Clements' (1990) model. The mapping of *sky* to [kay] rather than to *[say] demonstrates that we need to make a distinction in relative sonority among obstruents, *viz.*, fricatives > stops (cf. Benua 1997, Hironymous 1999, and §3.2.5.2). Otherwise, we miss a very simple and obvious generalization concerning the motivation for this straightforward process and have to complicate the analysis. This is of course not a quibble about the SDP *per se*, but rather about the sonority scale in (1.5) which Clements (1990) posits, lumping all obstruents into a single class. This topic — the nature of the divisions within the sonority hierarchy — is dealt with at length in chapters 3 and 5.

Concerning the SDP itself, I note that "reversed sonority" clusters such as the onset in the hypothetical syllable /rta/ have the same dispersion value as their counterparts which obey the SSP (/tra/ in this case). This is because the formula for D in (1.4) ***squares*** sonority distances, thereby canceling out a negative slope. Certainly this is an undesirable result since it implies that /rta/ and /tra/ are equally well-formed syllables. One could resolve this dilemma by appealing to the SSP, but inasmuch as one goal of the SDP is to explain SSP effects, that would be otiose.

In certain respects the two approaches to syllable phonotactics — the SDP and the minimum sonority distance (MSD) proposal (§1.2.2) — make different claims and therefore different predictions. This point shows up most clearly when we consider the status of C_1C_2V demisyllables. Assuming that C_1 is an obstruent, the SDP posits that the best C_2 is a liquid because liquids fall exactly midway between vowels and obstruents in terms of Clements' (1990) fivefold sonority scale, so an OLV demisyllable is optimally (most evenly) dispersed. In order for this result to be maintained, however, it is important that we not tamper with the sonority scale and/or indices. This is a drawback of the SDP model since, as we have seen, it is fairly well established that different sonority hierarchies are necessary in at least some languages (Baertsch 1998; cf. chapters 3 and 5). For example, if we divide obstruents into different sonority classes based on voicing and/or continuancy, then nasals rather than liquids might fall in the middle of the scale and therefore incorrectly be preferred in C_2 position.

A further potential problem with the SDP also relates to its claim that onset clusters of the type OL (obstruent + liquid) are less marked than OG (obstruent + glide). If this is true, we should find languages which permit the former but not the latter. One example of this type is Spanish. As Harris (1983) argues, in Spanish CGV sequences, the glide forms part of the nucleus rather than the onset because of details of stress placement (CGV syllables are heavy). However, a critical dilemma for the SDP is that its formulas do not directly evaluate onsets and nuclei *per se*, but rather ***demisyllables***. And Spanish clearly does permit OGV demisyllables along with OLV, as do all other languages which allow any onset clusters at all. That is, to my knowledge, there are no languages which restrict complex initial demisyllables to OLV only, without also permitting OGV. Consequently, a large part of the motivation for the SDP does not stand up to closer scrutiny.

A third problem with the SDP model is its claim that ONV and OGV demisyllables are equally harmonic, *ceteris paribus*, because they have the same *D* value. This simply appears to be wrong. There are many languages which attest OGV but not *ONV (examples below, plus Spanish), but no cases have been reported of languages with ONV but not *OGV. From this fact we can establish an implicational universal: if a language has demisyllables of the type ONV, it must also have OGV. The inverse of this statement is not true. Most of the problems with the SDP which have been mentioned above stem from one of its fundamental (and crucial) assumptions: that the nucleus of a demisyllable must be included in the dispersion calculation along with the marginal consonants. If we abandoned this assumption, all of the objections sketched above would disappear. However, if we do not take into account the sonority index of vowels, then we lose nearly all hope of generating a principled model in which OLV outranks OGV. I conclude that one of the most significant predictions of the SDP (OLV > OGV) is weakened by what may also be its fatal flaw. Finally, if we make distinctions in sonority among vowels based on features such as tongue height (cf. §1.2.5), then the SDP might predict the existence of languages in which initial demisyllables like /ta/, /ti/, and /la/ are grammatical, but */li/ is not, since its *D* value is too high. I am not aware of any attested cases of this kind.

As I have just argued, several problems with the SDP are automatically dissipated if we move vowels to the side and calculate sonority well-formedness based on consonants only (cf. Blevins 1995). This is exactly what the minimum sonority distance (MSD) approach does. In the models of Steriade (1982) and Selkirk (1984), for example, the optimal onset cluster is OG since it maximally separates its two members in terms of sonority. This predicts languages in which OG is possible but *OL is not. There are in fact a few such cases: in Huariapano (Parker 1994) and Minnesota Ojibwe (Nichols and Nyholm 1995), the only attested onset clusters involve a glide in C_2 position. (The latter case is mitigated somewhat by the fact that the language has no liquid phonemes at all.)

This would seem to suggest that we can tentatively posit another implicational universal: if a language permits OLV demisyllables, it must also allow OGV. Furthermore, in the MSD approach, OGV now correctly outranks ONV as well since there is less sonority distance between O and N than there is between O and G. In addition, with the MSD model we no longer have to worry about liquids falling in the middle when positing different sonority scales and/or indices. It would thus seem that the MSD theory enjoys several advantages over the SDP, all of which follow from the former's stance of not including vowels in sonority distance calculations among consonants.

Having established this point, we nevertheless run into another major obstacle now: what about languages like Spanish in which the only complex ***onsets*** are OL, not *OG? In this case appealing to the simultaneous existence of OGV demisyllables does not help us since in the MSD approach, glides are irrelevant when they occur in the nucleus. Therefore, the MSD model cannot account for these languages without complicating the theory by invoking some other principle to explain why *OG onsets are bad, while OL is good. We see then that the MSD approach suffers from a defect as well. We have thus reached an impasse. Furthermore, I suspect that the claims of the SDP model can be strengthened (corroborated) by evidence from other areas, such as statistical frequency of different onset types and the acquisition order of clusters among children. In addition, the SDP enjoys one very distinct advantage compared with the MSD approach: the SDP directly predicts the correct harmonic ordering of simple (*CV*) onsets (obstruents > nasals > liquids > glides) without any further machinery, but the MSD model has nothing to say about these at all. We have thus seen that the SDP and the MSD approaches make predictions which sometimes conflict, and the data available to help us resolve this dilemma are somewhat mixed. At the present moment, the question of which demisyllable is universally preferred — OLV or OGV — appears to be a major typological paradox. In addition, this problem is complicated even further by the very ambiguous status of glides cross-linguistically: are they best interpreted as consonants or non-moraic vowels; are they in the nucleus or in the onset; and if they are in the onset, are they independent segmental phonemes or just a secondary articulation on the preceding consonant? Given the very difficult nature of these issues, I cannot adequately resolve them here, so I will leave this topic as an interesting prospect for future research. However, before closing this discussion it would be beneficial to at least speculate on what kinds of data would be helpful in teasing apart the differences. On the one hand, the case for the SDP could be strengthened by providing documented examples of languages in which OLV demisyllables are grammatical but *OGV are not. On the other hand, evidence that would favor the MSD model would be cases of languages in which all of the following conditions are true: (1) OG onsets are possible, (2) OL onsets are not possible, (3) at least one liquid phoneme exists in the language in simple *CV* syllables, (4) glides are clearly in the onset, not in the nucleus, and (5) glides cannot be reanalyzed as nonsegmental features of the adjoining consonant. Huariapano (mentioned above) may be one language of this second type (Parker 1994).

1.2.5 Syllable weight effects

The final area of phonology in which sonority effects are often observed is stress assignment. It is well-known that the heavier a syllable is, the more likely it is to attract stress. Relative sonority has been claimed to be a primary factor in determining segmental weight, especially among vowels. Based on a number of case studies in works such as Bianco (1996), Kenstowicz (1996), and de Lacy (1997, 2002), we can posit a universal hierarchy of vowel weight/sonority from which languages exploit different subsets in assigning stress:

(1.9) *a* > *e*, *o* > *i*, *u* > *ə* > *ɨ*

(Bianco 1996, Kenstowicz 1996, de Lacy 1997, 2002)

In scale (1.9) we see that two different aspects of vowel quality correlate with sonority distinctions: height and peripherality. In establishing a unified definition of sonority, it would help if we could show that the combination *height* + *peripherality* can be reduced to a single physical parameter. Kenstowicz (1996) suggests what this may be: absolute duration. Vowels which are higher in sonority, i.e., farther to the left in (1.9), tend to be longer in phonetic duration than those lower in sonority (the former are also more intense than the latter). In chapter 4 I present instrumental evidence designed to test this hypothesis (sonority ≈ duration).

The Kobon language of Papua New Guinea nicely illustrates sonority-based differences in assigning stress. In Kobon, vowels are divided into four classes in terms of their propensity for attracting stress: /a/ > /e, o/ > /i, u/ > /ɨ, ə/. In unaffixed words, stress predictably falls on the most sonorous nucleus within a disyllabic window at the right edge. The following data illustrate this pattern, ignoring certain phonetic details (Davies 1980, 1981, Kenstowicz 1996, de Lacy 1997):

(1.10)	a ⟩ e	[hagápe]	'blood'
	a ⟩ o	[alágo]	'species of snake'
	a ⟩ o	[kɨdolmáŋ]	'type of arrow'
	a ⟩ i	[čáčiŋ]	'drum'
	a ⟩ i	[ki.á]	'species of tree'
	a ⟩ u	[xəgálu]	'spider'
	a ⟩ u	[xu.ám]	'species of tree'
	a ⟩ ə	[xábə]	'stone'
	a ⟩ ə	[xəfyá]	'rat'
	a ⟩ ɨ	[áñɨm-áñɨm]	'lightning'
	e ⟩ u	[uréf]	'short'
	o ⟩ u	[mó.u]	'thus'
	o ⟩ i	[si.óg]	'species of bird'
	o ⟩ ɨ	[gɨró-gɨró]	'to talk (mother pig to piglet)'
	i ⟩ ə	[gałínəŋ]	'species of bird'
	i ⟩ ə	[wí.ər]	'mango tree'
	i ⟩ ɨ	[íbɨl]	'very'
	u ⟩ ə	[łú.əł]	'horizontal house timbers'
	u ⟩ ɨ	[mú.ɨs]	'species of edible fungus'

Other languages in which sonority is claimed to be crucial for syllable weight distinctions include Axininca Campa (Payne 1990, Hung 1994, Hayes 1995, de Lacy 1997), Cowichan (Bianco 1996), Komi (Hayes 1995, de Lacy 1997), and Finnish (Anttila 1995, Hayes 1995). In Pirahã (Brazil), stress assignment is sensitive even to voicing contrasts among obstruents in onset position (Everett and Everett 1984, Hayes 1995, de Lacy 1997, Smith 1999).

1.3 Language-specific sonority effects

In this section I briefly review a number of sonority-based processes which are restricted to specific languages. These include an assimilation rule in Pali, onset preferences in Ịjọ, Sanskrit reduplication, and reduplicative nonce forms in English. All of these cases provide further evidence that sonority should be considered a universal phonological primitive.

1.3.1 Pali consonant assimilation

Hankamer and Aissen (1974) discuss a pervasive rule of consonant assimilation in Pali, a middle Indic dialect spoken in the 6th century B.C. When morpheme concatenation results in the juxtaposition of non-identical underlying consonants, the cluster is resolved in one of two ways: vowel epenthesis or consonant assimilation. Except in the case of nasal plus stop clusters, one of the two adjacent consonants assimilates completely to the other one. The direction of assimilation is strictly determined by the following principle: the consonant which is higher in sonority must assimilate to the one lower in sonority. (When the consonants are equal in sonority, the first one assimilates to the second one.) This process is interesting in that it favors low-sonority onsets over high-sonority codas (both preferred by the SDP), and thus further exemplifies the universal onset/coda asymmetry (Hooper 1976, Goldsmith 1990, Beckman 1998). Some illustrative data, in which /s/ causes aspiration of an adjacent stop, and *v* is the glide /w/:

(1.11) /vas-tuṃ/ → [vatt^{h}uṃ] 'dwell - infinitive'
/vak-ssa-/ → [vakk^{h}a-] 'speak - future'
/dis-ya-/ → [dissa-] 'see - passive'
/arab^{h}-ya/ → [arabb^{h}a] 'begin - gerund'
/kar-tuṃ/ → [kattuṃ] 'make - infinitive'
/lag-na/ → [lagga] 'attach - past participle'
/gam-ya/ → [gamma] 'go - gerund'
/kilbiṣa/ → [kibbisa] 'guilty' (Sanskrit > Pali)
/sup-ta/ → [sutta] 'sleep - past participle'
/sam-nisīd-/ → [sannisīd-] 'be quite - indicative'
/kar-ya-/ → [kayya-] 'make - passive'
/k^{h}an-ya-/ → [k^{h}añña-] 'dig up - passive'
/kalmāsa/ → [kammāsa] 'freckled' (Sanskrit > Pali)
/kalya/ → [kalla] 'ready' (Sanskrit > Pali)
/bilva/ → [billa] 'a fruit' (Sanskrit > Pali)
/kiṇva/ → [kiṇṇa] 'yeast (?)' (Sanskrit > Pali)

While many of these alternations can be explained by the SCL, some of them cannot. For example, the underlying representations in cases such as [vatt^{h}uṃ], [kattuṃ], [kibbisa], and [kammāsa] are well-formed according to the SCL, and the outputs involve fortition in coda position, contrary to the predictions of both the SCL and the SDP. Consequently, the process truly is mirror-image (bidirectional) in nature. These data once again provide evidence that fricatives need to be counted as higher in sonority than stops, lest we complicate the analysis and miss a simple, obvious generalization. Hankamer and Aissen (1974) formalize the rule as in (1.12b), assuming that sonority is a multi-valued hierarchical feature as in (1.12a):

(1.12)	(a)	stops	s	nasals	l	v	y	r	vowels
		1	2	3	4	5	6	7	9

$$\text{(b)}\quad [m \text{ sonority}] \rightarrow [\alpha \text{ Features}] \ \% \ \underline{\quad\quad} \begin{bmatrix} n \text{ sonority} \\ \alpha \text{ Features} \end{bmatrix}$$

$$\text{where } 7 \geq m \geq n$$

A minor problem with the rule as formalized in (1.12b) is that it does not specify the direction of assimilation when the two consonants are equal in sonority.

1.3.2 Ịjọ consonant strength

Williamson (1965, 1978) describes an intriguing pattern of consonantal strength in Ịjọ, a cluster of four closely related languages of Nigeria. In Ịjọ there is a strong correlation between the position of a consonant in the word and how strong or weak that consonant is. Based on a reconstruction of about 450 Proto-Ịjọ forms, she finds that an overwhelming majority of stems are subject to a constraint whereby a consonant cannot be stronger than a preceding consonant in the same word. It is clear from her division of Ịjọ consonants into three classes that her term *strength* is essentially the inverse of sonority:

(1.13) Classification of Proto-Ịjọ consonants as posited by Williamson (1978)

(a) Strong: p t k kp f s

(b) Medium: b d g gb ɓ ɗ (the latter two are implosives)

(c) Weak: ɣ m l r w y (all sonorants)

Ịjọ stems may contain up to three consonants, labeled C_1, C_2, and C_3, respectively. If C_1 is strong, C_2 can be essentially anything. However, if C_1 is medium, C_2 can be only medium or weak. Finally, if C_1 is weak, C_2 must also be weak. Williamson (1978:344) notes that the same restrictions hold between C_2 and C_3. The following Proto-Ịjọ forms illustrate these patterns, ignoring tones (Williamson 1978:345):

(1.14)	*/o-kosi/	'old (person)'	(strong, strong)
	*/kodmu/	'waist'	(strong, medium, weak)
	*/akalʊ/	'moon'	(strong, weak)
	*/ɗigi/	'rope'	(medium, medium)
	*/ɓeri/	'ear'	(medium, weak)
	*/o-molmi/	'slave'	(weak, weak, weak)

There also exist many counterexamples to these generalizations, but Williamson (1978:345) reports that more than two-thirds of the data are "regular." She discusses a number of lenition and reduction processes, mostly diachronic in nature, which help explain why these patterns are attested. She concludes by positing the following principle for Ịjọ: "If a consonant weakens in C_1 position, it will also weaken at C_2 and C_3: but a consonant can weaken at C_2 or C_3 without any corresponding change at C_1." (Williamson 1978:347)

For the Kolokuma dialect of Ịjọ, Williamson (1965) displays several useful charts which tabulate the lexical frequency of consonants in each position. For example, the following matrix gives the relative frequencies of plosives (P), fricatives (F), and sonorants (S) in biconsonantal roots. This division of segments differs somewhat from that of (1.13). Nevertheless, both schemes of classification test the same hypothesis, one based on sonority/strength.

Table 1.2: Distribution of consonants in Kolokuma (Williamson 1965:22)

		C_1			Total
		P	F	S	
C_2	P	131	12	17	160
	F	28	13	1	42
	S	232	65	60	357
Total		391	90	78	559

Two details of table 1.2 are noteworthy. First, for C_1 the frequencies inversely follow the sonority hierarchy. Second, sonorants are overwhelmingly predominant in C_2. A chi-square test which I calculated on the values of Table 1.2 indicates a strong statistical dependence between position in word and manner of articulation: $\chi^2(4) = 26.06, p < .0000$. In another chart analyzing 206 tri-consonantal roots, 147 begin with a plosive, 29 with a fricative, and 30 with a sonorant. In C_3 position we find 130 sonorants, 12 fricatives, and 64 plosives (Williamson 1965:23).

Smith (1999) posits the following constraint to account for the Ịjọ facts in OT:

(1.15) $\sigma_1 \rightarrow$ GOODONSET: $\forall x, x \in \sigma_1$, x has a low-sonority onset

However, the large number of exceptions to this very "soft" constraint indicate that it is only a statistical tendency, not an outright grammatical prohibition.

Nonetheless, the pattern of Ịjọ consonants does provide additional evidence for the sonority hierarchy.

1.3.3 Sanskrit reduplication

Another language-specific sonority pattern is found in Sanskrit. As many phonologists have noted, unmarked features and segments tend to emerge in reduplicants, especially when these are required to be prosodically simpler than their corresponding bases (McCarthy and Prince 1994). In Sanskrit, onset clusters are permitted in the base, but strictly proscribed in the reduplicant, as illustrated by the following data (Whitney 1889, Steriade 1982, 1988a, Gnanadesikan 1995b, Kager 1999, Morelli 1999). For the perfective the reduplicant is a light (*CV*) syllable. For the intensive it is a heavy syllable (*CV:* or *CVC*). A few minor adjustments are observed in reduplicated consonants, such as palatalization and loss of retroflexion. Suffixes are omitted here:

(1.16) Sanskrit full grade reduplication (reduplicant underlined)

(a) perfective, bases beginning with *CV*

[pa-pat]	'fly; fall'
[tu-tud]	'push'
[sa-sarǰ]	'send forth'
[mi-mikṣ]	'be situated'
[ru-rud^h]	'obstruct'
[ya-yat]	'stretch'
[wa-ward^h]	'grow'

(b) intensive, bases beginning with *CV*

[čar-čar]	'move'
[bad-ba:d^h]	'oppress'
[wa:-wad]	'speak'

(c) perfective, bases beginning with *CCV*

[pa-psa:]	'devour'
[pa-prač^h]	'ask'
[ta-tsar]	'approach stealthily'
[ta-tyaǰ]	'forsake'
[ču-kṣnu]	'whet'
[sa-swar]	'sound'
[si-ṣmi]	'smile'
[si-ṣnih]	'be sticky'
[su-ṣru]	'flow'
[ša-šrat^h]	'slacken'
[da-d^{h}ma:]	'blow'
[du-druw]	'run'
[da-d^{h}wans]	'scatter'
[ma-mna:]	'note'
[mu-mluč]	'set'
[pu-ṣp^{h}u]	'burst'
[ta-st^{h}a:]	'stand'
[tu-ṣtu]	'praise'
[ču-ščut]	'drip'
[ča-skand]	'leap'

(d) intensive, bases beginning with *CCV*

[čan-kram]	'stride'
[sa:-swap]	'sleep'
[ša:-šwas]	'blow'
[da:-d^{h}ya:]	'think'
[wa:-wyad^h]	'pierce'
[tan-stan]	'thunder'

In Sanskrit the reduplicant copies (portions of) the initial syllable of the verb stem. The relevant detail here is which consonant appears in the reduplicant when the base begins with a cluster. As the data in (1.16c-d) show, the choice is once again based on sonority: the consonant which is lowest in the hierarchy wins, just as in Gnanadesikan's (1995b) corpus of child English data cited in §1.2.4. Thus when the stem begins with a consonant cluster which obeys the SSP, C_1 emerges in the reduplicant since it is less sonorous: [pa-prač^h]. Clusters which violate the SSP are limited to a sibilant followed by a voiceless plosive. In such cases C_2 is copied: [tan-stan]. These facts indicate that in Sanskrit, the formal equivalent of the SDP (the Margin markedness hierarchy) crucially outranks three faithfulness constraints — MAX-BR, LEFTANCHORING-BR, and CONTIGUITY-BR — since all of the latter are compelled to be violated (albeit in different forms). See Gnanadesikan (1995b), Kager (1999), and Morelli (1999) for OT accounts of Sanskrit reduplication.

1.3.4 English reduplicative rhymes

A final language-specific phenomenon rooted in sonority involves reduplicative rhyming words in English, such as *roly-poly.* Several researchers have identified a series of phonological "laws" governing such forms (Cooper and Ross 1975, Drachman 1977, Pinker and Birdsong 1979). Two of these principles are relevant here: (1) the initial consonant of the first part prefers to be more sonorous than the onset of the second part (e.g., *willy-nilly, loosey-goosey*); and (2) the final consonant of the first "morpheme" tends to be lower in sonority than the coda of the second one (*thick and thin, push and pull*). However, there also exist numerous exceptions, e.g., *teenie-weenie.* Consequently, in chapter 6 I discuss three psycholinguistic experiments (one of them my own) designed to test these hypotheses and quantify their statistical validity. Since these phenomena are discussed extensively in that chapter, I do not consider them further here.

1.4 Summary

In this chapter I have reviewed a number of phonological patterns which, taken together, argue very strongly that some notion of sonority must be included in UG. Five mechanisms in particular are robustly attested cross-linguistically: (1) the Sonority Sequencing Principle, (2) constraints on minimum sonority distance, (3) the Syllable Contact Law, (4) the Sonority Dispersion Principle, and (5) sonority-based weight distinctions affecting stress assignment. I have also discussed four language-specific processes which involve sonority: (1) consonant assimilation in Pali, (2) consonant strength in Ịjọ, (3) Sanskrit reduplication, and (4) reduplicative nonce forms in English. The linguistic reality of sonority has been firmly established in the literature and should not be doubted. In the remaining chapters of this dissertation it now behooves us to provide answers to several related questions, such as, What is sonority?, and What does the sonority scale look like?

CHAPTER 2

THE CHALLENGE — DEFINING SONORITY

2.1 Introduction

My goal in this chapter is to show that *sonority* has never been defined in a universally agreed upon and satisfactory way, and that, consequently, this issue merits an in-depth study. I begin by demonstrating that the physical definition of sonority is a controversial and open-ended problem, plagued at times with circularity. To illustrate the dilemma, I offer a nearly exhaustive list of all the characterizations of sonority which have been proposed in the literature. I then argue that complex definitions of sonority as an interaction of several other phonological features are also inadequate.

2.2 What is sonority?

In chapter 1 we established the ***function*** of sonority in phonological systems. This naturally raises the question, what is the ***physical basis*** of sonority in the speech signal, if it even has one at all? If the sonority hierarchy is universal, as I claimed in the Introduction, then we should expect to find that it has identifiable correlates which derive from the architecture of the human vocal and/or auditory apparatus. Linguists have been keenly interested in this topic, yet the search for a reliable phonetic indicator allowing us to directly measure sonority has remained unfulfilled to this day. The following quotes exemplify the prevailing sentiments:

> "... the notion of relative sonority cannot be defined in terms of any single, uniform physical or perceptual property ..." (Clements 1990:298)
>
> "... a simple phonetic correlate to the phonological property of sonority has yet to be discovered ..." (Kenstowicz 1994:254)
>
> "The substantive uncertainty in finding theoretical or empirical correlates of sonority has led many researchers to give up the explicit definition of sonority and refer to a gradual scale—the sonority hierarchy... However, although many different proposals have been made, none of them, to my knowledge, has succeeded in reducing sonority to some more basic theoretical principle." (Dogil 1992:392)
>
> "It seems that ***any*** phonological phenomena could be brought together under the cover term of 'strength,' unless there were some empirically determinable property that defines the notion of 'strength.' What is particularly damaging to their claims is that there seems to be no clear physical parameter in terms of which one can characterize the hierarchy. In fact, attempts to find physical correlates for 'strength' and 'sonority' have not been very fruitful, if not totally unsuccessful." (Kawasaki 1982:44; emphasis in original)

Similar statements are found in Hooper (1976:198), Kenstowicz and Kisseberth (1979:21), Ohala and Kawasaki (1984:122), Selkirk (1984:111), Nathan (1989:56), Christman (1992:219), Larson (1993:59), Walther (1993:60), Laver (1994:503), Ladefoged (1997b:615), Kirchner (2000:524), and Wright (2001:2). This problem has resulted in an inability of researchers to offer a phonetic definition of sonority which covers the exact range of phonological distinctions that need to be made. Consequently, a few linguists have questioned the theoretical validity of sonority altogether. In this regard John Ohala is the most outspoken critic of sonority in the published literature (Ohala 1974, 1990a-b; Ohala and Kawasaki 1984). A separate list is warranted to highlight statements he has made:

> Sonority is a "meaningless label" typical of a "crypto-taxonomist" (Ohala 1974:252)
>
> "'Sonority' and its cousin 'strength' do not exist and should be abandoned for the sake of explaining universal sequential constraints." (Ohala 1990a:334)
>
> "The circularity would be avoided if the 'sonority' of segments were definable in some way that was independent of their position in this hierarchy. But this is not the case; sonority has never been satisfactorily defined, claims to the contrary notwithstanding (Hankamer & Aissen, 1974). Furthermore there are no prospects that anyone is even getting close to solving this problem—except, perhaps, by abandoning it and invoking an entirely new notion to explain segment sequences..." (Ohala 1990b:160)

In response to Ohala, three points deserve further scrutiny. First, as Hooper (1976) notes, the syllable is another theoretical concept which, like sonority, has never been adequately defined, especially in physical terms. Nevertheless, we should not for this reason abandon references to the syllable as being completely unprincipled. Even Ohala himself invokes the syllable when convenient. As in all science, the important attitude to adopt concerning phenomena which seem to exist yet defy explanation is to keep searching for a solution. Both sonority and the syllable merit a place in linguistic theory as primitive constructs which have some basis in phonetics yet are best appreciated for their role in more abstract phonological patterns, similar to phonemes (cf. Hooper 1976:198). Of course, Ohala is perfectly aware of the facts which need to be accounted for; it is just that in his approach there is no problem since, as noted in §1.2.2, the basis for phonotactics is not sonority but modulation.

Second, Ohala (1990b:160) claimed that "there are no prospects that anyone is even getting close to solving this problem...." One of the primary motivations for this dissertation is to respond to this very challenge. In chapter 4 I present the results of a major instrumental study designed to show that sonority can in fact be defined in a very precise and replicable way in terms of a single, uniform acoustic property (intensity) as well as a single aerodynamic property (intraoral air pressure). There I show that intensity consistently yields a correlation of .97 or higher with the traditional sonority hierarchy. Furthermore, air pressure measurements are inversely correlated with sonority indices to a degree of about –.84 (see table 5.1).

Finally, Ohala mentions the problem of circularity. This is concisely expressed by Walther (1993:60): "... segments are assigned to sonority classes on the basis of their distribution within the syllable, but syllabification itself is usually formulated in terms of sonority." The issue of circularity in defining sonority is also noted by Kawasaki (1982), Lass (1984), Malsch and Fulcher (1989), Butt (1992), Scheer (1998), and Basbøll (1999). On this particular detail I must confess a modicum of sympathy with the critics. The dilemma arises especially when we confront the question of how speech sounds should be arranged into a hierarchical scale reflecting their relative inherent sonority. Numerous scales have been proposed, many of them based on or motivated by details of language-specific consonant clustering (e.g., Steriade 1982, Selkirk

1984, Levin 1985). It is not surprising, then, that the location of certain segments in these hierarchies (such as /s/ and /h/), varies considerably from one researcher to the next, and at times in mutually contradictory ways. For example, Steriade (1982) claims that in Latin and Sanskrit, /t/ is more "sonorous" than /b/ and /g/, whereas in Greek and Attic, /b/ and /g/ are more "sonorous" than /t/. Furthermore, some scales are taken to the extreme of assigning a distinct place in the hierarchy for virtually every phoneme of the language, as Haddad (1984) does for Lebanese Arabic: vowels ⟩ glides ⟩ *ʕ* ⟩ *h* ⟩ ***h*** ⟩ *x* ⟩ *γ* ⟩ *l* ⟩ *m* ⟩ *n*, *r* ⟩ *ʔ* ⟩ coronal fricatives ⟩ non-coronal fricatives ⟩ plosives. In my opinion, defining *sonority* in this way abandons all hope of characterizing it in a precise, inherent, universal, and physical sense (cf. Zec 1988). When we arrange the phonemic inventory of a particular language into a hierarchy based on an exhaustive list of every possible sequence of segments, we are indeed defining something, namely, *phonotactics*. But this certainly does not serve as an illuminating definition of *sonority*, unless we wish to be completely circular. (I claim that it is not sonority *per se* which is permuted in different languages, but rather ***constraints*** which ultimately derive in part from sonority.) The solution to this problem lies in an intuition expressed in the quotes from Kawasaki (1982:44) and Ohala (1990b:160) above: we must define the sonority of segments in some *a priori* and empirical way which is completely divorced from their position in syllable-based hierarchies, especially those which are language-specific.

According to the *Oxford English Dictionary* (Simpson and Weiner 1989:1009), the English word *sonority* comes from either the French *sonorité* or the Latin *sonōritas*. It first appeared in writing in 1623 with the meaning "shrillness, loudness." The related word *sonorous* is defined as "giving out, or capable of giving out, a sound, esp. of a deep or ringing character." The following tables list a plethora of characteristics of human language claimed to correspond to sonority. In some cases the definition is not of sonority *per se*, but rather of the feature [sonorant], to which, *ex hypothesi*, it is related. Table 2.1 enumerates aspects of speech which are correlated with sonority in a positive direction. Table 2.2 lists negative or inverse correlates of sonority. These tables exhaust all the definitions of sonority given in works included in the bibliography of this dissertation. This list of references in turn is a very robust sample of the published literature dealing with sonority, at least in English. Tables 2.1 and 2.2 are divided into alphabetic groups based on logical relationships within the correlates, and the letters in 2.1 correspond to those in 2.2. That is, the factors in 2.1(a) are the opposite of those in 2.2(a), etc.

Themes for Tables 2.1 and 2.2:

> "In those days there was no king in Israel; everyone did what was right in his own eyes." (Judges 17:6 and 21:25)
>
> "There is nothing new under the sun." (Ecclesiastes 1:9)

Table 2.1: Correlates of sonority

(a)

- openness (of the vocal tract) (Lepsius and Whitney 1865, Bloomfield 1914, Jespersen 1922, Malmberg 1963, Lehmann 1976, Donegan 1978, Price 1980, Halle and Clements 1983, Lass 1984, Milliken 1988, Pāṇini [Cardona 1988], Katamba 1989, Nathan 1989, Durand 1990, Goldsmith 1990, Silverman and Pierrehumbert 1990, Beckman et al. 1992, Christman 1992, Churma and Shi 1996, Kingston 1998, Kirchner 1998, Nevin 1998, Howe and Pulleyblank 2001, Wright 2001)
- (supralaryngeal) aperture (Jespersen 1922, Grammont 1939, Allen 1973, Drachman 1977, de Saussure 1907/1983, Puppel 1992, Kirchner 1998, Nevin 1998, Scheer 1998)
- size of the resonance chamber (Jespersen 1932, Bloch and Trager 1942)
- largeness (Heffner 1950)
- fullness (Heffner 1950)
- volume (Bloomfield 1914)
- jaw lowering (Keating 1983, 1988, Lindblom 1983)
- jaw displacement (de Saussure 1907/1983, Malsch and Fulcher 1989)
- mandibular coarticulation (Lindblom 1983)
- separation (Pāṇini [Cardona 1988])
- F_1 (Donegan 1978, Keating 1983, 1988, Kingston 1998)
- unimpeded (voiced) air flow (Vennemann 1988, Fromkin and Rodman 1998)

(b)

- a clearly defined formant structure (Ladefoged 1971, 1997b, Price 1980)
- rich harmonic structures (Zhang 2001)
- periodic acoustic energy (Lass 1984)
- periodicity (Puppel 1992, Ladefoged 1997b, Heselwood 1998)
- resonance (Foley 1972, 1977, Ultan 1978, Marlett 1997, Heselwood 1998, Kingston 1998)
- non-turbulence (Puppel 1992, Heselwood 1998)

(c)

- (propensity for) spontaneous voicing (Chomsky and Halle 1968, Allen 1973, Donegan 1978, Brakel 1979, Price 1980, Katamba 1989, Nathan 1989, Kenstowicz 1994)
- strength of voicing (Pierrehumbert and Talkin 1992)
- unimpeded (voiced) air flow (Vennemann 1988)
- glottal airflow (Kenstowicz 1994)
- glottal vibration (Allen 1973, Ladefoged 1997b)

(cont. next page)

(Table 2.1 cont.)

- laryngeal source function (Price 1980)

(d)

- (acoustic) energy (Heffner 1950, Sigurd 1955, Ladefoged 1971, 1975, Allen 1973, Lass 1984, Keating 1988, Nathan 1989, Clark and Yallop 1990, Goldsmith 1990, Fromkin and Rodman 1998, Wright 2001)
- high frequency energy (Zhang 2001)
- phonetic power (Fletcher 1929)
- carrying power (Jones 1960, 1966, Clark and Yallop 1990)
- expiratory force (Allen 1973)
- (auditory) force (Bloomfield 1933, Bloch and Trager 1942, Jakobson and Halle 1968)
- audibility (Bloomfield 1914, Bloch and Trager 1942, Heffner 1950, Malmberg 1963, Allen 1973, Katamba 1989, Malsch and Fulcher 1989, Howe and Pulleyblank 2001)
- (inherent or perceived) loudness (de Brosses 1765, Bloomfield 1914, Jones 1960, Ladefoged 1975, 1993, Selkirk 1984, Catford 1988, Nathan 1989, Simpson and Weiner 1989, Clements 1990, Christman 1992, Corston 1993, Walther 1993, Laver 1994, Anttila 1995)
- (intrinsic) intensity (Sievers 1901, Malmberg 1963, Ladefoged 1975, 1993, Donegan 1978, Malsch and Fulcher 1989, Clements 1990, Churma and Shi 1996, Kingston 1998, Walker 1998, Lavoie 2000)
- shrillness (Simpson and Weiner 1989)
- amplitude (Lavoie 2000)
- (intrinsic perceptual) prominence (Jones 1960, Donegan 1978, Donegan and Stampe 1978, Anderson 1986, Christman 1992)
- perceptibility (Clements 1990, Perlmutter 1992, Howe and Pulleyblank 2001)
- (perceptual) salience (Clements 1990, Perlmutter 1992, Brentari 1993, Heselwood 1998)
- perceptual robustness (Wright 2001)

(e)

- vowel-likeness (Levitt et al. 1992, Bernhardt and Stemberger 1998)
- vocalicity/vocalicness (Anderson 1986, Nathan 1989)
- nuclearity (Durand 1987)
- propensity to vocalization (Foley 1977)
- vowel affinity (Fujimura and Erickson 1997)
- vowel adherence or coarticulation (Sigurd 1955, Lindblom 1983)
- syllabicity (Donegan 1978, Blevins 1995)

(cont. next page)

(Table 2.1 cont.)

(f)
- duration (especially among vowels) (Allen 1973, Donegan 1978, Nathan 1989, Beckman et al. 1992, Kenstowicz 1996)
- continuance (Donegan 1978)
- continuability (Lepsius and Whitney 1865)
- continuity of the spectrum amplitude (Stevens 1987, Stevens and Keyser 1989)
- prolongability (Nathan 1989)
- sustainability (Donegan 1978)

(g)
- formant amplitudes (Howe and Pulleyblank 2001)
- formant bandwidths (Howe and Pulleyblank 2001)
- harmonic phases (Howe and Pulleyblank 2001)

(h)
- structure (Rice 1992, Carnie 1994)
- headedness (Anderson 1986, Durand 1987)

(i)
- strength (Foley 1977)

(j)
- tonality (Nathan 1989, Boersma 1998a-b, Heselwood 1998)

(k)
- (inherent) activation (Goldsmith and Larson 1990, Goldsmith 1993)
- excitation (Larson 1993)

(l)
- source-filter dependency (Puppel 1992)

(m)
- innervation of the respiratory muscles (Malmberg 1963)
- tension of the laryngeal muscles (Malmberg 1963)

And, in American Sign Language,

(n)
- movement (Brentari 1993, Sandler 1993)
- perspicuity (Perlmutter 1992)
- (visual) salience (Perlmutter 1992, Brentari 1993, Sandler 1993)

Table 2.2: Negative/inverse correlates of sonority
(cf. Nathan 1989 — "antisonority)"

(a)

- degree of narrowing, stricture, blockage, constriction, closure (Lepsius and Whitney 1865, Pike 1954, Malmberg 1963, Allen 1973, Hankamer and Aissen 1974, Donegan 1978, Halle and Clements 1983, de Saussure 1907/1983, Katamba 1989, Nathan 1989, Durand 1990, Christman 1992, Carr 1993, Kenstowicz 1994, Churma and Shi 1996, Marlett 1997)
- supraglottal impedance (Brakel 1979, Silverman and Pierrehumbert 1990, Beckman et al. 1992)
- (linguopalatal) contact (Pāṇini [Cardona 1988], Lavoie 2000)
- resistance to air flow through the vocal tract (Lass 1984, Bauer 1988)
- jaw height (Beckman et al. 1992)
- vowel height (Donegan 1978)

(b)

- aperiodicity (Nathan 1989, Puppel 1992, Heselwood 1998)
- supralaryngeal sound source (Heselwood 1998)
- audible friction (Jones 1960)
- noise (Jones 1960, Nathan 1989, O'Grady et al. 1989, Lavoie 2000)
- hiss (Nathan 1989)
- turbulence (Puppel 1992, Heselwood 1998)
- "number of facultative resonance chambers used" (Brakel 1979:45)

(c)

- "deviation from the voiced state of the glottis" (Brakel 1979:45)

(d)

- silence (de Brosses 1765, Nathan 1989)
- softness (de Brosses 1765)
- reduced spectrum amplitude (Stevens and Keyser 1989)

(e)

- consonantality (Nathan 1989)
- non-nuclearity (Durand 1987)

(f)

- duration (among consonants) (Lavoie 2000)

(h)

- (left) branchedness of feature geometry structure (Dogil 1988, 1992, Dogil and Luschützky 1989)
- dependency/dependenthood (Anderson 1986, Durand 1987)
- government (Rice 1992)

(cont. next page)

(Table 2.2 cont.)

(i)
- (inherent segmental) strength (Vennemann 1972, Hooper 1976, Drachman 1977, Escure 1977, Vogel 1977, Bell and Hooper 1978, Brakel 1979, Murray and Vennemann 1983, Bauer 1988, Dogil 1988, 1992, Vennemann 1988, Dogil and Luschützky 1989, Katamba 1989, Nathan 1989, Puppel 1992)

(j)
- pitch (Howe and Pulleyblank 2001)
- F_0 (Howe and Pulleyblank 2001)

(m)
- (articulatory) effort (Pāṇini [Cardona 1988], Kirchner 1998)
- muscular energy (for consonants) (Allen 1973)
- activity of the posterior cricoarytenoid muscle (Bauer 1988)

(o)
- intraoral air pressure (for the feature [sonorant]) (Halle and Clements 1983, Milliken 1988, Durand 1990, Stevens 1994, Halle 1995, Ladefoged 1997b, Marlett 1997, Bernhardt and Stemberger 1998, Stevens 1998)

(p)
- perceptually salient release phase (Heselwood 1998)

Tables 2.1 and 2.2 list 98 different characteristics of language claimed to be related to sonority (some of these are clearly synonyms of one another, but this does not detract from the overall picture). Obviously one or more of these factors is likely to be on the right track, but there is no consensus about which one it is. Consequently, the experiment I discuss in chapter 4 has great potential to increase our understanding of what sonority is and, concomitantly, why it produces the phonological effects that it does. It is of course not a logical necessity that sonority be confined to just a single physical parameter. Indeed, the proliferation of proposals in Tables 2.1 and 2.2 suggests that sonority might be best characterized as a synergy of two or more separate forces. A complex definition of sonority is therefore not out of the question *a priori* (cf. Price

1980, Malsch and Fulcher 1989, Nathan 1989.) Keating (1988) in fact claims that the appearance of a single, unitary, and universal sonority hierarchy is a coincidence. As an analogy, the feature [±tense] is known to have multiple phonetic correlates, as do many other distinctive features (voicing, vowel height, etc. See Kingston (1991) and Kingston and Diehl (1994) for useful reviews of this issue). Given this, it would not be a major setback if sonority were found to correspond to a set of potentially overlapping phonetic dimensions. Nevertheless, *pace* Keating (1988), the reality and explanatory power of sonority will be served most ideally if we can establish a restrictive definition based on a unidimensional facet of the speech process, a goal I strive to achieve in chapter 5.

Having said this, let us now digress to consider several characterizations of sonority based on an interaction of more than one feature, if only to highlight their weaknesses. The most frequently cited correlate of sonority is *openness* (24 references in Table 2.1). It is true that as we go up the sonority scale the mouth tends to open more widely. However, the status of fricatives vs. nasals is a major contradiction to this generalization. Fricatives lack complete occlusion and are therefore [+continuant], but nasals involve a complete oral closure and are thus phonologically [–continuant]. In this sense fricatives are technically more "open" than nasals. Nevertheless, nasals are invariably classified as more sonorous than fricatives since nasals are [+sonorant] (Hankamer and Aissen 1974, Parker 1989). To resolve this dilemma, if *openness* is to serve as a comprehensive definition of sonority, it must be understood as referring to the entire supralaryngeal vocal tract combined (buccal plus nasal cavities). For this reason the feature [+sonorant] is sometimes defined as involving a relatively free passage of the air flow either through the mouth ***or the nose*** (Hyman 1975, Fromkin and Rodman 1998, Roca and Johnson 1999). This suggests that one possible way to measure sonority is by combined egressive air flow (oral plus nasal), a hypothesis I pursue in chapter 4. Along these lines, two rather complex definitions of sonority are given below:

> "Sonority requires a relationship between articulation and airflow such that no turbulence arises in the supraglottal chambers to function as an aperiodic sound source. It also requires an acoustic output such that the effect on the human auditory system is of the kind that gives rise to a tone percept." (p. 69) Sonority can therefore be defined as "perceptually salient periodicity and vocal tract resonance with no supralaryngeal sound source superimposed on it..." (Heselwood 1998:75)
>
> Strength is "a combination of the amount of impedence (*sic*) applied to the supraglottal egressive air stream, the number of facultative resonance chambers used, and deviation from the voiced state of the glottis." (Brakel 1979:45)

Ironically, Brakel (1979:45) concludes that "... strength is not difficult to define."! Because of the difficulty in arriving at a consistent phonetic characterization of sonority, some linguists posit instead that sonority is a secondary construct derived from a combination of several phonological parameters (Steriade 1982, Levin 1985, Clements 1990, Blevins 1995). For example, Clements (1990) proposes a grid-like representation of segments in which relative sonority corresponds to the number of positive specifications of four binary major class features (Clements 1990:299; cf. §1.2.4):

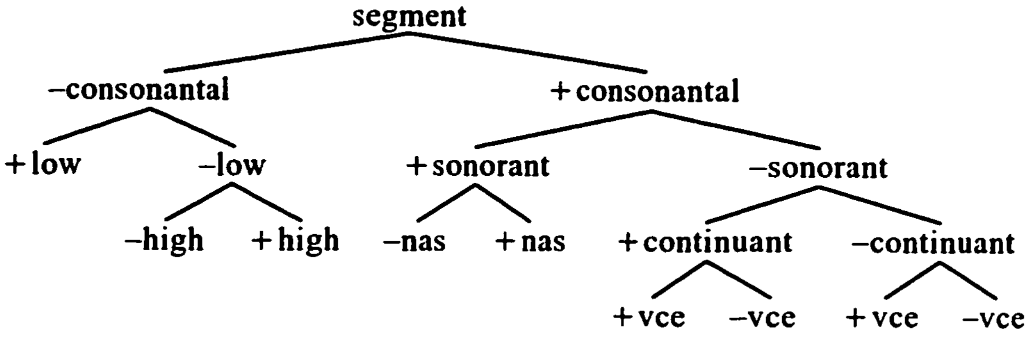
(2.1)		+				+			[syllabic]
		+				+	+		[vocoid]
		+			+	+	+		[approximant]
		+	+		+	+	+		[sonorant]
	t	*e*	*m*	*p*	*l*	*e*	*y*	*t*	
	0	4	1	0	2	4	3	0	sonority rank

(In (2.1) above Clements transcribes both vowels as *e*, presumably implying a broad (abstract) level of representation.) This grid then drives phonological mechanisms such as core syllabification and the Sonority Dispersion Principle (Clements 1990). It is important to note that in this model, the sonority scale is built into these four features indirectly, and in a hierarchical fashion: [+syllabic] implies [+vocoid]; [+vocoid] implies [+approximant]; etc. Consequently, just as in metrical theory, this type of grid is subject to the Continuous Column Constraint (Hayes 1995), so there can be no gaps underneath the topmost mark in any column. Other analyses utilizing a sonority grid include Jespersen (1904), van der Hulst (1984), Milliken (1988), Zec (1988), Parker (1989), Clements (1992), Kenstowicz (1994), and Roca and Johnson (1999). My main objection to Clements' (1990) proposal is that it does not sufficiently distinguish between all required natural classes (cf. Zec 1995). For example, in §1.2.5 we saw evidence that sonority differences based on vowel height and peripherality are necessary for assigning stress in various languages. We also need to divide obstruents into stops vs. fricatives and voiced vs. voiceless for English, Pali, Sanskrit, and Imdlawn Tashlhiyt Berber (cf. chapter 1 and Benua 1997). Nevertheless, Clements' (1990) model lumps all vowels and all obstruents together (cf. §1.2.4). Once these finer groupings are factored into the sonority hierarchy, (e.g., the 2 × 2 or 4-way distinction among obstruents (cf. §3.2.5.2)), we would need many more features than just the four used in (2.1). Furthermore, we then encounter a fatal difficulty if we wish to retain Clements' hierarchical approach: there is no combination of standard distinctive features which can generate all and only the exact set of natural class distinctions in the sonority scale which we encountered in chapter 1, without gaps in the columns. In other words, the implicational relationship between Clements' four features cannot be extended to features such as [±voice] and [±continuant]: [+voice] does not necessarily entail [+cont], nor does [+cont] entail [+voice]. The only way to produce the precise sonority hierarchy required in the analysis of all phonotactic patterns is to invoke an autonomous, stepwise feature which directly encodes sonority itself. In conclusion, it is simpler to view sonority as a primitive phonological feature which is scalar and hierarchical in nature, comprising all the natural classes which the processes in chapter 1 need to exploit.

A second weakness in Clements' (1990) approach is that laryngeal consonants have no inherent sonority rank and thus cannot participate in mechanisms such as the grid (2.1) and the SDP. In Clements' discussion of this issue (1990:322) he argues that the chameleon-like behavior of /h/ and /ʔ/ as both obstruents and sonorants is often due to their historical origins. I contend that a better explanation for the variable patterns of glottal consonants is their unique acoustic qualities, a hypothesis I pursue in chapters 4 and 5. Surely a sonority scale which is able to simultaneously evaluate all speech sounds in terms of the same physical parameter is more valuable than one which considers certain types to be diachronic accidents.

To close this section, I examine the approach of Blevins (1995), who posits the following diagram as a characterization of intersegmental sonority relationships:

(2.2)



In the tree in (2.2), the left branch of each node is to be understood as more sonorous than the corresponding right branch. Similar types of proposals are made by Farmer (1979) and Harris (1989). In response to this chart I have three fundamental misgivings: first, what unifying principle joins together the features in (2.2) to the exclusion of all others? That is, what does the list of features in (2.2) share in common (either articulatorily or acoustically) that other features do not? Specifically, what *a priori* reason explains why features like [high], [nasal], and [continuant], for example, should be relevant in determining sonority, whereas features like [lateral], [strident], and [distributed] are not? The only common factor uniting the set of features in (2.2) is that they somehow contribute to sonority, but that is precisely the notion we are trying to define. So a major problem with hierarchies such as (2.2) is that they do not capture the similarity between the phonetic correlates of the left-hand feature values vs. the right-hand ones. In other words, in this model the physical basis for sonority is assumed to be inconsistent across segment types. In chapters 4 and 5 I show that this flaw can be avoided.

On the other hand, if someone wished to defend Blevin's approach (for the sake of discussion), he or she could argue that vowels and consonants are inherently different types of segments and that within each of these two classes there is in fact a unifying physical characteristic. Specifically, the consonantal features all contribute to a sound source of some type (hence the appeals to noisiness and voicing in tables 2.1 and 2.2), whereas the vocalic features determine resonance qualities. While this is true, it still undermines the attempt to unify all speech sounds — vowels and consonants alike — into a single sonority hierarchy. There are several phonological motivations for a unitary scale. First, in many languages vowels alternate with glides: Bakwiri (Hombert 1986), Chamicuro (Parker 1989), Luganda (Clements 1986), etc. Second, glides (which are [–cons]) often harden into obstruents ([+cons]), as documented for Spanish (Harris 1983) and Iñapari (Parker 1999). Third, there is a clear continuum of propensity for moraicity which successively encompasses vowels, then sonorant consonants, then obstruents (Zec 1988, 1995). Finally, as Clements (1990) shows, the SDP requires us to posit sonority indices for vowels and consonants simultaneously (i.e., on the same scale) in order for all the facts of dispersion to fall out correctly. For example, in a syllable of type C_1C_2V, we need to know the sonority distance not only between C_1 and C_2, but also between C_2 and V. Consequently, I conclude that it is imperative to quantify sonority for all speech sounds at the same time, and a single physical correlate like intensity (chapters 4-5) does this much better than Blevins' (1995) tree approach can.

A second major problem with the hierarchy in (2.2) is that it is not clear where certain cross-linguistically common sounds, such as /h/, /ʔ/, and /č/, should fit in; the appropriate place for glottal consonants in particular is by no means obvious. Finally, another objection I have to the arrangement in (2.2) is that the [±voice] dichotomy is stated twice: first under [+continuant] and then under [–continuant]. This redundancy suggests that a significant generalization has been missed: voicing distinctions potentially contribute to sonority for all obstruents uniformly, regardless of whether they are fricatives or stops. In conclusion, a chart such as (2.2) can easily ***stipulate*** the featural correlates of sonority, but it does not ***explain*** them very well. I cannot help but think that diagrams such as (2.2) are proposed not as the *a priori* preferred manner for characterizing sonority, but rather as a last-recourse option simply because to date no one has discovered a precise and reliable way to define sonority as an incremental, *n*-ary feature.

2.3 Summary

Sonority has a long, glorious, and controversial history. The fact that it is invoked so often in phonological analyses (even in the 21st century) indicates that there is a coherent set of phenomena demanding a common explanation; sonority may ultimately prove to be that answer, especially if we can demonstrate that it has a clear phonetic basis. However, sonority has never been defined to the satisfaction of most linguists, myself included. One of the primary goals of this dissertation is to remedy this situation. In chapter 5 I show that sonority can in fact be reduced to a simple, precise formula based on cross-linguistic measurements of relative intensity. Hopefully this will dispel any remaining skepticism.

CHAPTER 3

THE SONORITY HIERARCHY — A HISTORICAL OVERVIEW

3.1 Introduction

My principal goal in this chapter is to critically examine a number of sonority scales which have been previously proposed in the literature. The order of presentation is roughly chronological in nature. We will focus on two main issues: (1) How many and what kinds of natural class divisions should be made in the sonority hierarchy?, and (2) How should these be quantified? The organization of the chapter is as follows. First I review early descriptions of the sonority hierarchy, up to about the 1950's. I then digress to consider several types of segments whose relative sonority is a matter of dispute. Next I argue that strength is not significantly different from sonority. I conclude by discussing five interesting characterizations of sonority which have been posited since 1950.

3.2 The sonority hierarchy

3.2.1 Pāṇini (500 B.C.)

The earliest recorded attempt to classify speech sounds on the basis of a notion akin to sonority is by the Sanskrit grammarians, most notably Pāṇini, circa 500 B.C. (Misra 1966, Katre 1987, Cardona 1988, Singh 1991). His scale, which appears to be based more on phonological than phonetic grounds, groups the phonemes of Sanskrit into 14 strings or natural classes called *sūtras* (grammatical statements expressed as algebraic formulae (Singh 1991)). Each group has an explicit name. The term used by Pāṇini to describe the substance of his hierarchy is *prayatna*, which Cardona (1988) translates as "articulatory effort." This may be taken as the first attempt to define sonority. The natural classes are grouped according to degree of "opening" (*vivāra*). For example, stops are considered to have full contact, semivowels have slight contact, and vowels involve complete separation or no contact (Cardona 1988). Below I list Pāṇini's first 14 *sūtras*, as annotated by Misra (1966), Katre (1987), and Cardona (1988). These are also known as the *śiva-sūtra* (*sūtras* given by the god *Śiva*), and are used like distinctive features in the elaboration of phonological rules such as Grassmann's law. A dot underneath a symbol indicates retroflexion.

Table 3.1: Pāṇini's *śiva-sūtras*

1.	/a i u/	simple vowels
2.	/ṛ ḷ/	sonant vowels
3.	/e o/	diphthongs
4.	/ai au/	diphthongs
5.	/h y v r/	voiced aspirate and semivowels
6.	/l/	semivowel
7.	/ñ m ŋ ṇ n/	nasal stops
8.	/jh bh/	palatal and labial voiced aspirate stops
9.	/gh ḍh dh/	voiced aspirate stops
10.	/j b g ḍ d/	voiced unaspirated stops
11.	/kh ph ch ṭh th c ṭ t/	unvoiced stops
12.	/k p/	unvoiced stops
13.	/š ṣ s/	sibilants
14.	/h/	voiced (velar) fricative

It is doubtful that the numbers Pāṇini assigns to these *sūtras* are intended to have any formal significance (*qua* sonority indices). Nevertheless, his scheme of organization indicates that he had a good grasp of articulatory phonetics and phonology.

3.2.2 de Brosses (1765)

The next mention of a concept like sonority (in more modern times) is by de Brosses (1765:130-33), as noted by Ohala (1990a-b). In this voluminous French work de Brosses posits a very informal sonority hierarchy as well as a notion similar to the SSP. He characterizes sonority (although not using the word *sonorité*) as loudness/softness both in terms of the mouth (articulation) and the ear (perception). He also posits that obstruents (*mutes*) are less marked than sonorants (*liquids*), i.e., they make better onset consonants. This is an important predecessor to the SDP.

3.2.3 The late 19th century: Wolf (1871)

The 19th century is the first one in which we find discussions of sonority by more than one author. Three important references are Lepsius and Whitney (1865), Sievers (1885/1901), and Whitney (1889). Wolf (1871) carried out an ingenious experiment to discover the relationship between speech sounds based on loudness. As an assistant repeatedly pronounced different German phonemes (most of them in isolation), Wolf walked away from him down the street. For each sound Wolf noted the maximum distance (in steps/paces) at which he could still distinguish which segment was being pronounced. He reports his results as follows (cf. Jespersen 1904:187, Nathan 1989):

(3.1) Wolf's (1871:71) loudness hierarchy

a	360	steps
o	350	
e	330	
i	300	
u	280	
š	200	
m, n	180	
s	175	
f	67	
k, t	63	
ř	41	
p	18	
h	12	

In the list above the relatively high rank of /š/ and /s/ is noteworthy (cf. §1.2.1 and 6.5). This is the earliest published record of an attempt to empirically confirm the physical reality of a concept like sonority. Fortunately, with modern technology we can make much more precise measurements of absolute intensity without having to get as much exercise as Wolf and his aide did.

3.2.4 The early 20th century: Jespersen (1904)

Analyses of sonority in the first half of the 20th century include Jespersen (1904, 1922), de Saussure (1907/1983), Bloomfield (1914, 1933), and Grammont (1939). The work of Jespersen (1904) represents two important milestones in the history of sonority. To begin with, he is the first recorded person to propose a sonority grid like that seen in (2.1) (1904:187). Second, his sonority scale is the first one which posits subdivisions such that the difference in sonority indices between certain natural classes is sometimes less than one:

(3.2) Jespersen's (1904:186) sonority hierarchy

1\. (a) voiceless stops
    (b) voiceless fricatives
2\. voiced stops
3\. voiced fricatives
4\. (a) voiced nasals
    (b) voiced laterals
5\. voiced *r*-sounds
6\. (voiced) high vowels
7\. (voiced) mid vowels
8\. (voiced) low vowels

The numbering scheme in (3.2) suggests very strongly that, in Jespersen's view, not all sonority distances are equal. In other words, some groups of segments may differ in absolute sonority value by more or less than other adjacent pairs of natural classes do. For example, the sonority difference between voiceless stops (1a) and voiceless fricatives (1b) is presumably less than that between voiced stops (2) and voiced fricatives (3). This implies that not all inter-class sonority distances are necessarily the same, and represents a significant first step towards the much more elaborate scales we will see later in this chapter. The practical importance of this innovation is that certain restrictions on minimal sonority distance may fall out directly from the indices used and therefore not require a language-specific stipulation. Nevertheless, we can already note a problem with the scale in (3.2) for the purposes of this dissertation: the use of non-numerical indices such as *1a* and *1b* makes it impossible to submit this hierarchy to evaluation by constraints such as the SDP. (This was obviously not Jespersen's concern.) This can easily be remedied by converting the indices *1a* and *1b* into something like *1.0* and *1.5*, respectively, and similarly for *4a* and *4b*. This simple adjustment is certainly consistent with the spirit of Jespersen's proposal, and at the same time it makes his scale more compatible with the mechanisms of current phonological theory.

3.2.5 The last 50 years

In the period from about 1950 to the present, discussions of sonority in the linguistic literature have exploded. As part of this enterprise, the number of proposed sonority scales has increased rapidly. There are far too many to cite each one individually, and doing so would be quite tedious for both the author and the reader. Nevertheless, in this section I review several of the most interesting breakthroughs as well as a few recurrent problem areas. Among the references listed in the bibliography of this dissertation are found more than 100 distinct sonority hierarchies which differ from one another in at least one detail. Some of these are claimed to be universal in nature, whereas others are posited for specific languages only; in this count I did not distinguish them on this basis. The sonority scale which is cited more often than any other is probably that used by Clements (1990) in (1.5) above, repeated here for convenience:

(3.3) modal sonority hierarchy

vowels > glides > liquids > nasals > obstruents

This scale is mentioned in the following works, *inter alia*: Bell and Hooper (1978), Harris (1983), van der Hulst (1984), Anderson and Durand (1986), Clements (1987, 1990), Milliken (1988), Corina (1990), Kenstowicz (1994), Smolensky (1995), de Lacy (1997), Holt (1997), Oostendorp (1999), and Hall (2000). Kenstowicz (1994:254) in fact claims that at least this much of the hierarchy is agreed on by all phonologists, but this is not true. Many linguists argue that positing a distinction in relative sonority between vowels and glides is at least unnecessary, if not counterproductive to phonological analyses (e.g., Selkirk 1984, Milliken 1988, Durand 1990, Gnanadesikan 1995b, 1997, Núñez Cedeño and Morales-Front 1999, Cohn and Lavoie 2000, and Orgun 2001). The reason for this is usually couched in terms of ***predictability***: given the universal timing tier (whether it be expressed by *C*'s and *V*'s, *X*'s, or moras), the distinction between high vowels and glides follows automatically and thus it would be redundant to differentiate them in terms of relative sonority at the same time. However, this argument is in danger of being somewhat circular unless we establish *a priori* definitions of syllables, vowels, and glides which do not rely on sonority (§2.2). The experimental data I present in chapter 4 show that it is in fact possible to distinguish glides from vowels ***phonetically***; whether it is beneficial to do so phonologically is of course a separate question. Given this controversy, it would be more accurate to state that the minimal sonority hierarchy which appears to be accepted by all linguists and which is valid for all languages is the following:

(3.4) universal sonority hierarchy (minimal version)

vowels > liquids > nasals > obstruents

The relative ranking of the four natural classes of sonority in (3.4) is basically indisputable, so long as we consider only prototypical exemplars of these categories, e.g., liquids and nasals which are voiced, etc. Nevertheless, when we press for more specific details in this scale, controversies begin to arise. For example, we just mentioned the debate over vowels and glides, and in chapters 1 and 2 we observed disagreement about whether obstruents should be divided into smaller sets. Consequently, in the next three sections of this chapter I confront several issues which persistently arise in discussions of sonority. These involve the appropriate place in the hierarchy for the following groups of sounds: (1) /h/ and /ʔ/, (2) voiceless fricatives vs. voiced stops, and (3) affricates. I note here at the outset that the experiments discussed in chapters 4-6 are designed in such a way as to provide empirical data that will help us resolve issues of this type.

3.2.5.1 On the relative sonority of glottal consonants

In this section I consider where /h/ and /ʔ/ should be assigned in the sonority scale. Specifically, are these segments sonorants or obstruents? (The same questions might also be asked for pharyngeal consonants as well.) It is widely known that laryngeal consonants pattern with glides (/y/ and /w/) in some languages (e.g., Guile 1973), whereas in others they behave like obstruents. There are even some cases in which they function as both in the same language (cf. Orie and Bricker 2000). Many versions of the sonority hierarchy avoid this problem by not mentioning /h/ and /ʔ/ at all. However, as I noted in §2.2, an adequate model of sonority should have something to say about every speech sound, especially those which are found in most languages. Among the works which explicitly mention the specification of glottal consonants for sonority (or for the feature [±sonorant]), all of the theoretically possible positions are attested:

(3.5) Classification of /h/ and/or /ʔ/

- They fall among the sonorants.
  (Pike 1954, Cooper and Ross 1975, Pinker and Birdsong 1979, Levin 1985, Parker 1989, Larson 1990, Gnanadesikan 1995b, 1997)

- They fall among the obstruents.
  (Heffner 1950, Lass 1976, Durand 1987, Dogil 1988, 1992, Zec 1988, Dogil and Luschützky 1989, Vijayakrishnan 1999, Orie and Bricker 2000)

- They fall on the border between sonorants and obstruents.
  (Lepsius and Whitney 1865/1971, Brittain 2000)

- They are both sonorants and obstruents at the same time.
  (Churma and Shi 1996)

- They are neither sonorants nor obstruents. / They lack inherent sonority.
  (van der Hulst 1984, Clements 1990, Boersma 1998b)

- /h/ is a sonorant while /ʔ/ falls on the border between sonorants and obstruents.
  (Haddad 1984)

As (3.5) illustrates, disagreement reigns. The issue of whether laryngeals are [+son] or [–son] depends to a large degree of course on how we define these features. SPE characterizes sonorants as sounds whose vocal tract configuration would permit spontaneous voicing (Chomsky and Halle 1968). Given this definition, they specify /h/ and /ʔ/ as [+son], but this seems rather counterintuitive (cf. Lass 1976, Dogil and Luschützky 1989, and Nevin 1998). If, on the other hand, one wishes to insist that all sonorants must be inherently voiced (Ladefoged 1971, Stevens and Keyser 1989, Basbøll 1999), the debate is probably over. Some interesting psycholinguistic data add more fuel to the controversy. Jaeger and Ohala (1984) designed an experiment to test whether native speakers of English group /h/ with sonorants or with obstruents. Using a concept formation procedure (Jaeger 1986), they presented several isolated words to 14 subjects via headphones and indicated that those beginning with one of the sounds /r m n w y/ are "positive" for a certain quality whereas /p t k b d g f v θ ð s š č ǰ/ are "negative" for that same quality. To control whether subjects correctly identified the feature ([±son]), they were required to judge /l/ as "positive" and /z/ as "negative" during the test phase. Only 7 of the 14 subjects correctly formed the category, with a mean practice length of 31 trials to reach criterion (15 tokens in a row with two or fewer errors). Given this "success" rate of only 50%, a skeptic might quibble about the following test results. Nevertheless, simultaneous experiments by Jaeger and Ohala (1984) also resulted in 50% or less of the subjects forming the categories [+anterior] and [±voice]. Furthermore, the number of trials to criterion for these other cases was always higher than 31 as well. The 7 subjects who succeeded in "acquiring" the feature [±son] were then tested to determine whether they classified /h/ as " + " or "–". The results are summarized below:

Table 3.2: Test data from Jaeger and Ohala (1984) on the category [±sonorant]

	positive tokens	% positive responses	% negative responses
training data	glides	93 (correct)	4
	nasals	95	5
	/r/	91	6
	(mean)	93	5
	negative tokens		
	voiced fricatives	23	73 (correct)
	voiced affricates	17	83
	voiceless affricates	13	87
	voiceless fricatives	10	87
	voiced stops	9	88
	voiceless stops	3	94
	(mean)	11	86
	control tokens		
test data	/l/ (positive)	86 (correct)	14
	/z/ (negative)	4	93 (correct)
	test tokens		
	/h/	36 (/h/ is [+son])	64 (/h/ is [–son])

As the data above show, an overwhelming percentage of the responses correctly identified glides, nasals, and liquids as [+son], whereas obstruents were strongly judged to be [–son]. Nevertheless, there was slightly more certainty in categorizing sonorants than obstruents. (Some of the totals do not add up to 100% because of extraneous and/or non-responses.) For the test of /h/, about two-thirds of all responses grouped it with obstruents, while one-third classified it as a sonorant. The conclusion is that native speaker intuition has a moderately strong tendency to identify /h/ as an obstruent in English, although the response totals for prototypical obstruents are more robust. This categorization is confirmed by the instrumental data I present in chapter 4, where English /h/ and /ʔ/ pattern overall as obstruents. In chapter 5 I return to this issue after the relevant physical data are introduced.

3.2.5.2 On the relative sonority of voiceless fricatives vs. voiced stops

As we saw in examples (1.5) and (3.3), many linguists claim that all obstruents are equal in sonority. Consequently, in their hierarchies obstruents are lumped together without any further subdivisions among them. This position is not universally accepted, however. Most researchers in fact posit at least one split in sonority within the class of obstruents, and many of them have several subgroups (I place myself in this latter category). Among those who divide obstruents into only two classes, the schism is usually made on the basis of the feature [±continuant], *viz.*: fricatives > stops. It is also possible in principle to keep stops and fricatives together but distinguish among them in voicing: voiced obstruents > voiceless obstruents. If we assume that these two rankings are universally impermutable (a restrictive claim that I am in favor of making), the two mini-scales can be joined together to yield four natural classes but only three logical hierarchies:

(3.6)

(a) voiced fricatives > voiceless fricatives > voiced stops > voiceless stops
(b) voiced fricatives > voiced stops > voiceless fricatives > voiceless stops
(c) voiced fricatives > voiceless fricatives = voiced stops > voiceless stops

Not surprisingly, each of these three possibilities has adherents in the literature, as I summarize below:

(3.7) (a) Voiceless fricatives are higher in sonority than voiced stops. (Lepsius and Whitney 1865/1971, Whitney 1889, Pinker and Birdsong 1979, Lass 1984, Selkirk 1984, Dell and Elmedlaoui 1985, 1988, Vennemann 1988, Harris 1989, Katamba 1989, Parker 1989, Durand 1990, Goldsmith and Larson 1990, Puppel 1992, Carr 1993, Ladefoged 1993, Blevins 1995, Gnanadesikan 1995b, 1997, Green 1997, Shin 1997, Bernhardt and Stemberger 1998, Nevin 1998, Morén 1999, Vijayakrishnan 1999, Morén 2000, Rose 2000, Barlow 2001, de Lacy 2002)

(b) Voiced stops are higher in sonority than voiceless fricatives. (Pāṇini [Misra 1966, Katre 1987, Cardona 1988], Jespersen 1904, Heffner 1950, Bolinger 1962, Williamson 1978, Brakel 1979, Alderete 1995, Boersma 1998b, Hironymous 1999, Struijke 1999, Gouskova 2001)

(c) Voiceless fricatives and voiced stops are equal in sonority. (Vennemann 1972, Hooper 1976, Escure 1977, Murray and Vennemann 1983, Larson 1990, 1993)

While the majority opinion in (3.6) and (3.7) sides with position (a), the choice between these options is ultimately an empirical matter, not a matter of just counting votes. Unfortunately, however, there is very little evidence from phonotactic patterns to help us settle the issue conclusively, a fact lamented by Hooper (1976) and Boersma (1998b) as well. The reason for this, I believe, is that obstruent clusters so strongly prefer to agree in voicing that crucial diagnostic examples involving a potential conflict are quite rare. Consequently, I suspect that many of these works simply copied the scales from one another, without motivating every single detail with explicit data. For reasons such as these, Basbøll (1994:59) concludes, "... all attempts to combine voicedness [voicing, S.P.] and the distinction between plosives and fricatives into one unique 'sonority hierarchy' have failed, as I see it." However, I do not agree that this situation needs to entail complete pessimism. While crucial data are not abundant, a few tokens do exist. For example, in Imdlawn Tashlhiyt Berber (Dell and Elmedlaoui 1985), voiceless fricatives are claimed to be higher in sonority than voiced stops. This is confirmed by forms such as /t-bXl=akk^{w}/ → [tbX.lakk^{w}] 'she even behaved as a miser' (p. 113), where /X/ rather than /b/ is selected as the nucleus of the first syllable, in keeping with the SSP (cf. §1.2.1). On the other hand, we saw (in §1.3.2) that Williamson's (1978) division of Ịjọ consonants into strength classes (1.13) provides good evidence that voiced stops may pattern as more sonorous than voiceless fricatives. Furthermore, the experimental data I present in chapter 4 generally favor voiced stops over voiceless fricatives as well, so I will ultimately conclude that this is the default universal ranking. However, in specific languages this ranking may be reversed, as we will see with the English rhyming pairs in chapter 6.

3.2.5.3 On the relative sonority of affricates

Another difficult question is where affricates fit in the sonority hierarchy. Since affricates tend not to cluster with other consonants as easily as stops and fricatives do, phonotactic evidence is more limited. *A priori* it is conceivable that affricates could be assigned a position separate from both fricatives and stops. If we factor into this the potential contrast in voicing, we derive six possible natural class divisions which can be made among obstruents.

This is disheartening since it yields 6! = 720 permutations. Fortunately, however, we saw in §3.2.5.2 that many of these rankings are universally fixed, so the number of obtained hierarchies is much smaller. Given the complications which affricates pose, many researchers ignore them completely in terms of the sonority hierarchy, as noted by Hankamer and Aissen (1974), Escure (1977), and Lavoie (2000). Among those who explicitly consider the position of affricates relative to other obstruents, we find the following proposals:

(3.8) (a) fricatives > affricates > stops
(Hankamer and Aissen 1974, Itô 1982, Lass 1984, Katamba 1989, Goldsmith 1990, Puppel 1992, Napoli 1996, Gouskova 1999)

(b) stops > affricates
(Pike 1954, Hooper 1976)

(c) affricates = stops
(Pāṇini [Misra 1966, Katre 1987, Cardona 1988], Whitney 1889, Bolinger 1962)

Early work on affricates considered them to be basically strident stops (Jakobson, Fant, and Halle 1952/1961). Later, SPE introduced the feature [±delayed release] to distinguish stops from affricates. Subsequent research, however, has shown rather convincingly that affricates are best seen as involving a complex geometric representation, not a unitary linear feature matrix (Sagey 1986, Lombardi 1990). Perhaps this is why the relative sonority of affricates has remained unresolved in the phonological literature: their very composition implies that they are both stops and fricatives at the same time. Nevertheless, my phonetic results in chapter 4 strongly support the classification of affricates as statistically indistinguishable from their corresponding stop cognates in terms of the five correlates of sonority I investigate. Consequently, this is the position I will ultimately adopt in my universal sonority hierarchy in chapter 5.

3.2.5.4 Sonority vs. strength

As mentioned in §1.2.3 and §2.2, the abstract notion of strength is sometimes posited as a scalar feature running in the opposite direction from sonority (cf. table 2.2). Except for this one inconsequential difference, the two hierarchies perform essentially the same functions and hence only one of them is needed; the other is redundant and should be discarded. However, Dogil (1988, 1992) suggests that we should invoke language-specific strength scales to fine tune the universal sonority hierarchy. I agree with him that the sonority hierarchy is universal (cf. Kiparsky 1981, Rose 2000), but language-specific idiosyncrasies are best handled by independent constraints rooted in some mechanism other than sonority. The definition of *strength* (among those who use this term) is just as nebulous as that of sonority (cf. Hooper 1976), so on this basis neither label is to be preferred. However, Davis (1998) claims that sonority has a phonetic basis while strength does not. I disagree; all one has to do is reverse tables 2.1 and 2.2 and we obtain a list of correlates of strength rather than of sonority.

There are actually two subtle differences between strength and sonority which sometimes emerge in the literature. First, strength tends to be mentioned in discussions of diachronic phonology more readily than it is in synchronic analyses (e.g., Foley 1970). Perhaps this is because over time we see which types of segments more stubbornly resist change, hence the allusion to strength. Second, distinctions between segments having the same manner of articulation but different points of articulation are more often attributed to strength than to sonority. For example, Hooper (1976) classifies Spanish /o/ and /u/ as stronger than /e/ and /i/, respectively. On this detail I remain a skeptic. In my view, positing differences between segments such as /f s š/ on the basis of strength or sonority is too language-specific to be of much use. The fact that /s/ is more likely than /f/ or /š/ to violate the SSP in the languages of the world, as in *snug* (§1.2.1), is due in part to the structure of the Place Node (alveolars are unmarked or underspecified relative to labials and palatals), not because /s/ is inherently stronger (cf. Zec 1988, Clements 1990, and Rice 1992). The place markedness hierarchy (Lombardi 1995) is best explained on grounds that have nothing to do with sonority *per se*. In conclusion, a distinction between strength and sonority is unmotivated, particularly for synchronic patterns. Only one such hierarchy needs to exist. I prefer to call this *sonority* for two reasons: (1) this term is more widely used than *strength*, and (2) it is more suggestive of the notion *intensity*, the physical characteristic with which it is most highly correlated (cf. chapter 5).

In the remaining sections of this chapter I discuss five interesting versions of the sonority hierarchy which are relevant to the theme of this dissertation. They are presented in chronological order.

3.2.5.5 Brakel (1979)

Brakel (1979) proposes that strength indices be derived for each segment type from the sum of positive specifications for the complete list of binary distinctive features (in this sense his model is an extension of that of Clements 1990). For this purpose Brakel posits an inventory of universal features which are based on the SPE model yet are more compact than it:

(3.9) Brakel's (1979:49) list of "revised distinctive features"

contoid
nasal
–voice
labial
high
raised
dorsal
palatal
occlusion
friction
slit
lateral
delayed trans. 1
delayed trans. 2
relatively wide glottis
relatively constricted glottis
suction
pressure
covered
velaric
glottalic
length

Given this group of features (which Brakel does not define), he then calculates the average number of " + " values in the exhaustive matrices for each natural class of segments. His results are as follows, where the values in parentheses reflect the corresponding totals when only voiced exemplars are included in the counts:

(3.10) "revised DF strength hierarchy" (Brakel 1979:49)

segment type	average number of +'s
voiceless occlusives	6.75
voiceless fricatives	5.61
voiced stops	5.41
voiced fricatives	4.92
nasals	4.50 (4.00)
liquids	4.16 (3.66)
glides	3.50
vocoids	3.29 (2.79)

The effect which Brakel's approach achieves is elegant since his strength scale follows the sonority hierarchy exactly. However, it appears that some of the names of Brakel's features were posited in an ad hoc way specifically to achieve the effect he desires. For example, [±contoid] is not a common feature in the literature; [±sonorant] is much more standard (although these two feature names may define slightly different classes). However, since obstruents have a "−" specification for [sonorant] but a " + " value for [contoid], the result is that obstruents are stronger than sonorants based on his criterion for strength. Similarly, his feature [voice] stands out as the only one having an explicit "−" sign in front of it, suggesting that he stipulates this only to make voiceless consonants stronger than voiced ones, given his definition. If these features were motivated on phonological grounds completely unrelated to sonority, I would have no qualms. As it stands, however, independent confirmation is lacking, so his list of revised features suffers from a touch of circularity.

What is primarily at stake here is whether all feature values (or their opposites) contribute in some way to sonority. Simply counting up +'s in itself is mechanical and theory neutral. If one can rank all feature values for their inherent sonority, then sonority might be discounted as just an epiphenomenon (*à la* Clements 1990). However, as I argued in §1.2.4 and 2.2, I do not think that this can actually be done.

3.2.5.6 Selkirk (1984)

The following sonority scale, which is typical of an entire class of related approaches (e.g., van der Hulst 1984, Durand 1990), is taken from Selkirk (1984:112), who categorizes it as *provisional*:

(3.11)

sound	sonority index
a	10
e o	9
i u	8
r	7
l	6
m n	5
s	4
v z ð	3
f θ	2
b d g	1
p t k	.5

The accompanying commentaries by Selkirk herself are very instructive:

> "It is not clear whether the absolute integer value of the sonority indices assigned to each of these segment types is important. I assign absolute values for expository convenience, though for the moment I will assume that only the sonority ***relations*** expressed by the indices are important. Later we will see that in fact a purely relational characterization of the sonority hierarchy is inadequate and that some indication of absolute sonority values is needed after all." (Selkirk 1984:112 — emphasis in original)

> [With respect to the sonority index,] "... the values are purely relational: the distance between each niche in the hierarchy has the same value.... It is not unlikely that this is the wrong approach, and that the sonority distances between segments of lesser sonority are smaller than those between segments of greater sonority, that is, that there are significant discontinuities in the sonority hierarchy.... So while the generalization to be expressed about R_2 with respect to R_1 is clearly that a minimum sonority distance is required between them, the specification of the value of *m* will have to await further research on the precise nature of the sonority hierarchy." (Selkirk 1984:121) [R_1 = 1st segment in the rhyme; R_2 = 2nd segment in the rhyme]

The statements from Selkirk (1984) above are echoed by several other researchers. For example, Dogil (1992) suggests that the sonority distance between glides and liquids is smaller than that between liquids and nasals, for structural reasons. (In his model sonority is inversely proportional to the number of left branches, i.e., articulatory components, in the feature geometry representation of segments.) Similarly, van der Hulst (1984:51) claims that the distance between obstruents and nasals is larger than that between nasals and liquids, based on the phonotactics of Dutch syllables, and his gradient scale reflects this. In discussing this issue, Larson (1993) concludes,

> "If the sonority hierarchy is quantized, it is also possible to posit a difference between successive categories that is greater than or less than one. For instance, it is not absolutely necessary to consider the difference between O [obstruents] and N [nasals] to be the same as the difference between L [liquids] and G [glides]." (Larson 1993:66)

The following two quotes further highlight the potential importance of such a development:

> [With respect to Selkirk's (1984) scale, Goldsmith (1990:112) says,] "... there may be something right about an account that is sufficiently oriented to measuring sonority differences to be able to state unambiguously that liquids are halfway between obstruents and vowels."
>
> "Although the distance metric ultimately found to be useful [for measuring sonority differences, SP] may be quite complex, it would be of significant benefit to our attempt to understand the organizational principles of phonology ..." (Laver 1994:505)

At this point it is worth noting that the desire for very precise sonority indices has in fact been fulfilled in two different models: that of Brakel (1979) above, and that of Larson (1993) in §3.2.5.8 below. (I could also produce an analogous gradient scale with my intensity values in chapter 4, but will refrain from doing so.) Nevertheless, in spite of this optimistic speculation, the impact of such exactness in phonological descriptions of actual languages has been quite minimal. Even though very precise sonority indices are available, it remains to be seen how they benefit phonology in any practical and informative way. Linguistic processes mainly require us to know only that segment *a* is specified positively for feature *x* and segment *b* is specified negatively or not at all for that same feature. In a few cases, such as sonority, it is also useful to know that segment *a* has more of feature *x* than segment *b* does, but no process I am aware of cares how much more segment *a* possesses of feature *x* than segment *b* does, at least not in an absolute, physical (phonetic) sense. Such exactitude, even if it is concrete and nonarbitrary, is for all meaningful purposes overkill (cf. Hankamer and Aissen 1974 and §3.3). Consequently, the position I will ultimately arrive at is that phonological sonority indices are all integers and therefore the spaces between them are all the same (*1*, *2*, *3*, ...). In other words, although phonetics may be gradient, phonology is categorical only.

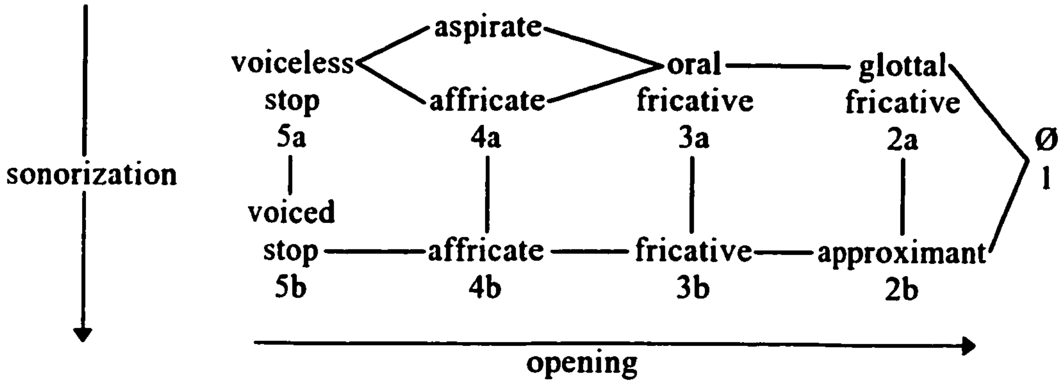
As mentioned in the Introduction, a related issue is whether the sonority hierarchy is universal or language-specific. My position is that sonority is an inherent, measurable characteristic of human speech which should therefore yield approximately equal phonetic values for the same segments, regardless of how they pattern in a particular language. This hypothesis will be confirmed if we can provide converging evidence from more than one physical domain, as well as analogous data from different languages. Consequently, the experiment I discuss in chapter 4 constitutes an important first step in this direction. The following observation by Price (1980:329) encapsulates this viewpoint: "If an acoustic definition of sonority is developed, the relative sonority of linguistic units from different languages can be compared without reference to the language-specific phonotactics of the two linguistic systems." This outcome would have the desirable effect of eliminating circular definitions of sonority based on idiosyncratic clustering tendencies (cf. §2.2).

3.2.5.7 Lass (1984)

Lass (1984) treats lenition and fortition as movement of segments along two potentially interactive strength scales, which he terms *openness* and *sonority*. His openness scale encodes "decreased resistance to airflow," and sonority involves "an increase in the output of periodic acoustic energy" (p.

178). Air flow is one of the physical correlates of sonority I pursue in chapter 4. Lass' two scales align in the following way:

Figure 3.1: Lass' (1984:178) strength hierarchies



In this model, lenition is defined as movement of a sound downward in sonority (voicing) and/or rightward in openness (continuancy). Fortition is movement in the opposite direction(s). Consequently, the ultimate weakening in this approach is complete segmental deletion, corresponding to the indices "1" and/or "Ø". Lass achieves some nice results with these scales, especially in terms of diachronic changes. Nevertheless, given his partially overlapping indices (e.g., *5a* and *5b*), it is not obvious how notions such as sonority difference could be computed in this approach.

3.2.5.8 Larson (1993)

Larson (1993) proposes a unique and interesting model which characterizes sonority as lateral (mutual) activation or excitation between adjacent segments, building on similar work by Goldsmith and Larson (1990), Larson (1990), and Goldsmith (1993). The basic idea is that sonority is a syntagmatic feature driven by inhibitory connections between units in a local computational network. In this approach sonority can vary contextually, that is, derived sonority resulting from segmental interactions may differ from input or inherent sonority. At the level of derived sonority, each unit either (a) reduces or (b) increases the activation of the next segment in the string proportionally to its own excitation level, depending on whether it is currently (a) positive or (b) negative, respectively. This sonority wave effect iterates bidirectionally until a state of equilibrium is achieved (Larson 1990). When Larson (1993) applied a connectionist algorithm of this type to a 400-word English corpus, his network converged on the following indices after the 100th trial:

(3.12)

segment	relative sonority coefficient
ə	9.21
a	9.10
e	8.72
u	8.29
i	8.28
o	7.99
ɛ	7.80
ʊ	7.79
ɪ	7.55
y	7.35
æ	7.02
ð	6.95
ɔ	6.45
ʌ	6.45
w	6.24
r	6.01
l	5.96
ž	5.84
ŋ	5.78
ǰ	5.62
n	5.31

m	4.97
v	4.83
θ	4.78
f	4.72
g	3.88
h	3.45
k	3.42
š	3.27
p	3.13
z	3.09
hw	2.92
d	2.66
t	2.60
s	2.48
č	2.45
b	0.90

A potential weakness in this sonority scale is that it is highly dependent on the phonotactic patterns of the lexical items to which it is exposed, so it is of limited use as a ***universal*** measure of sonority. In other words, the indices in (3.12) are rather language-specific and corpus-specific, and thus might change dramatically in a different language. Another concern is that several of the rankings are quite anomalous from a phonological point of view, for example, /y/ > /æ/, /ð/ > /ɔ/, /ž/ > /ŋ/, and /ə/ > all other vowels.

3.2.5.9 Gnanadesikan (1997)

Gnanadesikan (1997) claims that sonority is not a basic feature but rather derives from a confluence of several other smaller scales which are ternary in nature. Each of her three scales is relevant to sonority in some way:

(3.13) Gnanadesikan's (1997) ternary scales

(a) Inherent Voicing (IV)

voiceless obstruent	voiced obstruent	sonorant
1	2	3

(b) Consonantal Stricture (CS)

stop	fricative / liquid	vocoid / laryngeal
1	2	3

(c) Vowel Height (VH)

high vowel	mid vowel	low vowel
1	2	3

She posits a series of markedness and faithfulness constraints relative to these scales which achieve several nice results. Initially she claims that her scales make the sonority hierarchy redundant and thus proposes to abandon the latter and derive its effects from a combination of the three scales via a mechanism like harmonic alignment (Prince and Smolensky 1993) or local conjunction (Hewitt and Crowhurst 1996, Alderete 1997, Smolensky 1997, Zoll 1999). The hierarchy of natural classes which emerges is then the following:

(3.14) Gnanadesikan's (1997) indirect sonority hierarchy

low vowels
mid vowels
high vowels / glides
/ʔ/ and /h/
liquids
nasals
voiced fricatives
voiceless fricatives
voiced stops
voiceless stops

For example, voiceless stops correspond to the combination [IV1 & CS1]; voiced stops are [IV2 & CS1]; voiceless fricatives are [IV1 & CS2], etc. An interesting consequence of Gnanadesikan's (1997) approach is that laryngeal segments are higher in sonority than virtually all other consonants. In chapter 6 I discuss a psycholinguistic experiment which indicates that this may be correct, at least for English. On the other hand, a problem with Gnanadesikan's model is that it fails to distinguish between the liquids /l/ and /r/. At least four language-specific facts motivate a need for this finer split: (1) the existence of minimal pairs such as *Carl* (one syllable) vs. *caller* or *collar* (two syllables). This contrast follows automatically from the SSP, but only if /r/ is more sonorous than /l/ (Borowsky 1986, Hammond 1997:fn2); (2) English /r/ is [–consonantal] and [+continuant], whereas /l/ is [+cons] and [–cont]. Both of these feature specifications also suggest that /r/ is more sonorous than /l/; (3) /r/ occurs in nuclear position much more easily than /l/ does; words such as *bird* have no counterparts with a syllabic /l/; and (4) /r/ is the default epenthetic (intrusive) coda in Eastern Massachusetts English. Given the claims of the SDP, this fact follows most logically if /r/ is the most sonorous English consonant available in this position. In formal terms this implies that the Margin markedness constraint *CODA/*r* is the lowest ranked of this particular subhierarchy (Halle and Idsardi 1997). Because of other difficulties which arise when her three scales are joined together, Gnanadesikan concedes that constraints based directly on the sonority hierarchy are in fact also needed anyway (pp. 163-64). Consequently, I will continue to assume that sonority is a primitive feature which CON must be allowed to directly access and manipulate.

3.3 Discussion and conclusion

In this chapter we have examined a number of interesting proposals for describing the sonority hierarchy. Each one contributes insights into what sonority is and how it functions. Nevertheless, each one also entails one or more drawbacks. These can be concisely summarized as follows: (1) the sonority scale is sometimes too language-specific, which is true of Larson's (1993) model. (2) Not enough distinctions are made in the hierarchy: Clements (1990) and Gnanadesikan (1997). (3) Too many and/or the wrong kinds of distinctions are sometimes made in the hierarchy: Larson. (4) The definition of sonority is not well-grounded phonetically, i.e., there is no obvious connection between the indices and the physical substance on which they are based: Larson. (5) The definition of sonority is sometimes too complex: Brakel (1979), Lass (1984), and Gnanadesikan (1997). The latter two models posit parallel subscales which together derive sonority, but which are also correlated with the same physical parameter: intensity. When this goes unrecognized, the convergence of the subscales appears accidental and a crucial generalization is missed: the subhierarchies can be collapsed together into a single scale based on intensity measurements alone. (6) The sonority indices are sometimes overly precise: Brakel and Larson. Despite the numerous appeals for exact (gradient) indices, no work to date has demonstrated that these serve to improve actual phonological analyses. That is, no one to my knowledge has shown how the availability of sonority indices such as, e.g., 2.74, can be capitalized on in order to make formal devices such as the SCL and the SDP more simple or more explanatory. The overall theme of my comments could thus be summarized as, "Much progress has been made, but we can do better still." This is the major challenge I now take up directly.

PART 2

EXPERIMENTAL CONFIRMATION OF THE SONORITY HIERARCHY

CHAPTER 4

ACOUSTIC AND AERODYNAMIC CORRELATES OF SONORITY: AN IN-DEPTH EXPERIMENT AND ITS RESULTS

4.1 Introduction

In this second major part of the dissertation, I discuss several experiments which are designed to respond to those who doubt the reality of sonority because, they claim, sonority lacks a consistent phonetic correlate (cf. chapter 2). Here in chapter 4 I describe five acoustic and aerodynamic studies and their results. In chapter 5 I then evaluate those results in terms of their application to the sonority scale.

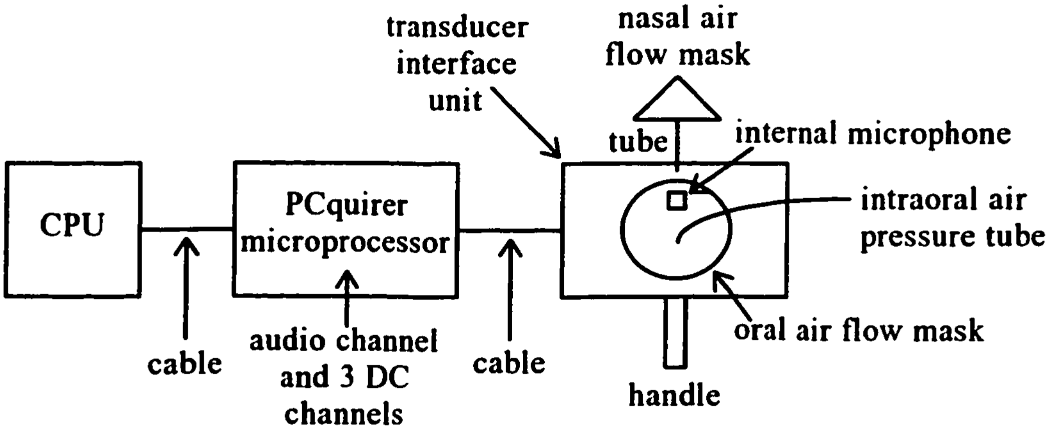
In the present chapter I discuss a series of five instrumental experiments designed to probe for physical correlates of the sonority hierarchy. My goal is to determine how well each of these phonetic parameters lines up with typical sonority hierarchies. A second and closely related goal is to demonstrate that at least one of these factors (intensity) consistently yields mean segmental and natural class values which are very highly correlated with predetermined sonority indices. I begin by describing the design and methodology which all five physical studies have in common. I then present the final, analyzed results of each one. The experiments are discussed in order of their goodness of fit with traditional sonority indices (cf. chapter 3). The five acoustic and aerodynamic measures are (in decreasing order) intensity, peak intraoral air pressure, F_1 frequency, peak air flow, and total segmental duration. Of these, intensity exhibits the strongest overall correlation with the sonority hierarchy, and duration the weakest.

4.2 Design and methodology

4.2.1 Equipment

All of the hardware and software used in this experiment was produced by Scicon Research & Development of Los Angeles. The primary device for obtaining speech signals is a conical face mask mounted on a transducer interface box (a schematic diagram of the setup is shown below). A handle is also attached to this device so that the speaker can press the oral mask tightly against the mouth, preventing any leak of egressive air flow. A nylon mesh is built into the base of the mask to provide resistance to the oral air flow. Beneath this mesh is a small, internal, condenser microphone flush with the outer surface of the transducer unit. Inside the facial mask are two Tygon brand flexible plastic tubes. The open end of the longer of these projects out of the mask and into the mouth in order to measure intraoral air pressure. It has an inner diameter (opening) of 3.2 mm (1/8"). The open end of the other tube hangs inside the mask to receive oral air flow. Each of these two tubes is connected at the opposite (closed) end to a transducer inside the hand-held device. This apparatus is also connected via a third short tube to a separate nasal mask. This fits comfortably over the nose and is held in place by Velcro straps around the back of the head. The nasal mask also contains a small nylon mesh so that the speaker can inhale and exhale normally at all times during the recording sessions. The open end of the third tube (attached to a hole in the nasal mask) collects egressive nasal air flow. The opposite end of this tube is plugged into a third transducer housed inside the interface box. All three of these aerodynamic signals (oral flow, nasal flow, and oral pressure) are low-pass filtered and then transmitted via cable to a stationary metal box for microprocessing. This device contains one 16-bit fully filtered audio channel and three 12-bit DC channels (one per transducer), each with a separate analog-to-digital converter. All four signals were exported from this box via another cable to a microcomputer. They were monitored and analyzed using the accompanying PCquirer software provided by Scicon. The following figure illustrates the complete setup:

Figure 4.1: Setup of the Scicon hardware system for collecting physical data



The live recordings were saved in 30-second long waveform files using most of the default options of the PCquirer program. These included an audio sampling rate of 11 kHz and a DC sampling rate of 1375 Hz for all three aerodynamic channels. Immediately before each recording session the three DC channels were calibrated with separate hardware produced by Scicon for this purpose. For each of the three channels the calibration device was set at five different and successively larger known values (controlled with gauges) at evenly spaced intervals. Signals lasting 10 seconds were then recorded in PCquirer files, and a peak measurement was taken in raw millivolts (the value in mv is equivalent to the value when flow or pressure is positive, minus the value when these are zero). These five measurements were then paired up with their corresponding gauge values and plotted using least-squares regression with an intercept of 0. The corresponding slopes were then entered into the PCquirer settings dialog box so as to directly display the appropriate calibrated units on the screen when analyzing the experimental stimuli.

4.2.2 Speakers

The fivefold phonetic experiment was run with four English-speaking men, four English-speaking women, four Spanish-speaking men, and four Spanish-speaking women. Each participant was a native speaker of the respective language. Prior to the recording sessions each one was screened to rule out any history of speech and/or hearing problems. In addition, none of the speakers at the time of recording had any symptoms of cough, cold, or nasal/sinus congestion that might distort their normal speaking voice. Speakers were not informed about the purpose of the experiment until after they were finished, and were paid for their participation.

4.2.2.1 English

The eight English speakers were undergraduate students currently enrolled in an introductory linguistics course at the U. Mass. Amherst campus. All had been born and raised in a northeastern state of the U.S. All were screened beforehand to rule out any significant dialectal difference that might affect the results. For example, speakers with accentual features typical of New York City or Boston were purposely excluded from participation. Specifically, for instance, no one dropped or inserted *r*'s, etc. The eight native speakers of English consisted of the following persons:

Table 4.1: Backgrounds of English speakers

gender	age	place of upbringing
male	22	Johnstown, NY
male	18	Pittsfield, MA
male	18	Middleton, MA
male	18	Mattapoisett, MA
female	17	Rockville Centre, NY
female	19	Somerset, MA
female	18	Methuen, MA
female	18	Attleboro, MA

4.2.2.2 Spanish

The eight Spanish speakers were current graduate students at U. Mass. All had been born and raised in the interior Andean highlands of northwestern Colombia, South America. All were screened beforehand to rule out any significant dialectal difference. The eight native speakers of Spanish consisted of the following:

Table 4.2: Backgrounds of Spanish speakers

gender	age	place of upbringing
male	33	Manizales (Colombia)
male	30	Bucaramanga
male	30	Bucaramanga
male	29	Barrancabermeja
female	30	Bogotá
female	30	Pamplona
female	30	Bucaramanga
female	27	Bogotá

4.2.3 Word lists

The complete lists of words used in eliciting data appear in Appendices A and B, along with glosses of the Spanish items. In this section I summarize the most important aspects of the lists, focusing on the contexts designed to control for contrasts of each language-specific phoneme. Most of the target segments I measured occurred in word-initial syllables bearing primary stress. This detail must be kept in mind when interpreting the results later in this chapter. In a few cases it was impossible to find a word exemplifying a particular sound in the desired context due to language-specific phonotactic restrictions. In such cases a word was sought in which the targeted segment occurred in either the initial syllable or the syllable bearing primary stress. All phonemes of both languages were included in the data, as well as a few tokens of [?] in English. Whenever possible, consonants were elicited in both onset and coda position, although never in the same word, i.e., I did not use any syllables of the type /pVp/. Words with complex onsets and codas were generally avoided so as to minimize the coarticulatory effects of consonant clustering. A somewhat different list of words was used to elicit data for F_1 measurements, for reasons to be explained in §4.3.3. In that section I discuss the words used there as well as the criteria for selecting them. The words listed immediately below were used for the other four phonetic studies (intensity, air pressure, air flow, and duration).

4.2.3.1 English

English items were mostly monosyllabic and were elicited in the frame *I wanna ____ again*. This context was chosen so as to have a very reduced environment ([ə]) immediately before and after the targeted word. Speakers were instructed to think of the word *wanna* as meaning *want to* when followed by a verb, and as *want a* when followed by a noun. In cases when a following noun began with a vowel, the reading list cued the speaker to say *want an* rather than *want a*. In all cases, however, speakers were instructed beforehand to pronounce the word *a/an* in a quick and reduced way, running it together with the word *want*, as in rapid, informal speech.

The primary context used to minimally contrast all vowel phonemes was [labial stop ___ t], as in the following list of words. Some of the speakers distinguished the vowels /a/ and /ɔ/, as in *bot* vs. *bought*. I transcribed such vowels based primarily on my impression of how they sounded, but in cases of doubt I also consulted their F_1 and F_2 values.

(4.1) **b*ee*t** **b*ai*t** **b*a*t** **b*oa*t** **b*oo*t** **b*u*tt**
b*i*t **b*e*t** **b*o*t** **b*ou*ght** **p*u*t**

When making phonetic measurements of the recorded lists, I included all segments in the targeted syllables. Therefore, the words in (4.1) above provided data not only for vowels, but also for many tokens of onset /b/ and coda /t/, for example. The vowel [ə] was elicited in the following items, where it occurs before at least one member of most natural classes of English consonants:

(4.2) *a*ttack *a*bode *a*ssist *a*larm
*a*ccord *a*ddress *a*mount *a*rrest

The following words were selected to contrast consonants in syllable-initial position:

(4.3)

obstruents and /h/	sonorants and /h/
*p*in	*m*ay
*b*in	*n*ay
*f*in	*l*ay
*v*ision (*v*)	*r*ay
*v*ane	*y*ea
*th*in	*w*ay
*th*en	*h*ay
*t*in	
*d*in	*gn*aw
*s*in	*l*aw
*z*en	*r*aw
*sh*in	
vi*s*ion (*ž*)	
*ch*in	
*g*in	
*k*in	
*g*ain	
*h*e	
*h*ay	

As seen in (4.3), all obstruent-initial words contain a front vowel (usually /ɪ/) in the first syllable and end with /n/. All sonorant consonants occur before /ey/, and three of them also occur before /ɔ/. The following words were used to contrast consonants in final position:

(4.4)

obstruents	sonorants
ma*p*	ca*m*
na*b*	ca*n*
lau*gh*	go*ng*
ha*v*e	ca*ll*
ma*th*	ca*r*
la*th*e	
ma*t*	co*mb*
ma*d*	co*n*e
ma*ss*	coa*l*
ja*zz*	co*r*e
ma*sh*	
rouge (*ž*)	
ma*tch*	
ba*dg*e	
ma*ck*	
atta*ck* (k)	
na*g*	

In (4.4), final obstruents occur following the vowel /æ/, except for the /ð/ in *lathe* and the /ž/ in *rouge*. Most of these items begin with a sonorant consonant, usually a nasal. Final sonorants in (4.4) are preceded by either /æ/ (or a similar vowel in *car*) or /ow/ and an initial /k/ (or /g/ in the case of *gong*). The following two words contained possible instances of a phonetic [ʔ]. Most of the speakers did in fact pronounce them with a [ʔ]; tokens pronounced without [ʔ] were excluded from the calculations for this segment:

(4.5) u*h*-oh La*t*in

The word *uh-oh* was often pronounced with an initial [ʔ] in addition to the expected intervocalic one. All such occurrences were also included in my measurements for the segment [ʔ].

4.2.3.2 Spanish

Spanish lexical items were elicited in the frame *Quiero un/una* ____ *ahora* 'I want a ____ now.' The contrast between *un* and *una* immediately preceding the target word is necessary in order to obtain tokens of both voiced stops and voiced fricatives in initial position. Speakers were instructed to use the indefinite article *un* with masculine nouns, and the corresponding *una* with feminine nouns, as Spanish requires. This context was chosen so as to match the English target frame as closely as possible in all respects — semantically, syntactically, phonologically, and prosodically. Targeted words are mostly disyllabic, with (default) stress usually on the penultimate syllable.

The primary contexts used to minimally contrast all vowel phonemes were the following word-initial stressed syllables (glosses are given in Appendix B). All of these words begin with /p/, and the vowels in the targeted syllables are followed by either an onset /s/ (first line) or a coda /n/ (second line):

(4.6) p*i*so p*e*so p*a*so p*o*zo p*u*so
p*i*nza p*é*ndulo p*a*nza p*o*nche p*u*nto

The following words were selected to contrast consonants in syllable-initial position:

(4.7)

obstruents and /h/
*p*ozo
*p*onche
*b*osque ([b])
*v*oz ([β])
*f*osa
*t*os
*d*os ([d])
*d*osis ([ð])
sopa
*ch*oza ([č])
*y*unque ([ǰ])
in*y*ección ([ǰ])
*c*osa ([k])
*g*ozo ([g])
*g*ota ([γ])
*j*ota ([h])

sonorants
*m*oza
*n*ota
*ñ*ata
*l*osa
re*l*oj
ho*r*óscopo ([ř])
*r*osa ([r̄])
*y*uca ([y] ~ [ǰ])
*hu*elga ([w])

Most of the targeted onset consonants in (4.7) are word-initial and followed by the vowel /o/. Concerning the voiced obstruents in (4.7), masculine nouns were used to obtain the initial stop allophones following the /n/ of *un* (*bosque*, *dos*, and *gozo*). Feminine nouns were used to elicit the corresponding continuant (fricative ~ glide) allophones following the /a/ of *una* (*voz*, *dosis*, *gota*). All eight speakers invariably pronounced the *jota* phoneme (/x/) as a glottal fricative, never as a velar like in other dialects (Castilian, etc.). Consequently, in my results sections I treat this segment as /h/. In the words (*un*) *yunque* and *inyección*, the /y/ was expected to be pronounced as the affricate [ǰ] due to the well-known post-nasal fortition effect, and it always was.

On the other hand, the feminine noun *yuca* was also included in the hope of obtaining some tokens of the pure glide [y] (following the /a/ of *una*). However, all eight speakers consistently pronounced this word with a [ĵ] as well. Consequently, in my results sections I lump together all such cases (from the three words *yunque*, *inyección*, and *yuca*) with the transcription [ĵ]. This move is confirmed by the fact that with respect to all five phonetic parameters measured, this segment consistently patterns as an obstruent, not a sonorant. The /w/ phoneme, however, never underwent fortition; all speakers pronounced it as a true glide, so in my results sections it is treated as such.

The following words were selected to contrast consonants in syllable-final position:

(4.8)

obstruents and /h/	sonorants
hi*p*nosis	ca*m*po
a*b*negación ([β])	pi*n*za
o*f*talmólogo	pa*n*za
é*t*nico	po*n*che ([ñ])
a*d*misión ([ð])	i*n*yección ([ñ])
to*s*	yu*n*que ([ŋ])
do*s*	a*l*to
vo*z* ([s])	a*l*ma
bo*s*que	hue*l*ga
horó*s*copo	ca*r*ne ([r̆] ~ [r̃])
ta*x*i ([*k*s])	ca*r*ta ([r̆] ~ [r̃])
a*g*nóstico ([γ])	
relo*j* ([h])	

In the list of elicitation items in (4.8) it was much more difficult to control the surrounding context due to a paucity of Spanish syllables ending with certain consonants. Nevertheless, in most cases the preceding vowel is either /a/ or /o/. The word *reloj* is the only canonical (non-borrowed) item in Spanish which contains a syllable-final /h/. In many dialects of Spanish (e.g., *andaluz*, *caribe*, etc.), /s/ is debuccalized to [h] in coda position, but none of my subjects did this. (I do not know whether other speakers in Colombia do so.) Consequently, in my results sections all syllable-final instances of /h/ are from the word *reloj*. The surface contrast between the flap [r̆] and the trill [r̄] is neutralized in coda position in Spanish (cf. *carne* and *carta*). Although both pronunciations can occur there (and both are attested in my data), the flap [r̆] is more common and expected syllable-finally. Consequently, my results sections do not distinguish coda [r̆] from coda [r̄]; for simplicity I lump both segments together and count all of them as /r̆/.

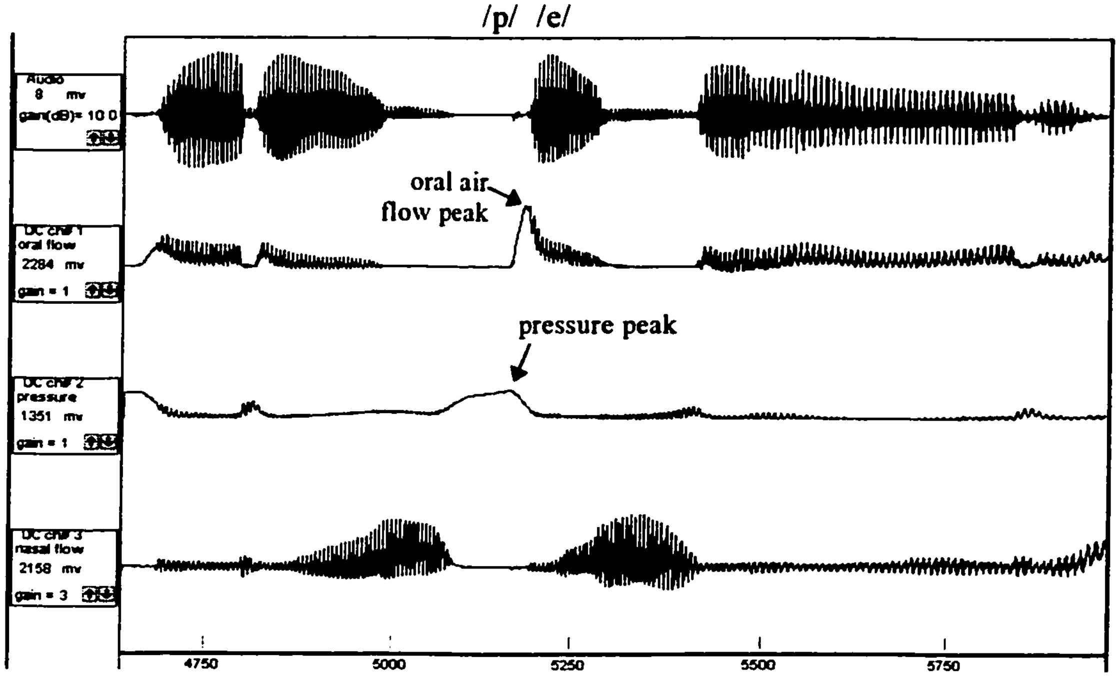
4.2.4 Procedures

In this section I discuss the general methodology used to elicit data for all five phonetic correlates of sonority. Procedures specific to a single physical parameter, such as how and where the measurement was made for each segment type, are explained in the respective background and results sections. Recording sessions took place in the U. Mass. phonetics lab during the fall 2000 and spring 2001 semesters. I ran several pilot experiments first in order to familiarize myself with the hardware and software. Each speaker initially read through the entire word list one time aloud so I could check their pronunciation and ensure that they were familiar with all the words. They were instructed to substitute each target word into the appropriate language-specific frame sentence and were requested to practice this a few times until they had the idea. They were asked to speak in a normal tone of voice, neither especially loud nor especially soft. They were also instructed to speak at a normal, relaxed, conversational rate of speed, neither too fast nor too slow. They were further requested to pause momentarily after each sentence as they read down the entire list of words. After this initial orientation, each speaker was seated near the hand-held transducer unit and shown how to press the oral face mask tightly against the mouth, sealing off the air flow. I then explained to each one how to insert the intraoral air pressure tube into the right corner of the mouth and push it up and around the right superior gingival sulcus, holding it in place between the cheek and the gums. From that position each speaker then bent the open end of the tube so as to project it past the distal surface of the last upper right molar (tooth no. 1) and into the open space in the back of the oral cavity. At this point the open end was roughly midsagittal and perpendicular to the direction of air flow, i.e., the longitudinal axis of the vocal tract. During this process I cut off the tip of the tube one or more times until it was exactly the right length to fit comfortably in each speaker's mouth. (A separate tube was used for each subject.) Furthermore, we also performed several trial recordings with the tube in place to ensure that it was picking up accurate pressure measurements. After several practice runs with the oral mask and pressure tube in place, I then assisted each speaker to slip on the nasal mask and secure it with the Velcro straps around the back of the head. The fit was tight but not uncomfortable. Once all three aerodynamic sensors were correctly positioned, we then carried out one or more final practice recordings until the PCquirer program was adequately tracking all channels simultaneously. At that point we then began the actual recording sessions in earnest. Each speaker read through the entire list of words three times. Each of the three sheets presented the same inventory of lexical items in a different randomized order. The recording time was set to 30 seconds. After each block of 30 seconds the speakers paused briefly so I could save the most recent recording as a waveform file. We also took longer breaks of up to five minutes after finishing the first and second readings of the entire word list.

4.2.5 Segmentation criteria

Given the convergence of five different visual representations of the speech stream on the PCquirer screen, it is relatively easy to determine segmental boundaries in a reliable and consistent way. These five images are the audio waveform, the oral air flow trace (U_o), the pressure trace (P_o), the nasal air flow trace (U_n), and the intensity trace (overlaid on the audio waveform). PCquirer automatically aligns these four windows with one another, so the location in time of the cursor or a selected stretch of speech is always synchronous across images. The following figure illustrates a typical PCquirer screen, corresponding to the utterance *Quiero un <u>péndulo</u> ahora* ‘I want a pendulum now’:

Figure 4.2: PCquirer display of the sentence
Quiero un péndulo ahora by a male speaker



In the PCquirer screen above, the topmost signal is the audio waveform. The second channel shows oral air flow, the third is intraoral air pressure, and the bottom display is nasal air flow. At the top of the screen I have superimposed labels corresponding to the segments /p/ and /e/ of the target word *péndulo*. Arrows mark the U_o peak (1370 ml/sec) and the P_o peak (9.0 cm H_2O) of the /p/. These values are very robust but are typical for this speaker. Later, in §4.3.1.1, figure 4.3 displays this same utterance with the intensity trace lines overlaid on these four channels.

Stops were identified by a gap in the audio waveform, steep descent of the intensity trace, a sharp rise in P_o at their beginning, and a U_o peak at the instant of release. Fricatives were similar to stops except that the falls and rises in the visual signals were less extreme. Also, fricatives often had a second U_o peak at their onset which stops lacked. In the few cases when I needed to parse a fricative + stop cluster (or vice-versa), I consulted a wide-band spectrogram and aligned the fricative with random high frequency turbulent noise, especially for sibilants. Nasals were easy to uniquely identify by the sharp and steady plateaus in the U_n trace. /h/ also tended to have very high nasal air flow in both languages; this is typical and is apparently due to the glottis being abducted to increase glottal air flow before the oral constriction is complete (cf. Cohn 1990, Walker 1998). Nasal consonants were also characterized by minimal U_o and a slight drop in the audio waveform and intensity trace relative to adjacent vowels. All other sonorant consonants (liquids and glides) were normally segmented with the aid of spectrograms, especially in English. The principal landmark was the beginning of a significant rise and intensity of the transition of F_2 into that of abutting vowels. In many cases there was no consonantal F_2 at all, so the border of vowels was posited at the point where F_2 began or ended. The other acoustic correlates of oral sonorant consonants were also helpful but less reliable, especially in coda position. These included minor dips in the audio waveform and intensity trace. The liquid consonants were easier to identify in Spanish than in English. This is because the English /r/ and the darkened allophone of /l/ are more vocalic in nature whereas the flap /ř/ and trilled /r̄/ in Spanish are more obstruent-like. For any token for which I had any doubt about the correct location of segmental boundaries, I consulted a spectrogram and studied the formants, primarily F_2 and, to a lesser degree, F_1. This was also necessary for many cases of voiced fricatives as well. (These sounds are often only weakly fricated, especially the nonstrident ones.) Finally, vowels were identified mainly by their high amplitude and strong periodicity on the audio waveform, as well as the beginning of an abrupt surge in the intensity trace compared to consonants. The other three (DC) channels were of little help in parsing vowels. A final aid which I often relied on was PCquirer's capacity to audibly replay any highlighted portion of the recording. After parsing each of the targeted syllables using these criteria, I wrote down by hand all of the relevant physical measurements on separate sheets of paper. These raw data were then entered into Excel (also by hand) on a different machine to serve as the basis for the statistical analyses which I now present.

4.3 Results

In this section I present the results of the five acoustic and aerodynamic measurements that I carried out in order to determine the closest physical correlates of the universal sonority hierarchy. The main criterion I will use for measuring strength of association between segmental means and sonority indices is Pearson's product-moment correlation coefficient (*r*). The five phonetic parameters are presented in order of decreasing goodness of fit: intensity, peak P_o, average F_1 frequency, peak U_t (total air flow), and segmental duration. Within each of these sections the organization is as follows. I first discuss any relevant background information, such as previous experiments and measurement techniques. I then present the data, first for English and next for

Spanish. Each set of data is broken up into three parts: consonants in onset position, consonants in coda position, and vowels. I conclude the discussion of each physical parameter by summarizing the data in terms of the appropriate correlations.

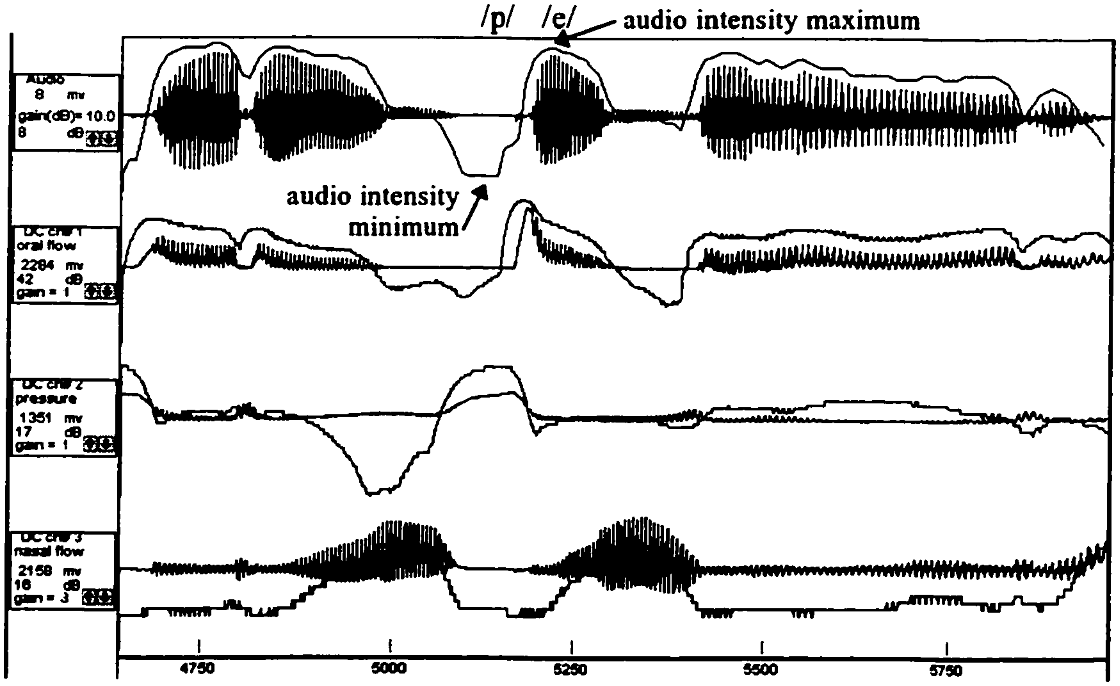
4.3.1 Intensity

4.3.1.1 Background

Intensity (or loudness) is often posited as a working definition or correlate of sonority (at least 24 references in Table 2.1). Of the five physical parameters I measured, intensity turns out to have the strongest correlation with the typical sonority hierarchy (a very high mean *r* value of about .96 or .97 across all data sets). Consequently, the idealized definition of sonority I pursue in chapter 5 is based primarily on these intensity results.

Ladefoged (1993) characterizes sonority in terms of acoustic intensity, which he defines as a sound's "loudness relative to that of other sounds with the same length, stress, and pitch." (Ladefoged 1993:245). To control for the variation of these factors across sentences, it is necessary to compare the intensity measurement of each target segment with that of a consistent landmark in every utterance. For English the point of comparison in each case was the /n/ of *wanna*. For Spanish it was the /n/ of *un* or *una*. The absolute intensity level in dB of these /n/'s was subtracted from that of each target segment in the same sentence to arrive at a relative loudness value appropriate for statistical purposes. For all consonants, the intensity value I measured was the minimum dB level which occurred at any point during the segment. For vowels I recorded the maximum dB level which occurred at any point during the segment. Ideally it might have been best to obtain a mean intensity measurement averaged across the total duration of each segment. Unfortunately, however, the version of PCquirer I used does not have this capability. Consequently, it was necessary to decide upon some predetermined point in each segment type at which to measure intensity. A very basic and consistent dichotomy in speech is that between vowels and consonants. One reliable perceptual indicator of this contrast is loudness: vowels are loud sounds and consonants are soft sounds, in keeping with their prototypical occurrence in syllable nuclei and margins, respectively. It is therefore logical to measure peak intensity in vowels since this is the point when they are most distinct from consonants. Conversely, the most consonant-like point of consonants is when their intensity is at a minimum. In most cases this corresponds to the moment in time at which the constriction is greatest. Normally these two loci (peak intensity in vowels and minimum intensity in consonants) correspond to the steady state and/or center of each segment type. Taking the intensity measurements at other landmarks, such as at the border between each consonant and vowel, would obscure their inherent differences since that is where the consonant's intensity is pulled up by that of the vowel, and conversely that of the vowel is pulled down by the low intensity of the consonant. Consequently, the location at which the intensity value was most typical for each manner of articulation was chosen to be the peak for vowels and the trough for consonants. Figure 4.3 below shows that these locations are easy to spot in a PCquirer display. This program does not have an automated function for extracting peaks and minima within a selected portion of speech, so it was necessary to sweep the cursor across the intensity trace line for each segment and "eyeball" these locations by hand. PCquirer calculates intensity using RMS energy amplitude with an audio window length of 30 ms and a step size interval of 10 ms. Given the default audio sampling rate of 11 kHz, this translates into RMS intensities based on a mean of around 330 points. The following figure shows the same utterance as the previous figure, but with the intensity trace lines superimposed on the four channels. Arrows indicate the audio intensity minimum for /p/ (3 dB) and the peak for /e/ (36 dB):

Figure 4.3: PCquirer display of the sentence *Quiero un péndulo ahora* by a male speaker, with intensity trace lines overlaid



Before presenting my own results, I first summarize several previously published experiments on intensity in English. To evaluate each of these I list the correlation value which I calculated by pairing up each segment's mean intensity measurement with the sonority index assumed for that natural class. For the purposes of the English results I discuss in this chapter, I temporarily posit the following (provisional) sonority hierarchy and scale, based on the findings of the previous chapters (the corresponding Spanish scale is presented in §4.3.1.3):

(4.9) English sonority hierarchy assumed for the purposes of correlation

class of segments	sonority index
low vowels	12
mid vowels (except [ə])	11
high vowels	10
[ə]	9
glides	8
rhotics	7
laterals	6
nasals	5
voiced fricatives	4
voiced stops / voiceless fricatives	3
voiceless fricatives / voiced stops	2
voiceless stops	1

The natural class divisions in the scale above are not arbitrary; rather, they are motivated by the universal and language-specific facts laid out in chapter 1. They are further informed by the discussion of the various proposed sonority hierarchies examined in chapter 3. As I concluded at various points, a separation of obstruents based on voicing and continuancy is necessary in order to capture several phonological generalizations (cf. §1.2.4, 1.3.2, 1.3.3, 3.2.5.2, etc.). However, the relative ranking of voiceless fricatives vs. voiced stops appears to be more tentative, so in this chapter I calculate correlations in both possible ways (e.g., *d* > *s* and *s* > *d*) to see which one better fits the phonetic data (the effect of this permutation on the obtained *r* values is never very large). Next, nasals are universally recognized as being higher in sonority than obstruents yet lower than liquids (cf. (3.4)). Among the liquids, the necessity of ranking English /r/ above /l/ is established in §3.2.5.9. The separation of most vowels into three height-based classes is also robustly assumed in the literature, especially in terms of comparative weight and stress assignment (cf. (1.9)). Finally, the classification of [ə] as lower in sonority than all other English vowels also follows from scale (1.9) and from its restriction to unstressed syllables only. Still, for the sake of comparison I will always test whether [ə] patterns as statistically distinct from the other mid vowels. As far as the sonority indices themselves are concerned, equal steps of whole integers are sufficient for all practical phonological purposes (cf. §3.2.5.6 and 3.3). The temporary hierarchy and scale which thus emerge are displayed in (4.9) above.

In applying the hierarchy in (4.9) to my experimental data, I will make two simplifying assumptions. First, the relative sonority of voiceless fricatives vs. voiced stops is not fixed. Rather, based on the discussion in §3.2.5.2, I will permit these two groups (and only these) to vary. Consequently, throughout this chapter I freely permute the sonority indices of these two classes depending on which ranking yields a stronger correlation for the data under consideration at that moment. Second, in table 4.3 below I do not include the intensity values for affricates and /h/ (when present) in my correlation calculations since their relative sonority has not yet been firmly established. This detail is left undetermined for the moment because of the controversies noted in §3.2.5.1 and §3.2.5.3. When I analyze my own data later in this chapter, I will incorporate glottal consonants and affricates into the correlations only when they statistically pattern with one of these traditional natural classes (which are independently motivated by *a priori* phonological facts). In the following table the column labeled "intensity scale" lists the English phonemes examined in 7 earlier studies, arranged from left to right in order of decreasing intensity, as measured in dB above or below a standard reference point established for each case. Not all of the differences between pairs of adjacent segments in these scales are necessarily significant, but they do at least reflect the overall trends.

Table 4.3: Summary of previous experiments on intensity in English

author(s)	date	intensity scale	*r*	*p*
Fletcher*	1929	æ ɛ e ʌ ɑ ɔ i o ɪ ʊ u r l m ŋ š n č ž s z ǰ v t ð g k b d p f θ	.94	.000
Black	1949	o ɑ æ ɔ ɛ ɪ u ʊ ʌ e i	.56	.074
Fairbanks *et al.*	1950	æ ɔ ɑ o e ɛ u ʌ i ʊ ɪ	.84	.001
Ladefoged	1975	æ ɔ o ʊ ɪ i l r m n w y s š f θ h p t k	.93	.000
Fry	1979	o ɔ ɑ ʌ æ ʊ ɛ ɪ i u w y r l š ŋ m č n ǰ ž z s g t k v ð b d f p θ	.89	.000
Kennedy *et al.*	1998	ŋ m n s z š d g ð v b t k θ p f	.80	.000
Lavoie	2000	r l n m ð ž v z ǰ d b g č θ š t s p f k	.91	.000

*Fletcher's data come from Sacia and Beck (1926).

To clarify, it bears repeating that in calculating the correlations in table 4.3 (a task which I, not these authors, performed) I utilized ***their*** intensity data (mean segmental values) but ***my*** sonority indices (from (4.9)). In table 4.3 the last column gives the two-tailed p value for the correlation which immediately precedes it. That is, it tests whether the slope is significantly greater than 0 or, equivalently, whether the corresponding regression reveals a significant linear relationship between sonority indices and mean segmental intensity levels. The following table provides two other details concerning these previous studies which may be helpful yet are less relevant to the correlations themselves. Cells with horizontal dashes (--) indicate that that information was not reported. The rightmost column (repetitions) is the number of times each segment was pronounced by each subject:

Table 4.4: Numbers of speakers and tokens from table 4.3

author(s)	speakers	repetitions
Fletcher	16	--
Black	16 men	1
Fairbanks *et al.*	10 men	10
Ladefoged	--	--
Fry	--	--
Kennedy *et al.*	--	1
Lavoie	5 men	5

The studies summarized in table 4.3 demonstrate that intensity is strongly correlated with sonority and therefore worth pursuing by means of an in-depth experiment. None of these works conclusively tests my hypothesis since all of them lack data of one kind or another. For example, Fletcher (1929) did not measure /y w h/, and Lavoie (2000) contains no data on vowels. (The numbers which Ladefoged (1975:270) provides are only estimates and thus involve, in his words, "... a great deal of guesswork...") Lavoie (2000) is concerned with lenition and therefore studies consonants only. Furthermore, although she also uses both English and Spanish speakers, all of these are men. In addition to intensity she analyzes duration and linguopalatal contact as well, but not F_1, P_o, or U_o and U_n. Consequently, her results need to be replicated for both male and female speakers and applied to all English phonemes, vowels and consonants alike, including /y w h/ and /ʔ/ (in the word *uh-oh*). Furthermore, it would be ideal to generalize this methodology to other languages. English and Spanish were chosen as the most practical pair for the purposes of this dissertation because (1) their segmental inventories complement each other quite well in terms of containing most of the cross-linguistically common phones; (2) it was easy to recruit volunteer subjects; and (3) I am fluent in both languages. In other words, it was expected that the Spanish findings would partially overlap with and confirm the English results, and this generally turned out to be true.

4.3.1.2 English intensity measurements

I now present the results of my intensity calculations on the eight English speakers, grouped by gender. In each table I list the individual segments from softest to loudest (relative to the *n* of *wanna*). Recall that virtually all of these occur in word-initial stressed syllables. From left to right I give the overall segmental mean (pooled across all four speakers), the total number of tokens analyzed, and the standard deviation. After the list of individual phones I then give the grand weighted means for each natural class combined. I begin with consonants that occurred in onset position:

Table 4.5: Intensity of onset consonants for English males (in dB)

segment	mean	*n*	sd
θ	−14.74	23	3.51
k	−13.86	130	3.63
p	−13.83	36	2.90
d	−13.27	11	3.58
č	−13.25	12	3.25
t	−13.22	23	3.83
g	−12.54	24	4.12
b	−12.37	154	3.67
ǰ	−12.22	36	3.67
ð	−11.25	12	3.49
f	−11.17	12	2.98
s	−11.14	35	3.51
ʔ	−11.10	30	5.51
š	−9.83	12	3.81
z	−7.58	12	4.85
h	−6.05	60	4.19
v	−5.50	24	5.56
n	−4.52	83	3.07
m	−3.91	119	3.03
ž	−1.67	12	3.73
y	2.42	12	4.66
l	2.51	69	3.72
r	2.53	45	3.50
w	5.42	12	2.19
p t k	−13.78	189	3.52
p t k + č	−13.75	201	3.50
b d g	−12.44	189	3.71
b d g + ǰ	−12.41	225	3.70
f θ s š	−11.96	82	3.86

(cont. next page)

Table 4.6: Intensity of onset consonants for English females (in dB)

segment	mean	*n*	sd
č	−15.08	12	3.45
k	−14.93	130	3.43
p	−14.89	36	3.69
θ	−14.33	24	3.58
t	−13.50	22	3.49
f	−13.50	12	3.85
s	−13.14	35	2.44
g	−12.63	24	3.50
b	−12.45	148	3.32
ǰ	−12.28	36	3.02
d	−11.25	12	2.99
ʔ	−10.71	31	6.65
š	−10.50	12	2.50
z	−9.92	12	2.71
h	−8.35	60	5.31
ð	−7.25	12	5.05
v	−4.91	22	5.88
ž	−4.00	12	6.65
m	−3.12	112	3.02
n	−2.96	79	2.60
r	2.67	39	3.90
l	3.62	65	4.12
w	3.64	11	5.63
y	4.80	5	2.39
p t k	−14.76	188	3.50
p t k + č	−14.78	200	3.49
f θ s š	−13.16	83	3.22
b d g	−12.40	184	3.32
b d g + ǰ	−12.38	220	3.27

(cont. next page)

(Table 4.5 cont.)

v ð z ž	–6.30	60	5.59
m n	–4.16	202	3.05
l r	2.52	114	3.62
y w	3.92	24	3.88

(Table 4.6 cont.)

v ð z ž	–6.24	58	5.69
m n	–3.05	191	2.85
l r	3.26	104	4.05
y w	4.00	16	4.79

To clarify, I reiterate that in all such tables in this chapter, calculations are always done using the pooled tokens from all four speakers combined. Because of the breadth and scope of this experiment, it would have taken too much time and paper to present the results for each speaker broken down separately. In the tables above (and all subsequent ones in this chapter), a " + " symbol among the grouped natural classes (e.g., "p t k + č") has the following interpretation: the segment to the right of the " + " is not statistically distinct from the group made up of all the sounds to the left of the " + " in the same cell. For example, among the males, /p t k/ as a class by themselves have a mean intensity of –13.78 dB. When this is compared with the individual mean for /č/ (–13.25), the difference is not significant. Unless specified to the contrary, all such contrasts between two means in this dissertation are evaluated by conservative, heteroscedastic (Welch's) *t* tests at a one-tailed α level of .05. Once this determination is made, the individual segment (/č/ in this case) is added to the rest of the group (/p t k/) and new statistics are calculated for the entire natural class combined (/p t k č/). In those tables in which /č/ is not grouped with /p t k/ in this way (via a " + " sign), this signifies that the two means (/p t k/ vs. /č/) are reliably different. For the purposes of this dissertation, the contrasts which are of most interest in English are (1) /p t k/ vs. /č/, (2) /f θ s š/ vs. /č/, (3) /b d g/ vs. /ǰ/, (4) /v ð z ž/ vs. /ǰ/, (5) /f θ s š/ vs. /h/, and (6) /e ɛ ʌ o ɔ/ (mid vowels) vs. [ə], when relevant (e.g., for P_o and U_t measurements). The reason why these particular comparisons are worth pursuing is because each one involves a segment whose relative position in the sonority hierarchy is especially disputable (cf. chapter 3). As we see in the two tables above, English /ǰ/ and /č/ pattern as statistically equivalent to their corresponding (voiced or voiceless) plosive counterparts in terms of intensity, for both males and females, at least in onset position. (Soon we will see that these relationships obtain in codas as well.) In the tables in this chapter I also calculate group means for English /l/ and /r/ combined (but not for the Spanish liquids) since the former are almost always statistically indistinct from each other. However, when calculating correlations I always assign laterals and rhotics a different sonority index (per the hierarchy in (4.9)) since we can *a priori* assume that they represent distinct phonological classes (they involve different manners of articulation; cf. §3.2.5.9). Furthermore, in §5.8 in the next chapter I present exhaustive comparisons indicating for each data set whether /l/ and /r/ are statistically separable (table 5.25). Finally I do not explicitly compare English /h/ and [ʔ] since their phonemic status, phonotactic distribution, and phonetic qualities are so different.

With respect to intensity measurements, obstruents have negative values (in this study) since the point of reference is a nasal. Nasal consonants in target words are usually (mildly) negative also since they occur later in the utterance than the *n* of *wanna*, so intensity is beginning to trail off. (A possible alternative explanation is that word-initial consonants may be hyperarticulated compared to consonants in other prosodic positions; this may be reflected here as a reduction in sonority — exaggeration of consonantality — due to being in a syllable margin. See Fougeron and Keating 1997.) All other sonorant consonants have positive values, as expected. The rank order of the male natural classes in table 4.5 is noteworthy since it follows the sonority hierarchy exactly, even in terms of /l/ and /r/. Given the minute difference in means between these latter two segments (2.51 dB vs. 2.53), they are obviously not statistically distinct. In this chapter I do not attempt to make pairwise comparisons for all segments and/or groups which are adjacent on my sonority scale since this would be quite tedious, and it would serve little purpose with respect to the hypotheses being tested. Furthermore, most of these tables are not going to serve directly as a basis for establishing a concrete definition of sonority. If the reader wishes to calculate *t* tests or confidence intervals for any pairs of means, the data given in the tables are sufficient to do so. Consequently, I wait until the next chapter to pursue further tests of separability in just those cases when it is crucial to the larger analysis.

There are three final details worth pointing out in the tables above. First, for the males, voiceless fricatives as a group pattern as more intense than voiced stops, whereas for the females the reverse trend is observed. The fluctuation in ranking between these two natural classes is a tendency we will encounter in my data again. Given the controversy discussed in §3.2.5.2, this is not particularly surprising, nor should it be a major worry. Furthermore, there may be a logical explanation for why the intensity values for voiceless fricatives tend to be rather low: PCquirer's default sampling rate of 11 kHz. Strident consonants in particular might be affected the most by low-pass filtering, causing them to lose intensity. Second, for both sexes [?] and /h/ clearly fall among the obstruents. However, they do not group together with their most obvious potential counterparts — voiceless stops and fricatives, respectively. Third, there is one potential sonority "reversal" in the female data: /l/ is higher in intensity than /r/ (but this difference is not significant; cf. table 5.25 in the next chapter). Given the fact that the male /l/ and /r/ are so close, this too is not completely unexpected. Furthermore, we have seen that some sonority scales in the literature do not posit any distinctions among liquids at all (cf. §1.2.4 and 3.2.5). Nevertheless, when I give the corresponding correlations between these data and their sonority indices at the end of this section, reversals of this type will show their effect by resulting in a lower value of *r*.

I now present the corresponding data for consonants in coda position:

Table 4.7: Intensity of coda consonants for English males (in dB)

segment	mean	*n*	sd
p	–14.50	12	4.21
č	–14.00	12	2.89
k	–13.09	23	4.20
θ	–12.67	12	3.87
f	–12.45	11	3.47
s	–12.15	13	3.34

(cont. next page)

Table 4.8: Intensity of coda consonants for English females (in dB)

segment	mean	*n*	sd
k	–15.14	22	3.21
θ	–14.55	11	3.39
f	–14.20	10	3.46
s	–14.08	12	3.12
p	–13.33	9	3.35
č	–13.20	10	4.24

(cont. next page)

(Table 4.7 cont.)

ð	−11.33	12	3.55
ǰ	−8.50	12	2.97
g	−8.42	12	6.72
š	−7.83	12	4.61
b	−7.55	11	3.21
ž	−6.83	12	4.15
t	−5.58	135	9.09
z	−4.58	12	4.44
ŋ	−1.83	12	5.72
n	−.74	213	3.28
m	−.52	23	4.75
v	−.20	10	6.71
d	1.13	23	7.48
l	9.29	17	2.23
r	10.53	15	2.80
p k	−13.57	35	4.20
p k + č	−13.68	47	3.88
p t k	−7.22	170	8.92
f θ s š	−11.27	48	4.24
b g	−8.00	23	5.24
b g + ǰ	−8.17	35	4.55
b d g	−3.43	46	7.88
v ð z ž	−5.98	46	6.08
m n ŋ	−.77	248	3.57
l r	9.88	32	2.55

(Table 4.8 cont.)

g	−10.64	11	4.18
š	−10.36	11	2.69
ǰ	−10.25	12	3.19
t	−9.41	138	7.80
ð	−8.58	12	7.43
b	−8.36	11	4.61
z	−7.75	12	5.19
ž	−4.50	12	4.30
m	−4.19	21	3.76
d	−3.43	21	5.90
v	−3.00	11	7.59
ŋ	−2.67	12	3.96
n	−2.50	202	3.37
l	7.50	16	3.25
r	8.08	13	3.15
p k	−14.61	31	3.30
p k + č	−14.27	41	3.55
p t k	−10.36	169	7.46
f θ s š	−13.30	44	3.51
b g	−9.50	22	4.45
b g + ǰ	−9.76	34	4.02
b d g	−6.53	43	5.99
v ð z ž	−6.02	47	6.47
m n ŋ	−2.66	235	3.46
l r	7.76	29	3.16

In English, /h/ does not occur in coda position, nor does [ʔ] in my test stimuli, so these two segments are not included in the two tables above. Similarly, following a vowel the glides /y/ and /w/ might best be analyzed as part of a diphthong rather than true coda consonants, so no measurements were made of these segments in this position. A word of clarification about the phonemes /t/ and /d/ is also apropos here. Given the context in which they occur (word-finally in a stressed syllable followed by the unstressed [ə] of *again*), in many tokens they are pronounced as a flap. This effect (lenition) causes them to have much higher intensity levels than their bilabial and velar counterparts, so /t/ and /d/ here pattern as more sonorant-like than they do in onset position. Consequently, in the natural classes at the bottom of the English coda tables, I treat them in a special way. For the group of voiceless stops I give two sets of statistics — one with /p t k/ together, and another with only /p k/ but not /t/. The same is done with /d/ *vis-à-vis* /b g/. The data show that this adjustment is correct since /p k/ clearly behave as we would expect of voiceless stops (lowest in intensity) when /t/ is excluded, but when we lump /p t k/ together the biased group mean is abnormally high. Therefore, when I calculate correlations for the English data at the end of this section, I exclude the segments /t/ and /d/ in coda position in order to control for this factor. Obviously I might have also separated /t/'s and /d/'s according to their phonetic realization — stops vs. flaps — but that was a complication I chose not to pursue. Nevertheless, it is worth noting that the intensity values for /t/ vs. /d/ remain distinct in the two coda tables above. This suggests that the contrast between them has not been completely neutralized. Their standard deviations are also somewhat higher than those of most other segments, indicating that their realizations fluctuate quite a bit. This is compatible with the hypothesis that some of them really are flaps and others are true stops (another possibility is that some tokens of /t/ are glottalized). To summarize this paragraph, I strongly reiterate that in the English coda tables, statistics are given for stops at all three points of articulation together only for the sake of consistency and completeness. From a practical point of view, these group values are likely to have little importance.

Concerning the overall natural class means, we see that both sexes follow the sonority hierarchy exactly, provided that we leave out /t/ and /d/ as just discussed. In this case even the females' /l/ and /r/ are in the correct order. Once again /č/ and /ǰ/ pattern as stops, and for both sexes voiced stops are louder than voiceless fricatives. Because of the close match in rank between these group means and traditional sonority indices, the overall correlations (to be listed below) are extremely high, even when we include vowel measurements, which, as we will now see, are more messy:

Table 4.9: Intensity of vowels for English males (in dB)

segment	mean	*n*	sd
ə	5.73	86	3.56
ɔ	8.76	76	3.31
æ	9.32	227	3.24
ɛ	9.42	36	3.63
i	9.44	36	3.50
e	10.56	127	3.35
ɪ	10.59	156	3.11
a	10.69	64	3.26
ʌ	10.83	24	3.87
o	11.02	97	3.25
ʊ	11.50	12	2.54
u	11.54	48	3.63
æ a	9.62	291	3.29
e ɛ ʌ o ɔ	10.21	360	3.47
i ɪ u ʊ	10.65	252	3.29

Table 4.10: Intensity of vowels for English females (in dB)

segment	mean	*n*	sd
i	7.38	34	3.47
ə	7.64	84	2.36
ɔ	8.04	74	3.43
æ	8.64	202	3.15
ʌ	9.22	23	3.70
o	9.56	94	3.54
ɛ	9.67	36	3.75
ɪ	9.72	145	3.49
ʊ	10.25	12	3.08
e	10.64	121	3.27
a	11.02	62	2.54
u	11.06	48	2.76
æ a	9.20	264	3.18
e ɛ ʌ o ɔ	9.60	348	3.57
i ɪ u ʊ	9.69	239	3.48

The two tables immediately above show that, except for [ə], the group means for the three height-based natural classes inversely follow their relative sonority rankings: low vowels have the lowest intensity, then mid vowels, and high vowels are the loudest. This result is both surprising and disappointing. It is surprising since a number of previous studies have found that low vowels are more intense than high vowels (cf. table 4.3). Nevertheless, my data are consistent across genders, and the Spanish vowel measurements in the next section also involve some significant sonority reversals along these lines as well. However, given the very compressed range in dB between the three vowel natural classes in table 4.10, none of the female vowel height group means is significantly distinct from the other two. The differences are not very large for the males, either. This implies that many of these reversals are only apparent, and therefore not such a serious problem after all.

Having established this point, we should still seek to explain these sonority reversals, even if some of them are only a trend. The key is the quote from Ladefoged (1993:245) back in §4.3.1.1: sonority is a sound's "loudness relative to that of other sounds with the same length, stress, and pitch." This is unfortunately a case when the *ceteris* are not *paribus*: it is well-known that high vowels inherently tend to have higher pitch than lower vowels (Kingston 1991), and I believe this factor is responsible for the effects seen in my data. To test this hypothesis, I made a few sample measurements for some of the English vowel tokens pronounced by my subjects. The following tables display the results:

Table 4.11: F_0 values of vowels for English males (in Hz)

segment	mean	*n*	sd
i	127.8	12	21.4
u	127.0	12	20.9
o	123.8	11	18.9
e	121.1	12	18.2
æ	121.0	12	18.3
i u	127.4	24	20.7
e o	122.4	23	18.2

Table 4.12: F_0 values of vowels for English females (in Hz)

segment	mean	*n*	sd
u	227.6	12	10.2
i	222.5	11	14.0
o	220.9	12	12.9
æ	216.9	10	13.0
e	215.8	12	11.6
i u	225.1	23	12.2
e o	218.4	24	12.3

The pitch analysis summarized in tables 4.11 and 4.12 was carried out with the following PCquirer settings: a window length of 35 ms for the males and 15 ms for the females, a step size of 10 ms, a frequency deviation of 50 Hz, a tracking threshold of 2%, and a calculation range of 70-500 Hz. The vowels studied were those which occurred in the words *beet*, *bait*, *bat*, *boat*, and *boot*. The measurement I recorded for each segment was its F_0 maximum. The range of the mean values is small, especially for the males, and I only looked at a few tokens of each phoneme. Nevertheless, insofar as the trends are reliable, the male data completely follow the expected pattern: the higher the vowel, the higher its pitch. For the females (table 4.12), /æ/ has a slightly higher mean than /e/, but this difference is not significant. When /e/ is grouped with /o/ for the females, the mid vowels as a class are higher in pitch than /æ/. I conclude that the F_0 values of English vowels strongly follow their predicted rankings, and this factor is very likely to be implicated in the sonority reversals among our vowel intensity data. The generalization is that the higher a vowel is in intrinsic

F_0, the louder it tends to be, and vice-versa. Some of the previous studies mentioned above control for this effect by manipulating forces such as subglottal pressure (Ladefoged and McKinney 1963), but we were not set up to do this. Nevertheless, I did carry out a few simple measurements (about 3 tokens of each vowel) and found that when vowels are pronounced at the same fundamental frequency, height is inversely correlated with intensity, as predicted by the sonority hierarchy (even though this may be true only for vowels which bear a pitch-accent.) Obviously, however, natural unguarded speech is not limited by this artificial constraint. Consequently, the conclusion to be drawn from my data is that the correlation between sonority and vowel height may run in a negative direction. This is disappointing since it suggests that the sonority scales for vowels and consonants cannot be directly combined without adjusting for this factor in some way. In light of this, one possible way to proceed would be to limit our theoretical focus to sonority scales for consonants only, and leave vowels for future research. I prefer not to do this since a model of sonority which encompasses all speech sounds simultaneously has more explanatory power than one which does not. Also, in order for a mechanism such as the SDP to work correctly, we need to be able to directly compare the relative sonority of vowels and consonants at the same time. Consequently, I will continue to discuss phonetic measurements for all segments alike.

I now summarize the English intensity data in terms of goodness of fit with the sonority hierarchy posited in (4.9). The mean intensity level of each segment and each natural class is correlated with the corresponding sonority index from the scale in (4.9). To illustrate this technique, for the male speakers with consonants in onset position, some of the match ups would be as follows (for individual segments, not natural classes):

(4.10)

p	−13.83	1
s	−11.14	2 / 3
z	−7.58	4
m	−3.91	5
:	:	:
:	:	:
i	9.44	10
æ	9.32	12
(from tables 4.5 and 4.9)		(from (4.9))

Two complete hierarchies are analyzed for each gender: onset consonants plus vowels, and coda consonants plus vowels. The vowel measurements in each case are taken from tables 4.9 and 4.10, i.e., the same set of vowel intensities is added to both the onset consonant list and the coda consonant list. For each gender-specific hierarchy I calculate the correlation in two ways: (1) by individual segments, and (2) by grouping segments into their respective natural classes, when appropriate. In this latter case I use the overall group means which appear at the bottom of the tables (but keeping /l/ and /r/ separate, as discussed above). In the English correlations listed in this chapter I always use all segments measured except /č/, /ǰ/, /h/, [ʔ], /t/, and /d/. The first four are included only when they clearly pattern with a pre-established phonological natural class, since otherwise their sonority index is *a priori* a subjective matter. And /t/ and /d/ are included only for onset correlations, not for codas (in English), as explained above.

Table 4.13: Correlations between English intensity data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.97	.98	.94	.96	.96
by natural classes	.97	.96	.89	.92	.94

In table 4.13 the column labeled *means* on the far right is the average of the four correlations to the left of it on the same line. Since the two methods of correlating (by segments and by classes) employ largely overlapping intensity values, it makes sense to keep them separate and not average all 8 cells together. (Within each method of correlation the same number of data points are involved in each set, so the *p* values are inversely proportional to the strength of the correlations themselves.) In this table we see a tendency which shall appear in other correlation summaries: the *r* values calculated for individual segments are slightly higher than those for natural classes. A probable explanation for this is that there are always more segments than classes, so the larger number of paired measurements factored into the correlations lead to more robust results. As noted above, these correlations might be stronger if we calculated them separately for vowels and consonants and then averaged those two numbers together. As it stands, the sonority reversals among the vowels clearly pull these *r*'s downward (although obviously not very far). Nevertheless, as argued earlier, a single sonority scale for vowels and consonants combined is more desirable, so I will not separate them in these tables. Finally, I reiterate that for all eight cells in tables like 4.13, I tabulate the correlations in two ways: with voiceless fricatives ranked over voiced stops, and the inverse. The *r* value I report is the larger of the two in each case. In table 4.13 and elsewhere this permutation makes a (small) difference in some of the cells but not all of them; when the two rankings result in distinct correlations, the degree of difference is usually only .01.

4.3.1.3 Spanish intensity measurements

In this section I present the corresponding results for my intensity analyses on the eight Spanish speakers. The sonority scale I use for correlations in all Spanish tables in this chapter is the following (it is derived from the universal sonority hierarchy but is temporarily adapted for the inventory of Spanish phonemes):

(4.11) Spanish sonority hierarchy assumed for the purposes of correlation

class of segments	sonority index
low vowels	12
mid vowels	11
high vowels	10
glides	9
laterals	8
flaps (/r̆/)	7
trills (/r̃/)	6
nasals	5
voiced fricatives	4
voiced stops / voiceless fricatives	3
voiceless fricatives / voiced stops	2
voiceless stops	1

The scale in (4.11) is different from the corresponding English hierarchy (4.9) in a few crucial respects, and merits discussion. Obviously [ə] is left out since it does not occur in Spanish. Secondly, /r̆/ and /r̄/ are ranked below laterals in Spanish whereas English /r/ is ranked above /l/. This is justified by their different articulatory properties (/r̆/ and /r̄/ are [+consonantal] while English /r/ is [–consonantal]) and by the fact that it fits best with virtually all of my Spanish acoustic data. (Lavoie's (2000) results below confirm this as well.) Furthermore, I am not aware of any phonological facts in Spanish which crucially require /r̆/ and /r̄/ to be ranked ***above*** /l/; it is only necessary that these segments be ***adjacent*** on the sonority scale. In addition, I have tentatively ranked /r̆/ above /r̄/ for now since this trend is most consistent with my data (/r̄/ usually patterns as more obstruent-like than /r̆/), and the mean values for these two segments are nearly always statistically distinct (cf. §5.8). Furthermore, phonological evidence from Spanish also indicates that /r̆/ is more sonorous than /r̄/: in word-initial position the contrast between them is neutralized in favor of /r̄/ (fortition); in syllable-final position it is neutralized in favor of /r̆/ (lenition); and phonotactic and stress patterns suggest that /r̄/ is really a geminate /r̆/ (Harris 1983). For example, /r̆/ and /l/ may appear as the second member of a complex onset, but /r̄/ may not. This can be seen as a minimum sonority distance effect if /r̄/ is less sonorous than /r̆/. In terms of stress, hypothetical forms having the prosodic shape [... V C_0 V r̄ V C_0 #] cannot bear antepenultimate stress, indicating that the penult is closed (Harris 1983). For reasons such as these, Hooper (1976) places Spanish /r̄/ among the obstruents in her strength scale. In other words, it appears that my physical measurements in English and Spanish do not support the existence of a single, monolithic phonological class of *rhotics*, at least not in terms of the sonority hierarchy (cf. Jones 1999). A final note concerns the relative sonority of the Spanish segments [β ð γ]. For our purposes here I count them as voiced fricatives, but this does not always reflect their true phonetic realization as lenited allophones of /b d g/, respectively. For example, Lavoie (2000) classifies them as approximants, and this label is a more accurate description of their pronunciation in many cases in my data as well. Nevertheless, for the sake of simplicity I do not attempt to distinguish between the two manners of articulation (voiced fricative vs. approximant) for these three phonemes in my statistics. The most important detail is that they should necessarily outrank all other obstruents in terms of their sonority index, and they do.

Before presenting my own results I briefly review one rather substantial previous study on intensity of Spanish consonants. It is based on 4 Mexican male speakers, each pronouncing 5 repetitions of all segments:

Table 4.14: Summary of a previous experiment on intensity in Spanish

author	date	intensity scale	*r*	*p*
Lavoie	2000	y ñ l n m r̄ β ð γ ř v x s č p t f k	.83	.000

The somewhat lower correlation for Lavoie's (2000) intensity hierarchy in table 4.14 (compared to my own results below) is probably due in part to the lenition effect just discussed, i.e., I assign [β ð γ] a sonority index of *4* even though they are often approximants. Also, her study involves a different number of data points than mine, making a direct comparison of the correlations problematic. I now present my own Spanish intensity data, beginning with syllable-initial consonants:

Table 4.15: Intensity of onset consonants for Spanish males (in dB)

segment	mean	*n*	sd
č	–13.00	12	4.92
f	–12.67	12	4.66
p	–12.56	120	3.51
k	–12.15	48	3.19
t	–11.83	24	3.78
s	–11.42	12	4.14
h	–7.67	12	3.98
ǰ	–5.46	24	2.80
g	–4.46	13	2.82
d	–4.23	13	2.49
b	–3.38	13	1.85
ñ	–1.83	12	1.95
γ	–1.55	11	5.57
m	–1.00	12	2.13
n	.08	12	1.68
r̄	2.92	12	2.27
ð	3.09	11	7.08
β	5.05	21	6.30
ř	5.73	11	3.61
l	7.92	24	2.81
w	9.00	12	5.49

(cont. next page)

Table 4.16: Intensity of onset consonants for Spanish females (in dB)

segment	mean	*n*	sd
p	–12.33	120	2.62
k	–11.98	48	3.07
č	–11.83	12	4.11
t	–11.00	23	2.37
f	–10.75	12	2.77
s	–10.64	11	3.44
h	–8.17	12	1.64
ǰ	–5.75	24	2.40
γ	–5.67	12	4.66
ð	–4.75	12	5.48
g	–4.67	12	2.35
b	–3.77	13	2.77
d	–3.60	10	2.17
ñ	–0.92	12	1.44
m	–0.33	12	1.23
n	–0.25	12	1.22
β	0.09	23	8.45
r̄	2.92	12	3.12
ř	6.33	12	4.21
l	9.04	24	2.99
w	10.83	12	3.19

(cont. next page)

(Table 4.15 cont.)

p t k	−12.36	192	3.46
p t k + č	−12.40	204	3.55
f s	−12.04	24	4.36
b d g	−4.03	39	2.40
m n ñ	−.92	36	2.03
β ð ɣ	2.86	43	6.76

(Table 4.16 cont.)

p t k	−12.08	191	2.73
p t k + č	−12.07	203	2.82
f s	−10.70	23	3.04
f s + č	−11.09	35	3.42
b d g	−4.03	35	2.44
β ð ɣ	−2.62	47	7.34
m n ñ	−0.50	36	1.30

Since the point of comparison for intensity measurements in both Spanish and English is the segment /n/, the data across the two languages are quite comparable. For the male speakers above (table 4.15), /č/ once again patterns as a voiceless stop, and voiced stops are louder than voiceless fricatives. The primary mismatch with the sonority hierarchy is that [β ð ɣ] outrank the nasals, for the reasons just cited. (The relatively high variances for these segments suggest the possibility of another bimodal distribution — fricative vs. glide — as was likely the case with English alveolar stops in coda position.) For the females (table 4.16), /č/ is statistically indistinct from both voiceless stops and voiceless fricatives. The female natural class rankings follow the scale in (4.11) exactly, even insofar as the liquids are concerned. For both sexes /h/ patterns as an obstruent but cannot be combined with the other two voiceless continuants (/f s/), nor does /ǰ/ group with the voiced stops /b d g/. In other words, a statistical contrast proved that these segments are reliably distinct ($p < .05$).

I now consider consonants in syllable-final position:

Table 4.17: Intensity of coda consonants for Spanish males (in dB)

segment	mean	*n*	sd
h	−13.30	10	3.80
k	−11.25	12	3.47
f	−11.25	12	3.89
s	−9.59	70	2.91
γ	−8.50	12	6.11
t	−7.83	12	5.31
β	−7.00	11	5.27
ð	−3.90	10	2.18
p	−1.70	10	1.70
m	−.50	12	1.88
ñ	−.50	12	1.24
n	.17	47	2.22
ŋ	1.08	12	1.62
ř	6.83	24	4.30
l	8.11	36	3.31
t k	−9.54	24	4.72
β ð γ	−6.61	33	5.15
m n ñ ŋ	.11	83	2.01

Table 4.18: Intensity of coda consonants for Spanish females (in dB)

segment	mean	*n*	sd
f	−12.83	12	4.39
h	−12.08	12	3.37
s	−10.88	69	2.68
k	−10.33	12	2.31
t	−8.67	12	4.52
γ	−5.83	12	5.31
β	−4.42	12	5.71
ð	−4.25	12	4.03
p	−4.08	12	5.28
ñ	−.50	12	2.02
n	.00	47	2.60
m	.50	12	2.02
ŋ	1.25	12	2.01
ř	6.33	24	3.56
l	9.28	36	4.15
s + h	−11.06	81	2.80
t k	−9.50	24	3.61
β ð γ	−4.83	36	4.97
m n ñ ŋ	.18	83	2.38

In the coda tables above, the values for the segments [p β ð γ f] must be taken with some caution since they occurred in a slightly different environment than the rest of the phonemes (with secondary stress or no stress at all). This is because in the Spanish word list I used, it was not possible to contrast all coda consonants in syllables bearing primary stress due to phonotactic infrequency effects (§4.2.3.2). Because of the potential effect of stress differences, I do not count these five segments in the Spanish intensity correlations below, to ensure that the environment remains constant (for the other segments which ***are*** involved in the correlations). Nevertheless, for the sake of completeness I do include their statistical values in the tables above. A few gaps occur in tables 4.17 and 4.18 because certain contrasts are neutralized syllable-finally (/ř/ vs. /r̃/) or simply because the voiced stops [b d g] cannot surface following a vowel (§4.2.3.2). Furthermore, /č ǰ w/ are systematically unattested as codas in Spanish. Finally, the point of articulation of nasals is homorganic with that of a following consonant, so [m n ñ ŋ] do not contrast here either. Nevertheless, their allophonic realizations are included in these measurements so that they can be compared with their English counterparts. An important trend for both sexes is that all sonorants follow the sonority hierarchy exactly (*l* > *ř* > nasals). Nevertheless, there is one potential reversal among the obstruents: for the females, /s/ and /h/ group together and are less intense than the stops /t k/.

I now consider the vowels:

Table 4.19: Intensity of vowels for Spanish males (in dB)

segment	mean	*n*	sd
i	13.69	35	4.35
a	15.66	108	3.20
o	16.00	238	3.08
e	16.36	47	2.55
u	16.46	48	3.14
i u	15.29	83	3.92
e o	16.06	285	3.00

Table 4.20: Intensity of vowels for Spanish females (in dB)

segment	mean	*n*	sd
i	12.72	36	3.27
a	14.85	108	2.97
u	14.94	48	2.79
e	15.58	48	2.90
o	15.85	236	2.72
i u	13.99	84	3.18
e o	15.81	284	2.74

For both sexes the Spanish vowels follow the same height patterns in terms of peak intensity: mid > low > high. Consequently, their overall fit with the sonority hierarchy is better than that of their English counterparts, but there is still one reversal: mid vowels are out of place since they are louder than low vowels. For the sake of completeness I also report a few F_0 values for these same Spanish vowels. The tokens analyzed were taken from the initial (stressed) syllables of the words *piso*, *peso*, *paso*, *pozo*, and *puso*:

Table 4.21: F_0 values of vowels for Spanish males (in Hz)

segment	mean	*n*	sd
u	181.5	12	30.2
i	168.8	12	29.4
e	166.6	12	27.9
o	158.2	12	19.9
a	157.4	12	27.0
i u	175.1	24	29.9
e o	162.4	24	24.1

Table 4.22: F_0 values of vowels for Spanish females (in Hz)

segment	mean	*n*	sd
i	280.0	12	33.9
u	279.9	12	30.4
e	271.7	12	25.3
o	264.1	12	26.9
a	253.5	12	23.2
i u	280.0	24	31.5
e o	267.9	24	25.8

The Spanish vowels above are completely well-behaved in terms of fundamental frequency. They are also more spread out in range than their English counterparts in tables 4.11 and 4.12. The relationship between F_0 and intensity undoubtedly continues to underlie some of the sonority reversals observed among the Spanish vowel intensity measurements, just as it does in English.

I now give the overall correlations for the Spanish intensity data, using the scale from (4.11). Similarly to English, I include the segments /č ǰ h/ in these calculations only when their raw individual means allow us to statistically match them up with an already established natural class.

Table 4.23: Correlations between Spanish intensity data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.96	.99	.99	.98	.98
by natural classes	.97	.99	.99	.98	.98

As table 4.23 shows, correlations for Spanish intensity measurements are slightly more robust than those of English and thus come quite close to perfection. It doesn't get much better than this. To anticipate later discussions, intensity is the strongest possible way to characterize relative sonority among the physical correlates studied in this experiment. Consequently, I return to these data in chapter 5 and show how we can use them to derive a precise definition of sonority. But first I present the rest of my instrumental results.

4.3.2 Intraoral air pressure

4.3.2.1 Background

The major class feature [–sonorant] is often defined as characterizing segments which involve a build up of air pressure (behind an oral constriction) which is significantly higher than that of ambient air outside the mouth (9 references in table 2.2). This suggests that the relative amount of intraoral pressure might be strongly correlated with the sonority hierarchy in a negative direction. The results I present here confirm this hypothesis; the mean correlation across all data sets is about –.84. Before I discuss my own data, I first summarize one previous experiment that measures P_o for most of the consonants of American English (using 10 male speakers, with only one repetition each of all the segments):

Table 4.24: Summary of a previous experiment on P_o in English

authors	date	pressure scale	*r*	*p*
Subtelny *et al.*	1966	č p t ǰ f s d b z v l r w n m	–.91	.000

The P_o scale in table 4.24 is for onset position and runs from high to low (left to right). It is correlated once again with the sonority hierarchy from (4.9). For my own P_o measurements I report the peak value which occurs at any point during all consonant segments. For all vowels I report the peak value which occurs during the steady state near the center of the segment. This adjustment is necessary because the high P_o of consonants does not fall off abruptly upon their release but rather slopes gradually downward into the following vowel. When vowel P_o is measured right at the boundary with adjoining consonants, it is artificially high and depends more on the nature of the consonant than on its own inherent quality. After calibration, PCquirer reports pressure readings in hundredths of cm H_2O, but the hardware may not be accurate to this degree of precision. For most purposes tenths of a cm H_2O is sufficient.

4.3.2.2 English P_o measurements

The following results are for English consonants in onset position:

Table 4.25: Pressure of onset consonants for English males (in cm H_2O)

segment	mean	*n*	sd
t	6.19	22	1.35
č	6.18	12	1.18
s	6.10	34	1.32
θ	5.65	22	1.72
p	5.58	31	1.05
d	5.55	12	.99
f	5.50	11	1.29
š	5.47	12	.77
ǰ	5.00	35	.99
b	4.71	148	1.35
k	4.55	120	1.99
ð	4.15	9	1.16
ž	3.91	12	.88
z	3.90	11	1.89
v	3.77	20	.91
g	3.74	22	1.67
h	1.94	46	1.01
m	1.31	90	.42
y	1.31	7	.41
n	1.27	66	.41
r	1.22	36	.66
l	1.04	54	.48
w	.96	6	.47
ʔ	.77	22	.37
f θ s š + č	5.85	91	1.36
f θ s š	5.80	79	1.38
p t k	4.95	173	1.88
b d g	4.64	182	1.43
v ð z ž	3.90	52	1.19
m n	1.29	156	.42
y w	1.15	13	.46
l r	1.11	90	.56

Table 4.26: Pressure of onset consonants for English females (in cm H_2O)

segment	mean	*n*	sd
č	7.07	12	1.36
ǰ	6.86	27	1.18
d	6.78	10	1.43
t	6.50	24	1.41
p	6.13	34	1.16
s	5.96	25	.90
š	5.93	9	1.18
k	5.87	118	1.77
g	5.81	22	2.41
θ	5.72	18	1.10
b	5.66	136	1.32
f	5.55	9	.54
ž	4.86	12	1.50
v	4.25	22	1.37
z	4.16	12	1.29
ð	4.02	12	1.64
h	2.51	53	1.72
y	1.45	4	.35
n	1.41	81	.60
m	1.34	105	.49
r	1.27	22	.47
l	1.22	64	.49
w	1.13	4	.57
ʔ	.57	26	.49
p t k	6.00	176	1.63
f θ s š	5.82	61	.96
b d g	5.75	168	1.53
v ð z ž	4.16	58	1.44
m n	1.37	186	.54
y w	1.29	8	.47
l r	1.23	86	.48

For the male speakers (table 4.25), /č/ patterns as a voiceless fricative. This class unexpectedly has higher P_o than voiceless stops. Another sonority reversal is that /l/ is lower than both /r/ and /y/. For the females (table 4.26), voiceless stops now have higher P_o than voiceless fricatives, as they should since their degree of occlusion is greater. For the females we also find the infelicitous subhierarchy *y* > *r* > *l*. For both sexes /h/ falls right on the boundary between obstruents and sonorants, but is closer to the latter. Also, [ʔ] is at the very bottom in both tables since the tube obviously could not get behind the constriction. These facts help explain why glottal consonants behave as obstruents in some languages but as sonorants in others: their contribution to the physical signal is mixed, depending on the phonetic parameter we refer to (recall that in terms of intensity [h ʔ] clearly group with obstruents). A minor concern in the two tables above is that we would expect higher P_o for /k/ and, to a lesser extent, /g/, since their point of articulation is relatively close to the glottis (Stevens 1998). Given the placement of the P_o tube (§4.2.4), it is very possible that it interfered slightly with dorsovelar occlusion. Nevertheless, in all my other data sets (both in Spanish as well as English), /k/ behaves much more "regularly". Thus we do not need to worry about this one glitch.

Another strong trend is that for both genders, voiceless obstruents have higher P_o than their voiced counterparts. This universal pattern, confirmed by at least 22 other experiments (Müller and Brown 1980), is attributable to the aerodynamic requirements of voicing. A very important factor in sustaining vocal fold vibration is transglottal air flow differential or velocity. A higher supralaryngeal vs. sublaryngeal pressure inhibits this rate. The markedness of voiced obstruents is a direct consequence of this inherent tension. In order to reduce intraoral pressure, the volume of the supralaryngeal cavity must expand (Boyle's law). This is accomplished by a number of unconscious yet partially active manipulations: lowering the larynx and hyoid bone, advancement of the tongue root and epiglottis, retraction of the posterior pharyngeal wall, increased elevation of the soft palate, downward compression of the superficial muscles of the tongue, and greater distension of the cheeks and lips. The configuration and elasticity of the vocal folds can also contribute to this effect. Another strategy to inhibit P_o buildup is to shorten the constriction duration of voiced segments (cf. Malécot 1966 and §4.3.5). All of these physiological adjustments have been confirmed and quantified by instrumental techniques (Arkebauer 1964, Warren 1964, Warren and DuBois 1964, Brown 1969, Brown and McGlone 1969b, Kent and Moll 1969, Perkell 1969, Subtelny *et al.* 1969, Lubker 1973, Westbury 1983, Warren *et al.* 1992, Moon *et al.* 1993, Stevens 1998, Zemlin 1998). For example, the total increase in vocal tract volume that can be achieved in these ways amounts to about 20% (Stevens 1998).

I now consider consonants in syllable-final position:

Table 4.27: Pressure of coda consonants for English males (in cm H_2O)

segment	mean	*n*	sd
č	5.99	12	2.57
p	5.44	10	1.76
ǰ	5.37	12	1.26
s	5.01	12	1.91
f	4.93	11	1.59

(cont. next page)

Table 4.28: Pressure of coda consonants for English females (in cm H_2O)

segment	mean	*n*	sd
č	5.97	12	1.15
ǰ	5.86	12	1.55
p	5.28	11	1.97
f	5.19	7	1.52
k	5.06	23	1.79

(cont. next page)

(Table 4.27 cont.)

š	4.84	12	1.32
θ	4.75	10	1.93
k	4.12	19	1.91
ð	4.08	12	1.18
ž	4.05	12	1.20
b	3.95	10	1.53
z	3.63	10	1.43
v	3.15	7	.79
g	2.80	11	.98
d	2.79	20	.70
t	2.38	118	1.10
ŋ	2.25	10	.89
m	1.58	19	1.01
n	1.56	192	.49
l	1.12	14	.65
r	1.01	12	.48
p k + č	4.99	41	2.20
p k	4.58	29	1.93
p t k	2.81	147	1.57
f θ s š	4.89	45	1.65
v ð z ž	3.80	41	1.21
b g	3.35	21	1.37
b d g	3.07	41	1.12
m n ŋ	1.60	221	.60
l r	1.07	26	.57

(Table 4.28 cont.)

θ	5.03	9	2.12
z	4.93	9	.81
š	4.80	9	1.35
ž	4.68	9	1.26
ð	4.59	9	1.43
s	4.11	9	1.64
b	3.90	10	1.44
g	3.78	11	1.61
t	3.59	130	2.10
d	3.46	21	1.41
v	2.94	7	1.63
m	1.61	21	.58
n	1.47	195	.60
ŋ	1.39	11	.32
l	1.07	16	.40
r	.91	12	.41
p k	5.13	34	1.82
p t k	3.91	164	2.14
f θ s š	4.76	34	1.67
v ð z ž	4.36	34	1.44
b g	3.84	21	1.50
b d g	3.65	42	1.45
m n ŋ	1.48	227	.59
l r	1.00	28	.40

For the males (table 4.27), /č/ patterns as a voiceless stop, and the only reversal involves voiced fricatives and voiced stops (recall that /t/ and /d/ are flapped and are therefore expectedly anomalous). All of the sonorants are in the desired order. For the females (table 4.28), both /č/ and /ǰ/ are distinct from their counterparts (stops and fricatives). Once again voiced fricatives have higher P_0 values than voiced stops, and all sonorants are where we would like them to be.

I finish the presentation of English data with the vowels:

Table 4.29: Pressure of vowels for English males (in cm H_2O)

segment	mean	*n*	sd
ʊ	1.65	7	.50
i	1.44	34	.48
o	1.36	66	.88
u	1.35	38	.53
ɪ	1.34	144	.45
ɛ	1.13	31	.43
æ	1.08	186	.41
a	1.07	49	.48
ʌ	1.03	18	.37
e	1.00	98	.48
ɔ	.96	58	.65
ə	.95	68	.41
i ɪ u ʊ	1.37	223	.47
e ɛ ʌ o ɔ	1.09	271	.66
æ a	1.08	235	.43

Table 4.30: Pressure of vowels for English females (in cm H_2O)

segment	mean	*n*	sd
i	1.51	28	.65
u	1.21	38	.52
e	1.02	109	.43
ʊ	1.01	9	.34
ɪ	1.00	140	.45
o	1.00	73	.42
ɛ	.97	36	.29
a	.95	52	.40
ʌ	.90	19	.33
ə	.88	78	.35
æ	.86	195	.41
ɔ	.79	65	.42
i ɪ u ʊ	1.11	215	.52
e ɛ ʌ o ɔ	.95	302	.41
e ɛ ʌ o ɔ + ə	.94	380	.40
æ a	.88	247	.41

A noteworthy characteristic of both sets of vowel measurements is that the three height-based natural classes follow the sonority hierarchy exactly (in an inverse direction, and without testing for intergroup significance). This is an improvement over the vowel intensity data, and helps the pressure/sonority correlations insofar as mitigating the weakening effects of certain consonant reversals. However, there is another important difference between intensity and P_o: whereas the intensity levels of all vowels are usually greater than those of all consonants, the same pattern (in reverse) is not true of pressure. There is a partial overlap of vowels and sonorant consonants in terms of P_o in that the highest vowels have absolute values equivalent to those of certain nasal consonants and, *a fortiori*, liquids and glides. This fact offsets somewhat the advantage of vowel pressure over intensity in terms of correlation with the sonority hierarchy. Later we will see that U_t measurements strongly mimic this situation and that P_o and U_t values are positively correlated with each other to a large degree.

I now summarize this section with overall correlations:

Table 4.31: Correlations between English P_o data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	–.89	–.91	–.84	–.87	–.88
by natural classes	–.83	–.87	–.85	–.86	–.85

The average correlations in table 4.31 are a little weaker than those of English intensity, but are still very robust. This is encouraging. A continuing tendency is that correlating by segments is stronger than correlating by classes. Furthermore, consonants in onset position overall yield better *r* values than those in codas (cf. table 4.13). Another tendency is for females to show slightly higher correlations than males. However, in chapter 5 we will see that this effect is not significant.

4.3.2.3 Spanish P_o measurements

I begin the discussion of Spanish P_o results with consonants in onset position:

Table 4.32: Pressure of onset consonants for Spanish males (in cm H_2O)

segment	mean	*n*	sd
č	9.26	9	3.94
t	8.84	20	3.11
s	8.07	10	3.22
k	7.89	36	3.65
f	7.40	9	1.97
p	7.33	101	2.25
ǰ	6.14	20	3.53
r̄	5.08	10	1.35
d	4.56	11	2.65
g	4.39	10	1.84
γ	3.91	10	1.62
b	3.77	11	.76
ð	3.28	9	2.28
w	2.69	10	1.40
β	2.55	16	1.19
ř	2.52	8	1.26
h	1.97	10	1.17
l	1.71	16	.62
m	1.61	9	1.01
n	1.37	10	.49
ñ	1.27	10	.57
f s	7.75	19	2.65
p t k	7.65	157	2.77
b d g	4.24	32	1.89
β ð γ	3.13	35	1.70
m n ñ	1.41	29	.70

Table 4.33: Pressure of onset consonants for Spanish females (in cm H_2O)

segment	mean	*n*	sd
č	7.35	9	2.53
t	6.31	15	2.09
f	6.06	9	2.26
p	5.96	89	1.61
k	4.85	35	2.31
s	4.38	7	2.53
ǰ	4.00	18	1.95
d	3.32	7	1.90
γ	3.15	9	1.39
b	2.96	10	.94
r̄	2.89	9	1.35
ð	2.65	7	1.60
g	2.56	8	1.78
β	2.33	15	1.53
w	2.05	9	1.27
h	1.89	8	.83
m	1.85	9	1.22
ř	1.57	8	1.03
n	1.29	6	.46
l	1.03	10	.65
ñ	.94	5	.31
p t k	5.72	139	1.92
f s	5.33	16	2.45
b d g	2.93	25	1.50
β ð γ	2.64	31	1.50
m n ñ	1.45	20	.93

For the Spanish males (table 4.32), voiceless fricatives have higher P_o than voiceless stops, just like the corresponding English data. Furthermore, /w/ and the nasals are inverted. For both sexes, /č/ and /ǰ/ are distinct from the other classes, i.e., they exhibit higher P_o than both stops and fricatives, and /h/ falls right between the obstruents and the sonorants. For both genders /r̄/ also has values typical of an obstruent. For the females (table 4.33), all obstruent classes follow the desired order (as do those of the English females), but /w/ and /ř/ are higher in P_o than the nasals. Overall the female P_o values are lower than those of the males.

I now present the corresponding data for coda position:

Table 4.34: Pressure of coda consonants for Spanish males (in cm H_2O)

segment	mean	*n*	sd
k	7.78	11	3.04
s	6.38	59	2.38
t	6.32	8	2.88
f	6.13	8	1.78
γ	4.63	7	2.25
p	4.56	8	4.91
β	4.41	9	2.20
h	4.22	8	2.87
ř	4.02	17	1.11
ŋ	3.71	9	1.73
ð	2.96	7	1.60
m	2.68	10	.70
n	1.93	38	.78
ñ	1.86	20	.74
l	1.62	26	.70
p t k	6.39	27	3.76
f s	6.35	67	2.31
β ð γ	4.03	23	2.09
m n ñ ŋ	2.22	77	1.09

Table 4.35: Pressure of coda consonants for Spanish females (in cm H_2O)

segment	mean	*n*	sd
f	6.01	9	1.41
k	4.97	8	2.71
s	4.79	51	2.24
t	3.89	7	2.68
β	3.10	7	1.32
h	2.95	8	1.98
ř	2.79	18	1.43
p	2.09	8	1.69
m	1.86	7	.47
ŋ	1.77	9	.78
ð	1.70	6	1.23
n	1.27	34	.53
ñ	1.14	12	.46
γ	1.06	7	.73
l	.95	21	.35
f s	4.98	60	2.17
p t k	3.64	23	2.60
β ð γ	1.97	20	1.39
m n ñ ŋ	1.38	62	.60

This time the voiceless obstruent classes follow the sonority hierarchy for the men (table 4.34), but are reversed for the women (table 4.35). For both sexes /h/ and /r̄/ fall among the obstruents. The female values overall continue to be lower than those of the males.

Now for the vowels:

Table 4.36: Pressure of vowels
for Spanish males
(in cm H_2O)

segment	mean	*n*	sd
u	2.30	39	1.22
i	1.68	42	.80
o	1.42	203	.82
a	1.40	112	1.09
e	1.23	38	.76
i u	1.98	81	1.07
e o	1.39	241	.81

Table 4.37: Pressure of vowels
for Spanish females
(in cm H_2O)

segment	mean	*n*	sd
u	1.34	33	.88
o	1.14	169	.74
i	.87	35	.50
a	.80	77	.58
e	.72	24	.48
i u	1.10	68	.74
e o	1.09	193	.73

For the males in particular the vowel P_o levels follow the sonority hierarchy rather well and in the same direction as the consonants. Again we see that the vowels with the highest P_o values overlap with some of the sonorant consonants, so the corresponding pressure × sonority regression line (if plotted) would have a curvilinear component.

Table 4.38: Correlations between Spanish P_o data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	–.77	–.82	–.83	–.70	–.78
by natural classes	–.79	–.85	–.89	–.80	–.83

Overall the Spanish P_o correlations are somewhat weaker than their English counterparts, but are still moderately robust. Peak intraoral air pressure is a fairly consistent predictor of a segment's sonority rank. This would be even more the case if we analyzed vowels and consonants separately. Along with the intensity data, these P_o results confirm the physical reality of the sonority hierarchy. The most obvious difference between them — the sign or direction of the correlation — is inconsequential. On the contrary, the two parameters (intensity and P_o) complement each other in a rather satisfying way since they demonstrate that we can in effect approach the phonetic sonority scale from either end (top or bottom) and still get analogous results.

4.3.3 F_1 frequency

4.3.3.1 Background

In this section I present the results of a study designed to test the hypothesis that sonority indices are correlated with segmental F_1 measurements. A relationship between sonority and F_1 is posited by Donegan (1978), Keating (1983, 1988), and Kingston (1998), as noted in table 2.1. Nevertheless, while studies of F_1 values in vowels are abundant, much less work has been done on F_1 frequencies of consonants. Consequently, the present experiment undertakes an analysis of F_1 for all phonemes simultaneously — vowels and consonants alike — for both English and Spanish. The overall results indicate a fairly good match between F_1 values and the sonority hierarchy — a mean correlation of about .77.

A relevant question is how exactly to measure F_1 in consonants, especially for segments like voiceless obstruents? Observations by Stevens (1998) suggest how we might approach this problem. He notes that the F_1 frequencies of vowels drop downward rapidly at their boundaries with consonants. During a period of total occlusion, the lowest natural frequency of the supraglottal vocal tract is about 180-200 Hz (p. 334). Most of the vowel's F_1 movement induced by adjacent stops is completed within about 10-20 ms (p. 474). For fricatives the average transition duration is 30-40 ms (p. 387). Stevens notes that F_1 values for vowel edges which are adjacent to fricatives are higher than those next to stops. The total amount of F_1 trajectory at a vowel-fricative boundary can be as much as 200 Hz (p. 401). His estimates for minimum F_1 in glides are 260 Hz for /y/ and 270 Hz for /w/ (pp. 516-17). All of these facts suggest that F_1 measurements of vowels at the point of their transition into and away from adjoining consonants might be influenced in direct proportion to the relative sonority of the consonant. Furthermore, there will obviously be a strong effect of the vowel's F_1 on that of the consonant as well, if the latter has an intrinsic F_1 (Stevens 1998). Nevertheless, a potential confound in this approach is that after voiceless aspirated stops, a vowel's F_1 is expected to be higher than after voiceless unaspirated stops, because of when voicing begins relative to the moment of opening the mouth. A similar difference should be observed before voiceless vs. voiced stops, again due to the timing of glottal and oral articulations. These tendencies have been observed with stops in English, especially in onset position (Stevens 1998). These expectations obviously reverse the predicted relationship between F_1 at the edge of vowels and consonantal sonority. In short, VOT differences in obstruents skew what might otherwise be a regular effect of consonants on vocalic F_1's.

This effect notwithstanding, the F_1 contribution of each consonant was therefore determined by measuring the 25 ms of the vowel immediately before or after the release of adjacent consonants, where vowel formant transitions are affected most strongly by the degree of occlusion of the consonant. I proceeded as follows. The initial and final 25 ms span of each vowel (adjacent to consonants) was selected on the screen. An automated function was then run to calculate the average FFT and LPC values for each highlighted 25 ms stretch. PCquirer options for FFT analysis were set to a frame length of 512 points (21 Hz), a frame window length of 23 ms, a frequency range of 5000 Hz (about half of the sampling rate), and an average step size of 10 ms. The LPC analysis used 14 coefficients. For measuring inherent F_1 values corresponding to each vowel segment I selected the entire steady state up to but not including transitions from and into adjacent consonants. The FFT/LPC averages across all of these spans were directly displayed in a subwindow. PCquirer reports the average values for up to five formants, when appropriate, in whole Hz.

The stimuli for F_1 measurements were originally elicited along with those of the other four phonetic studies, so the speakers had on the oral and nasal masks described in §4.2.1. However, Peter Ladefoged (p.c.) advised us that utterances spoken into the conical oral mask would probably be subject to a low frequency resonance that should elevate the first formant of higher vowels. This turned out to be true. Consequently, the F_1 stimuli were subsequently re-elicited using a head-mounted microphone, rather than the one built into the PCquirer oral mask and transducer interface unit. This external microphone was suspended at a fixed distance of 1-2" to the left of the mouth, and recordings were made in a sound-attenuated booth. The F_1 vowel measurements obtained in this way yielded results much more typical of what was expected, so they serve as the basis for the statistical analyses discussed below.

To control for the natural effect of vowel quality/height on adjacent segments, all language-specific consonants were elicited in syllables containing the vowel /i/. In all data sets this was the vowel exhibiting the lowest F_1. The average F_1 measurements for all segments — vowels and consonants alike — can then be directly correlated with sonority indices and result in a fairly good fit since the mean values for most consonants are expected to be lower than that of /i/, and ranked roughly according to manner of articulation. At the same time, however, this is a very compressed range within which to contrast the entire set of consonants (≤ 330 Hz approximately). Consequently, a second list of data was simultaneously elicited in which every consonant occurred next to the vowel with the highest F_1 (/æ/ in English and /a/ in Spanish). This context provides a much wider space in which to separate all consonants. For the purpose of correlating these latter F_1 values with sonority indices, a simple adjustment is then made: the mean F_1 value of /æ/ minus that of /i/ is subtracted from each English consonant's measurement, and for Spanish consonants, F_1(/a/) minus F_1(/i/). This simplification allows us to simultaneously correlate consonant and vowel F_1's on the same scale by factoring out the contextual influence of the nuclei /æ/ and /a/.

I close this section by listing the stimuli used for F_1 purposes in each language. For both English and Spanish, the words used to minimally contrast all vowels were the same as for the other four physical experiments. These were presented in §4.2.3: example (4.1) for English and example (4.6) for Spanish. The English consonants which were elicited to study F_1 occurred tautosyllabically with the vowel /i/ in the following words:

(4.12) *peel* *beet* *geek* *fear* *sheep* *z*ebra *l*eague *y*east
team *bean* *cheese* *thief* *v*isa *meet* *reach* *wing*
*quich*e *deed* *jeep* *s*iege *th*ee *niece* *wreath* *h*eave

All English consonants were also elicited next to the vowel /æ/ (or a vowel similar to /æ/) in the following words:

(4.13) *path* *car* *dash* *chat* *thatch* *van* *mass* *rack* *have*
tag *bat* *gal* *jazz* *sap* *that* *nab* *yak*
calf *badg*e *gath*er *fang* *sham* *zap* *lad* *whack*

Spanish consonants occurred next to /i/ in the following words (*yuca* was used to get [ɉ] before the high vowel /u/ since the sequence /yi/ is not standard in Spanish):

Table 4.39: Spanish words (containing the vowel /i/) used for F_1 elicitation

*p*iso	[um pí.so]	'floor; ground'
*pin*za	[una pín.sa]	'tweezers; clamp'

(cont. next page)

(Table 4.39 cont.)

ti***l***de	[un/una tíl.de]	'accent mark'
qui***n***to	[uŋ kín.to]	'fifth'
bizco	[um bís.ko]	'cross-eyed person'
di***s***co	[un dís.ko]	'record; disk'
guiso	[uŋ gí.so]	'stew; casserole'
chi***s***me	[uñ čís.me]	'gossip; rumor'
yuca	[una ǰú.ka]	'piece of manioc'
fi***r***ma	[una fíř.ma]	'signature'
si***gn***o	[un síɣ.no]	'sign; signal'
a***b***i***s***mo	[un a.βís.mo]	'abyss, chasm'
dicha	[una ðí.ča]	'happiness; luck'
gui***n***da	[una ɣín.da]	'sour cherry'
miga	[una mí.ɣa]	'crumb; bit'
nigua	[una ní.ɣwa]	'chigger flea'
ñizca	[una ñís.ka]	'bit, pinch'
e***r***izo	[un e.ří.so]	'hedgehog'
ri***t***mo	[un řít.mo]	'rhythm'
li***d***	[una líð]	'fight; combat'
whi***s***ky	[uŋ wís.ki]	'whiskey'
hui***n***cha	[una wíñ.ča]	'hair ribbon'
gira	[una hí.řa]	'tour; excursion'
hi***p***nosis	[una ip.nó.sis]	'hypnosis'
i***c***tiólogo	[un ik.tyó.lo.ɣo]	'ichthyologist'
í***m***petu	[un ím.pe.tu]	'impetus, momentum'
i***n***ca	[un/una íŋ.ka]	'Inca person'

Spanish consonants were also pronounced next to /a/ in the following items (I could not come up with a good word beginning with the sequence /wa/):

Table 4.40: Spanish words (containing the vowel /a/) used for F_1 elicitation

paso	[um pá.so]	'step'
pa***n***za	[una pán.sa]	'belly'
ta***x***i	[un ták.si]	'taxi'
cá***p***sula	[una káp.su.la]	'capsule'
ba***n***co	[um báŋ.ko]	'bank'
dato	[un dá.to]	'datum, fact'

(cont. next page)

(Table 4.40 cont.)

ga***s***to	[uŋ gás.to]	‘expense’
cha***n***cho	[uñ čáñ.čo]	‘pig, hog’
yate	[uñ ǰá.te]	‘yacht’
yapa	[una ǰá.pa]	‘bonus, extra’
fase	[una fá.se]	‘phase, stage’
sa***l***sa	[una sál.sa]	‘sauce’
ba***r***ba	[una βář.βa]	‘beard’
da***n***za	[una ðán.sa]	‘dance’
gala	[una γá.la]	‘festive dress’
ma**g**nitud	[una màγ.ni.túð]	‘magnitude; size’
nave	[una ná.βe]	‘ship’
ñata	[una ñá.ta]	‘pug-nosed female’
a***r***aña	[una a.řá.ña]	‘spider’
ra***s***go	[un řás.γo]	‘trait; feature’
lá***m***para	[una lám.pa.řa]	‘lamp’
jarra	[una há.řa]	‘jar, pitcher’
a***t***mósfera	[una at.mós.fe.řa]	‘atmosphere’
a***f***gano	[un af.γá.no]	‘Afghan person’
a***b***domen	[un aβ.ðó.men]	‘abdomen’
a***d***jetivo	[un àð.he.tí.βo]	‘adjective’
a***d***verbio	[un að.βéř.βyo]	‘adverb’

4.3.3.2 English F_1 measurements

I begin the discussion of English F_1 results with onset consonants occurring in syllables whose nucleus is /i/. It is very important to keep in mind that F_1 measurements were never taken during consonants themselves. Rather, what these values represent are averages across the first 25 ms of the vowel /i/ when each of these consonants preceded it. This same procedure was also used for sonorant consonants as well, including glides.

Table 4.41: F_1 frequency of onset consonants before /i/ for English males (in Hz)

segment	mean	*n*	sd
g	259.1	12	41.6
h	273.2	12	33.5
y	273.7	12	30.6
n	276.8	12	30.7
m	277.3	12	20.2
k	278.0	11	27.6
b	280.4	24	43.4
d	280.6	12	38.4
ǰ	285.8	12	23.7
š	291.1	12	27.4
v	291.1	12	26.2
č	293.0	12	30.8
s	294.0	12	37.0
p	294.3	12	35.1
t	298.8	12	44.2
θ	299.0	12	35.6
z	299.0	12	25.1
f	305.8	12	26.1
l	314.7	12	34.3
r	315.0	24	31.2
ð	315.6	11	21.4
w	403.8	12	50.2
b d g	275.1	48	42.0
b d g + ǰ	277.3	60	39.1
m n	277.0	24	25.4
p t k	290.7	35	36.5
p t k + č	291.3	47	34.9
f θ s š	297.5	48	31.4
v ð z	301.5	35	25.8
l r	314.9	36	31.8
y w	338.8	24	77.9

Table 4.42: F_1 frequency of onset consonants before /i/ for English females (in Hz)

segment	mean	*n*	sd
h	274.2	12	45.5
t	286.3	12	37.9
k	289.7	12	36.2
m	301.7	12	47.4
y	303.9	11	42.6
n	305.0	11	42.7
g	316.0	12	51.9
č	316.8	12	47.8
p	324.5	12	45.5
š	328.2	12	43.2
b	329.5	24	45.9
f	336.1	11	45.3
d	338.8	12	27.4
ǰ	342.1	12	24.3
v	344.9	12	40.1
z	349.8	12	41.6
θ	358.3	12	31.8
l	366.5	12	39.9
ð	376.9	10	20.6
s	380.1	12	38.5
r	388.3	24	21.0
w	440.4	12	51.2
p t k	300.1	36	42.7
p t k + č	304.3	48	44.1
m n	303.3	23	44.2
b d g	328.4	48	43.7
b d g + ǰ	331.2	60	40.7
f θ s š	351.0	47	43.7
v ð z	356.1	34	37.7
v ð z + ǰ	352.4	46	35.0
y w	375.1	23	83.7
l r	381.0	36	30.0

For the male speakers (table 4.41), two major sonority "misplacements" involve the voiced stops and the nasals. However, given the VOT dynamics mentioned above, this is expected, even for the nasals (at least in initial position). All of the remaining natural classes, including the liquids, follow the sonority hierarchy quite well. Affricates pattern as stops, and for both sexes /h/ is clearly an obstruent. For the females (table 4.42), voiceless stops are now the lowest of all groups (somewhat surprisingly), but the nasals are still out of place. /ǰ/ patterns equally well with voiced stops or voiced fricatives. For both sexes the voiceless fricatives outrank the voiced stops. The large separation between the glides /y/ and /w/ is a glaring curiosity in both tables; the very low F_1 of /y/ in particular is surprising and obviously contributes to this gap. The very high standard deviations for /w/, as well as its relative distance from the next closest consonant in each scale, cast some doubt on the reliability of its measurements. At the moment I do not know what caused this. As an overall observation for both sexes, the range of consonantal F_1 values is so tightly compressed that it may be difficult to draw reliable conclusions about the separation between successive segments.

Table 4.43: F_1 frequency of coda consonants after /i/ for English males (in Hz)

segment	mean	*n*	sd
t	283.5	24	21.7
k	287.8	12	18.4
s	289.1	11	37.5
ǰ	291.7	12	22.1
n	293.3	12	45.5
g	296.7	12	22.0
č	297.3	12	26.1

(cont. next page)

Table 4.44: F_1 frequency of coda consonants after /i/ for English females (in Hz)

segment	mean	*n*	sd
m	297.7	12	46.4
s	306.9	12	60.3
f	311.9	12	59.1
š	321.1	12	50.6
ŋ	323.1	9	54.5
n	324.0	9	50.0
θ	330.3	12	64.3

(cont. next page)

(Table 4.43 cont.)

š	299.4	11	27.1
d	300.6	12	25.9
p	302.8	24	30.7
z	304.8	12	33.9
m	305.7	12	31.9
ŋ	307.1	12	54.3
v	312.9	12	23.1
θ	316.8	12	40.5
f	323.8	12	27.9
r	382.8	12	43.3
l	387.9	11	31.4
p t k	292.1	60	26.3
p t k + č	292.9	72	26.2
d g	298.6	24	23.6
d g + ǰ	296.3	36	23.0
m n ŋ	302.0	36	44.0
f θ s š	307.8	46	35.5
v z	308.9	24	28.7
l r	385.2	23	37.3

(Table 4.44 cont.)

č	331.9	12	50.5
g	333.0	12	53.6
p	337.0	24	46.5
z	340.8	11	54.0
k	342.1	12	56.9
t	344.3	24	55.6
ǰ	358.2	12	46.2
v	362.6	12	48.8
d	376.6	11	34.6
l	415.4	12	36.6
r	421.6	11	35.8
m n ŋ	313.2	30	49.9
f θ s š	317.6	48	57.6
f θ s š + č	320.4	60	56.2
p t k	340.9	60	51.6
p t k + č	339.4	72	51.2
v z	352.2	23	51.4
v z + ǰ	354.2	35	49.1
d g	353.9	23	49.7
d g + ǰ	355.3	35	47.9
l r	418.4	23	35.5

In coda position the nasals once again have relatively low F_1 values for both sexes. The affricates pattern as stops, and for the females (table 4.44), /ǰ/ also groups with the voiced fricatives. For the males (table 4.43) the voiceless fricatives outrank the voiced stops, while for the females we observe the opposite trend. The liquids nicely fall at the top of both scales. The direction of the ranking between voiced and voiceless obstruents is once again opposite to the expectations argued for above.

Table 4.45: F_1 frequency of vowels for English males (in Hz)

segment	mean	*n*	sd
i	271.1	12	24.7
u	319.6	12	35.7
e	410.8	12	36.9
ɪ	444.0	12	26.2
o	449.7	12	38.1
ʊ	484.2	12	28.6
ɛ	641.2	12	39.5
ʌ	646.3	12	33.7
ɔ	690.5	12	71.3
a	784.5	12	59.7
æ	792.6	12	69.3
i ɪ u ʊ	379.7	48	92.6
e ɛ ʌ o ɔ	567.7	60	123.4
æ a	788.5	24	63.4

Table 4.46: F_1 frequency of vowels for English females (in Hz)

segment	mean	*n*	sd
i	330.6	12	52.0
u	406.8	12	30.2
e	459.6	12	54.2
ɪ	512.6	12	53.5
o	557.3	12	43.3
ʊ	625.3	12	87.6
ɛ	768.8	12	66.3
ʌ	803.3	12	61.3
ɔ	844.2	12	52.1
a	881.8	12	77.8
æ	900.8	12	91.3
i ɪ u ʊ	468.8	48	126.2
e ɛ ʌ o ɔ	686.6	60	161.2
æ a	891.3	24	83.6

There are no surprises in the vowel data. All natural classes for both sexes follow the sonority hierarchy as expected. (I inadvertently forgot to include target words with [ə] in my list for F_1 elicitation.) Since /i/ has the lowest mean F_1 for both genders, the overall correlations combining vowels and consonants together on a single scale are fairly strong:

Table 4.47: Correlations between English F_1 data (with /i/) and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.75	.78	.77	.79	.77
by natural classes	.78	.82	.83	.85	.82

In table 4.47 the correlations by natural classes are consistently higher than those obtained with individual segments. The females also yield better results than the males. Finally, correlations for coda consonants are higher than those for consonants in onset position. This may be due to an increase in the confounding effects of glottal abduction in onsets *vis-à-vis* codas.

Let us now consider the analogous data for consonants occurring in the same syllable with /æ/ rather than /i/ (recall that onset /k/ comes from the word *car*):

Table 4.48: F_1 frequency of onset consonants before /æ/ for English males (in Hz)

segment	mean	*n*	sd
g	484.7	24	62.2
v	496.0	12	32.2
f	502.0	12	65.4
š	508.3	11	73.6
d	522.0	12	86.5
ǰ	539.8	12	106.0
z	552.3	12	61.4
ð	562.3	11	44.0
č	576.0	12	139.7
y	580.3	12	47.7
b	590.0	24	67.3
n	591.0	12	113.8
s	609.8	12	122.2
θ	617.7	12	71.4
r	617.7	12	70.0
m	629.8	12	89.9
w	655.0	12	62.3
k	675.4	24	99.5
t	701.5	12	130.9
l	706.5	12	53.7

(cont. next page)

Table 4.49: F_1 frequency of onset consonants before /æ/ for English females (in Hz)

segment	mean	*n*	sd
ǰ	492.4	12	53.6
g	529.6	24	68.1
d	558.2	12	77.2
v	576.0	12	78.2
z	589.1	12	95.1
š	590.8	12	75.2
y	598.8	12	90.2
r	602.0	11	50.7
ð	605.9	12	51.1
f	637.1	12	40.9
s	647.1	12	59.8
n	665.0	12	52.2
b	673.5	24	70.4
m	686.5	12	55.3
θ	694.2	12	62.3
č	699.5	12	70.8
w	783.6	12	65.2
l	787.4	12	88.8
t	844.5	12	87.0
k	856.7	23	86.5

(cont. next page)

(Table 4.48 cont.)

p	784.4	12	87.3
h	806.2	12	86.9
b d g	534.3	60	83.4
v ð z	536.1	35	54.8
v ð z + ǰ	537.1	47	70.1
f θ s š	560.5	47	100.1
f θ s š + č	563.7	59	108.1
m n	610.4	24	102.2
y w	617.7	24	66.3
l r	662.1	24	76.0
p t k	709.2	48	112.6

(Table 4.49 cont.)

h	939.2	11	157.1
p	942.0	12	81.4
v ð z	590.3	36	75.8
b d g	592.9	60	96.8
f θ s š	642.3	48	62.9
m n	675.8	24	53.7
y w	691.2	24	121.8
l r	698.7	23	118.7
p t k	875.4	47	92.5

For both genders the voiceless stops are now at the top of the F_1 scales. Voiceless fricatives are also higher than voiced stops and voiced fricatives. All of these differences are in the expected direction with respect to voicing, and with an effect as large as that observed here, this obviously contributes substantially to the lower correlations for F_1 which I will shortly present (relative to intensity and P_o). /h/ clearly falls among the sonorants in both sets of data, suggesting that it is really a voiceless vowel. For the males (table 4.48), both affricates pattern as fricatives. For the females (table 4.49), the two affricates are distinct from both stops and fricatives. For both sexes the sonorants clearly follow the sonority hierarchy better than the obstruents do.

Table 4.50: F_1 frequency of coda consonants after /æ/ for English males (in Hz)

segment	mean	*n*	sd
z	545.2	11	53.5
g	573.5	11	53.3
ǰ	594.0	12	62.8
ŋ	598.2	9	137.2
n	631.9	9	60.6
v	677.9	12	69.5
m	681.1	10	89.6
r	683.1	12	39.1
b	683.6	11	57.0
ð	707.8	12	61.2
d	719.8	12	64.3
š	737.4	12	118.7
t	757.8	35	108.5
č	764.3	12	109.7
k	767.2	36	115.5
l	767.9	12	73.4
θ	768.0	12	75.4
s	774.2	12	105.0
p	795.2	24	82.8
f	798.2	12	85.0
m n ŋ	638.6	28	102.8
v ð z	646.4	35	93.0
b d g	660.7	34	84.9
l r	725.5	24	72.0
f θ s š	769.4	48	96.8
f θ s š + č	768.4	60	98.6
p t k	770.8	95	105.5
p t k + č	770.1	107	105.4

Table 4.51: F_1 frequency of coda consonants after /æ/ for English females (in Hz)

segment	mean	*n*	sd
ŋ	618.5	12	95.1
z	664.5	12	64.3
g	664.9	12	74.0
n	701.5	12	66.1
ǰ	701.8	12	60.6
m	702.2	12	77.4
v	736.5	12	57.7
ð	768.9	12	55.9
r	810.3	12	77.3
d	813.6	12	50.6
b	824.3	11	89.3
č	837.9	12	96.0
š	845.8	12	72.4
s	847.6	12	97.8
t	850.7	36	79.4
l	867.1	12	48.0
θ	883.6	12	74.1
p	889.0	24	64.5
k	890.9	36	73.5
f	921.0	12	51.0
m n ŋ	674.1	36	87.7
v ð z	723.3	36	72.7
v ð z + ǰ	717.9	48	69.9
b d g	766.0	35	102.2
l r	838.7	24	69.3
f θ s š	874.5	48	79.6
f θ s š + č	867.2	60	83.5
p t k	875.4	96	75.4

In coda position after the vowel /æ/, the natural classes for both sexes completely reverse the sonority hierarchy. For the males (table 4.50), /č/ patterns with both the voiceless stops and the voiceless fricatives, and /ǰ/ is independent from both types of voiced obstruents. For the females (table 4.51), both affricates group with their respective (voiced or voiceless) fricatives.

I now give the corresponding correlations involving the English consonants which are tautosyllabic with the nucleus /æ/. As explained in §4.3.3.1, an adjustment is made first since these "consonant" measurements are really values for the first or last 25 ms of the vowel /æ/, which naturally has a higher F_1 than that of /i/. Consequently, the mean difference between /æ/ and /i/ for each sex is subtracted from each consonant's mean F_1 value in order to counteract this effect. This amounts to 521.5 Hz for the males and 570.2 Hz for the females. The resulting correlations are then more or less comparable to those calculated with consonants adjacent to /i/:

Table 4.52: Correlations between English
F_1 data (with /æ/) and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.82	.77	.77	.77	.78
by natural classes	.80	.75	.79	.80	.79

In table 4.52, the correlations show no overall tendencies for an effect either by gender, position in syllable, or segments vs. classes. However, it is clear that the strong fit between the vowel F_1 data and sonority indices for both sexes offsets the major reversals among the coda consonants. When the coda consonants by themselves, i.e., without vowels, are paired with sonority indices, the correlations are in fact negative rather than positive. As explained above, this is actually expected, at least for obstruents, because of the profound effect of voicing (glottal abduction) on F_1 measurements.

4.3.3.3 Spanish F_1 measurements

I now present F_1 values for Spanish consonants in onset position:

Table 4.53: F_1 frequency of onset consonants before /i/ for Spanish males (in Hz)

segment	mean	*n*	sd
ñ	264.6	12	38.8
g	278.8	12	39.4
γ	284.5	12	27.3
k	294.2	12	39.3
č	305.3	12	22.3
h	305.8	12	51.3
m	306.8	12	42.2
p	312.3	24	35.7
b	316.2	12	19.0
d	323.8	12	14.2
w	323.8	24	30.1
ř	328.3	12	19.9
n	331.8	12	68.0
ǰ(u)	333.3	12	23.8
ð	337.4	12	24.8
t	339.3	12	18.4
f	340.3	12	15.4
β	346.3	12	27.0
s	362.4	12	17.8
l	364.7	12	30.1
r̄	372.8	12	36.6
m n ñ	301.0	36	57.2
b d g	306.3	36	32.6
p t k	314.5	48	36.5
p t k + č	312.7	60	34.1

(cont. next page)

Table 4.54: F_1 frequency of onset consonants before /i/ for Spanish females (in Hz)

segment	mean	*n*	sd
h	263.2	12	21.2
g	265.2	12	28.6
γ	270.3	11	40.3
k	274.7	12	20.2
ñ	282.0	12	29.6
č	289.8	12	26.4
m	295.3	12	42.7
t	295.9	12	41.1
p	298.3	24	33.7
n	304.3	12	51.3
f	308.1	12	48.2
β	318.6	12	49.0
b	325.1	12	46.3
d	326.7	12	51.7
ð	332.0	12	53.4
ǰ(u)	357.1	12	42.3
w	363.8	24	62.6
ř	365.4	12	47.2
s	366.9	12	50.3
l	378.9	12	49.0
r̄	388.8	12	85.4
p t k	291.8	48	33.9
p t k + č	291.4	60	32.3
m n ñ	293.9	36	42.0
b d g	305.6	36	51.1

(cont. next page)

(Table 4.53 cont.)

β ð γ	322.7	36	37.7
β ð γ + ǰ	325.4	48	34.8
f s	351.3	24	19.8

(Table 4.54 cont.)

β ð γ	308.0	35	53.7
f s	337.5	24	56.8

For both genders there are several sonority reversals among the natural classes, and /h/ falls relatively low in both sets of data. /č/ patterns with voiceless stops and, for the males (table 4.53), /ǰ/ groups with the voiced fricatives. The nasals are also relatively low in both scales. Recall that /ǰ/ (/y/) does not occur before /i/ in my word list, so it was elicited preceding /u/ instead. In Spanish we do not expect large effects of voicing among stops (unlike English) since the vocal folds initiate vibration at or very shortly after the release of occlusion. With fricatives, on the other hand, higher F_1 values are still expected for vowels next to voiceless varieties, for the same reasons as in English.

Table 4.55: F_1 frequency of coda consonants after /i/ for Spanish males (in Hz)

segment	mean	*n*	sd
ŋ	280.7	12	37.6
ñ	282.9	12	46.8
m	294.6	12	41.6
n	295.8	36	38.2
s	300.4	72	50.3
k	319.0	12	41.8
l	340.0	12	25.2
ð	349.8	12	25.0
γ	351.1	12	26.8

(cont. next page)

Table 4.56: F_1 frequency of coda consonants after /i/ for Spanish females (in Hz)

segment	mean	*n*	sd
ŋ	282.2	12	24.2
m	285.2	12	28.4
ñ	286.8	12	31.0
n	291.0	36	33.3
s	293.1	72	34.5
k	299.5	12	47.0
ð	323.3	12	49.2
t	325.9	12	42.7
p	328.0	12	63.6

(cont. next page)

(Table 4.55 cont.)

p	353.2	9	79.9
t	364.8	12	31.4
ř	376.5	12	24.2
m n ñ ŋ	290.9	72	39.9
p t k	345.0	33	54.4
ð γ	350.5	24	25.3

(Table 4.56 cont.)

γ	330.7	12	63.7
l	331.6	12	55.4
ř	356.8	12	64.2
m n ñ ŋ	287.9	72	30.4
p t k	317.8	36	52.1
ð γ	327.0	24	55.8

In coda position /ř/ is at the top of the scale for both genders, as we want it to be. However, the nasals are invariably the lowest of all segments, a pattern we have seen in several other sets of F_1 results as well.

Table 4.57: F_1 frequency of vowels for Spanish males (in Hz)

segment	mean	*n*	sd
i	307.7	24	29.2
u	340.4	24	39.3
o	496.4	23	43.1
e	502.3	24	58.8
a	725.0	24	87.6
i u	324.1	48	38.0
e o	499.4	47	51.2

Table 4.58: F_1 frequency of vowels for Spanish females (in Hz)

segment	mean	*n*	sd
i	282.5	24	29.7
u	332.8	24	39.3
o	483.6	24	78.9
e	492.5	24	76.9
a	869.5	24	108.2
i u	307.6	48	42.9
e o	488.0	48	77.2

The Spanish vowels follow the same unremarkable pattern for both sexes. I now give the first set of correlations, for consonants occurring tautosyllabically with the vowel /i/, which has the lowest F_1 value for both sexes:

Table 4.59: Correlations between Spanish F_1 data (with /i/) and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.63	.64	.60	.60	.62
by natural classes	.65	.65	.67	.65	.66

In table 4.59 there is only one clear pattern: correlating by natural classes yields higher values than correlation by segments. The Spanish correlations with /i/ in this table are noticeably weaker than those of their English counterparts in table 4.47. This may be due in part to the fact that English has more vowel phonemes, a factor which helps to pull the correlations up.

I now consider Spanish consonants which surrounded the vowel /a/:

Table 4.60: F_1 frequency of onset consonants before /a/ for Spanish males (in Hz)

segment	mean	*n*	sd
ǰ	476.5	21	91.3
g	543.7	12	44.2
d	546.8	12	35.0
γ	563.8	11	46.9
č	577.3	12	91.3
ð	602.8	12	51.7
r̃	602.8	12	59.4
b	609.6	12	53.3
β	611.6	12	46.3
t	629.7	12	53.5
n	631.6	12	108.3
s	638.7	12	97.4
ñ	641.8	12	67.5
ř	647.1	12	54.3
m	649.7	12	82.2

(cont. next page)

Table 4.61: F_1 frequency of onset consonants before /a/ for Spanish females (in Hz)

segment	mean	*n*	sd
ñ	615.5	12	78.8
ǰ	626.2	24	69.1
g	656.3	12	46.1
r̃	658.4	12	48.1
γ	669.3	12	74.6
n	669.7	11	98.0
m	672.5	12	62.8
d	696.0	12	74.5
ð	712.8	12	70.5
β	739.3	12	87.9
ř	752.2	12	64.8
t	752.6	12	81.8
b	773.7	12	95.2
l	800.1	12	63.0
k	814.2	12	60.7

(cont. next page)

(Table 4.60 cont.)

f	669.7	12	80.2
l	683.5	12	71.1
k	684.3	12	85.7
p	688.7	24	74.8
h	840.7	11	110.9
b d g	566.7	36	53.3
β ð γ	593.5	35	51.3
m n ñ	641.0	36	85.4
f s	654.2	24	88.7
p t k	672.9	48	75.9

(Table 4.61 cont.)

č	814.3	12	99.2
f	844.4	12	70.1
s	848.9	12	66.7
p	849.3	24	98.4
h	1049.4	12	52.2
m n ñ	652.1	35	82.7
β ð γ	707.1	36	81.2
b d g	708.7	36	87.8
p t k	816.3	48	93.6
p t k + č	815.9	60	93.9
f s	846.7	24	67.0

For both sexes the voiceless obstruents outrank their voiced counterparts. In both scales /h/ also has the highest value, unlike the F_1 data with the vowel /i/ (further evidence that /h/ is a voiceless vowel). For the females (table 4.61), /č/ patterns as a stop.

Table 4.62: F_1 frequency of coda consonants after /a/ for Spanish males (in Hz)

segment	mean	*n*	sd
ð	598.4	23	95.7
t	627.7	12	97.6
ñ	628.7	12	112.1
β	629.9	12	97.1
γ	638.0	12	104.2
k	644.5	12	54.1
s	660.5	24	143.1
l	670.8	12	50.9
n	675.2	24	88.6
ř	679.7	12	65.7
ŋ	686.3	12	105.5
p	709.8	12	55.8

(cont. next page)

Table 4.63: F_1 frequency of coda consonants after /a/ for Spanish females (in Hz)

segment	mean	*n*	sd
t	553.3	12	62.0
ð	580.0	24	46.6
β	610.2	12	41.5
ñ	657.7	10	82.9
f	702.8	12	93.0
l	715.3	12	68.4
s	715.9	24	86.8
p	735.0	12	59.3
k	749.2	12	46.7
n	775.6	22	78.1
γ	792.6	12	52.8
m	800.7	10	84.4

(cont. next page)

(Table 4.62 cont.)

m	721.3	12	102.3
f	741.3	12	96.6
β ð γ	616.6	47	97.8
p t k	660.7	36	78.6
m n ñ ŋ	677.3	60	101.6
f s	687.4	36	133.7

(Table 4.63 cont.)

ŋ	825.3	11	61.8
ř	859.3	12	52.5
β ð γ	640.7	48	100.6
p t k	679.2	36	105.7
f s	711.5	36	87.8
m n ñ ŋ	768.4	53	94.2

In the two coda tables above, the nasals are about where we would want them to be for the first time (insofar as F_1 data are concerned). However, the voiced fricatives are at the bottom of the scales.

I now give the correlations with Spanish consonants adjacent to /a/. For all consonant values the amount of 417.3 Hz is subtracted for the males and 587 Hz for the females to adjust for the respective difference between /a/ and /i/:

Table 4.64: Correlations between Spanish
F_1 data (with /a/) and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.76	.64	.73	.79	.73
by natural classes	.77	.69	.75	.81	.76

In table 4.64, correlations with natural classes are consistently higher than those with segments. In Spanish, consonants adjacent to /a/ yield more robust overall correlations than those pronounced next to /i/ (table 4.59). This tendency is not observed with the English correlations, however. Nevertheless, the overall conclusion is that measuring F_1 for consonants adjacent to a low vowel produces better results than measuring it in a high vowel since there is much more room for the contrasts between consonants to emerge (spread out) in the F_1 "space" underneath /a/ and/or /æ/. A further finding is that F_1 is a weaker phonetic correlate of the phonological sonority hierarchy than both intensity and P_o. This is largely attributable to the somewhat expected reversals among obstruents due to VOT effects, especially in English. However, this outcome was also observed (to a lesser degree) in Spanish. This suggests that F_1 may be higher next to voiceless stops regardless of whether they are pronounced with a large opening of the glottis.

4.3.4 Total air flow

4.3.4.1 Background

As I noted in §4.3.2, when segmental air flow values are arranged in a hierarchical scale, the relative rankings tend to correspond quite closely to those of P_o measurements. Consequently, U_t should also be strongly correlated with sonority indices in a negative direction. Furthermore, U_t and P_o values should be highly correlated with each other as well. In other words, there is a sense in which P_o and U_t are not completely independent characterizations of sonority, nor for that matter are intensity and F_1. In this section I present data which test these hypotheses and quantify their statistical validity. First I summarize three previous studies on air flow rates of English consonants:

Table 4.65: Summary of previous experiments on air flow in English

authors	date	air flow scale	*r*	*p*
Isshiki and Ringel	1964	p k t θ č b š ǰ s d f g ž ð m v n z l r	–0.88	.000
Emanuel and Counihan	1970	t p k d b g	–0.95	.004
Stathopoulos and Weismer	1985	t k p d š f s θ ž ð z g v b	–0.82	.000

In table 4.65, the air flow scale lists the phonemes measured in each case, arranged from high to low (left to right) in terms of cc/sec U (it is not clear in their descriptions whether the air flow is oral plus nasal combined, or just oral). The following table provides some supplemental information on these experiments:

Table 4.66: Numbers of speakers and tokens from table 4.65

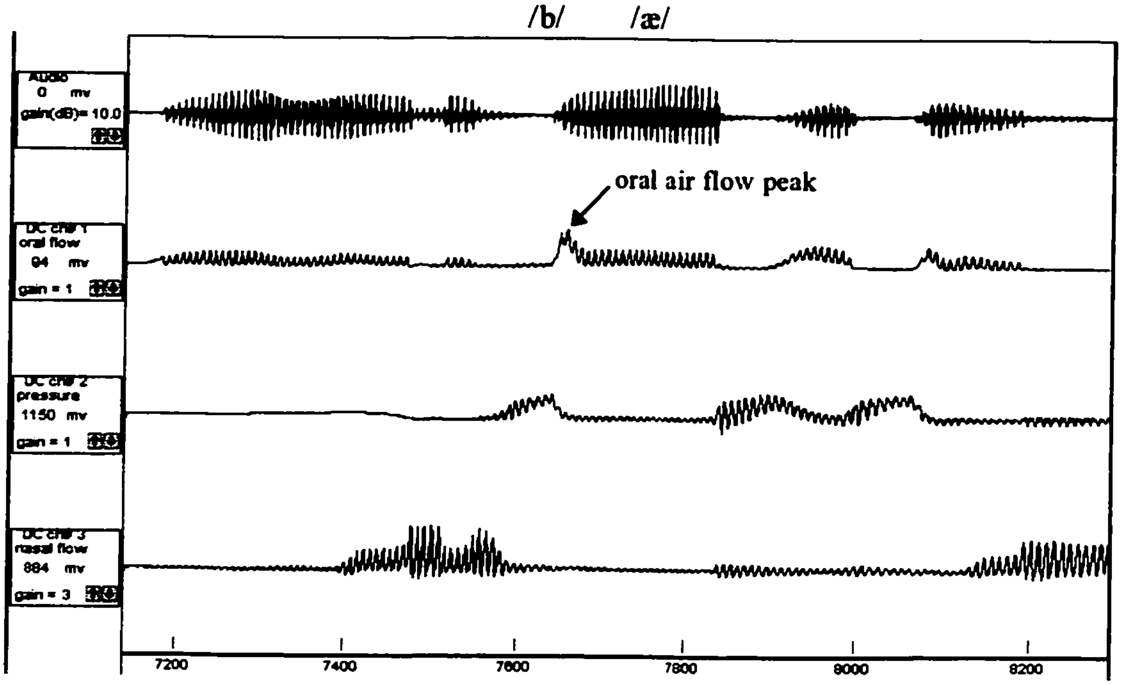
author(s)	speakers	repetitions
Isshiki and Ringel	4 men 4 women	1
Emanuel and Counihan	25 men 25 women	4
Stathopoulos and Weismer	5 men 5 women 10 children	3

In table 4.65 we see that consonantal U corresponds quite well to sonority. However, when vowels are factored into the correlations, the overall goodness of fit decreases somewhat, as we observed with P_o (see below).

Neither oral air flow nor nasal air flow by themselves are good indicators of sonority rank because in both cases nasal consonants are anomalous. When we measure U_o only, nasals logically have lower values than all other consonants. And if we consider only U_n, nasals obviously are the highest of all segments. When we combine oral + nasal flow into a total for each segment, however, the overall natural class rankings follow the sonority hierarchy quite well. Nasal consonants in particular pattern as they should when we measure total egressive air flow from the entire vocal tract ($U_{total} = U_{oral} + U_{nasal}$). Consequently, for each segment I calculated the instant in time at which combined oral plus nasal flow was at its peak. For most natural class types this corresponded to the point at which U_o was at its maximum, in which case the (usually negligible) U_n value at that moment was added to it. For nasal consonants, however, the peak combined flow usually occurred when U_n was at its highest, in which case the corresponding U_o at that cursor location was added in. For many tokens of /h/ in both languages, U_n was also quite high (see figure 4.5 below).

For measuring U_t in vowels, an adjustment was made similar to that of P_o: high U_o right after a consonant's release was considered to correspond to the consonant's U_t pattern. In such cases the peak U_t for the vowel was measured during the steady state of the vowel, distant from the influence of adjacent consonants. The following display of *I wanna <u>badge</u> again* shows that the U_o peak coinciding with the release of the /b/ (332 ml/sec) actually occurs during the initial pulses of the vowel /æ/:

Figure 4.4: PCquirer display of the sentence
I wanna badge again by a male speaker



After calibration, PCquirer reports U values in tenths of ml/sec. In this chapter I analyze peak U only for oral plus nasal values combined. In appendices C and D I give the corresponding segmental results broken down for each air flow channel separately.

4.3.4.2 English U_t measurements

Below are the U_t values for English consonants in onset position:

Table 4.67: Air flow of onset consonants for English males (in ml/sec)

segment	mean	*n*	sd
p	1469.4	36	363.9
t	1447.2	23	375.0
k	1263.9	131	386.1
h	1147.2	60	325.0
č	1102.8	12	358.3
š	977.8	12	183.3
f	738.9	12	172.2
b	716.7	152	197.2
s	705.6	35	250.0
d	675.0	13	169.4
θ	669.4	24	180.6
ž	597.2	12	116.7
ǰ	572.2	36	138.9
ð	544.4	12	105.6
v	527.8	24	163.9
z	469.4	12	144.4
g	444.4	23	105.6
n	363.9	84	69.4
m	327.8	120	66.7
r	261.1	45	58.3
y	258.3	12	61.1
l	247.2	69	80.6
w	188.9	12	55.6
ʔ	136.1	30	88.9
p t k	1325.0	190	388.9
f θ s š	738.9	83	230.6
b d g	680.6	188	205.6
v ð z ž + ǰ	547.2	96	141.7
v ð z ž	533.3	60	144.4
m n	341.7	204	69.4
l r	252.7	114	61.9
y w	222.2	24	66.7

Table 4.68: Air flow of onset consonants for English females (in ml/sec)

segment	mean	*n*	sd
p	1316.7	36	502.8
t	1269.4	24	366.7
h	988.9	60	477.8
k	916.7	132	441.7
č	905.6	12	247.2
f	683.3	11	233.3
š	672.2	12	197.2
s	622.2	35	194.4
θ	563.9	24	227.8
b	519.4	149	213.9
d	419.4	12	163.9
ǰ	408.3	36	161.1
z	355.6	12	127.8
v	336.1	23	136.1
ð	308.3	12	150.0
ž	294.4	12	138.9
g	283.3	24	125.0
n	219.4	84	66.7
m	194.4	120	63.9
r	191.7	42	66.7
w	183.3	12	52.8
y	175.0	10	33.3
l	169.4	69	47.2
ʔ	105.6	31	50.0
p t k	1036.1	192	477.8
p t k + č	1028.3	204	467.5
f θ s š	619.4	82	211.1
b d g	480.6	185	216.7
v ð z ž	325.0	59	136.1
m n	202.8	204	66.7
y w	180.6	22	44.4
l r	177.8	111	55.6

For the males (table 4.67), /ǰ/ patterns as a voiced fricative. For the females (table 4.68), /č/ groups with the voiceless stops. Both sexes follow the sonority hierarchy quite well, especially among obstruent natural classes, where voiceless fricatives have higher values than voiced stops. The main reversal involves /l/: for the males it has lower U_t than /r/, while for the females it is lower even than the glides. For both sexes /h/ clearly falls among the obstruents, while /ʔ/ is at the very bottom of both scales (just as it is in terms of P_o, and for a similar reason). The female values are invariably lower than those of the males, presumably due to their smaller vocal tract size and higher rate of glottal pulsing. Stevens (1998) estimates that average U for females is about two-thirds that of males. Table 4.67 (the males) is perhaps the most orderly display of all the measures seen so far in this chapter, with the exception of /g/. We would therefore expect that it should correlate exceptionally well with sonority. The fact that it does worse than intensity (r = –.71) is due to the addition of the U_t values for vowels, which are interspersed among those of the consonants. For example, in table 4.71 below, U_t(ʊ) = 438.9, which is higher than that of all sonorant consonants. This clearly weakens the correlations (to be given later).

Table 4.69: Air flow of coda consonants for English males (in ml/sec)

segment	mean	*n*	sd
š	927.8	12	150.0
f	872.2	12	280.6
s	825.0	13	266.7
p	794.4	12	213.9
θ	772.2	12	180.6
k	738.9	23	275.0
č	691.7	12	152.8

(cont. next page)

Table 4.70: Air flow of coda consonants for English females (in ml/sec)

segment	mean	*n*	sd
š	852.8	12	247.2
θ	727.8	12	150.0
s	722.2	12	283.3
f	719.4	10	330.6
k	638.9	24	233.3
č	530.6	12	147.2
p	450.0	12	141.7

(cont. next page)

(Table 4.69 cont.)

b	683.3	12	233.3
ž	658.3	12	180.6
ð	650.0	12	113.9
d	602.8	23	111.1
ǰ	550.0	12	111.1
v	475.0	10	88.9
z	472.2	12	138.9
t	422.2	138	158.3
n	422.2	214	77.8
ŋ	422.2	12	61.1
r	419.4	15	108.3
m	411.1	24	75.0
g	383.3	12	122.2
l	369.4	17	72.2
f θ s š	850.0	49	227.8
p k	758.3	35	254.1
p k + č	741.4	47	232.9
p t k	488.9	173	227.8
v ð z ž	572.2	46	161.1
b d g	566.7	47	188.9
b d g + ǰ	563.9	59	175.0
m n ŋ	422.2	250	77.8
l r	392.8	32	94.4

(Table 4.70 cont.)

b	363.9	11	152.8
ð	344.4	12	66.7
d	327.8	22	80.6
t	308.3	140	169.4
v	300.0	11	86.1
ǰ	283.3	12	102.8
z	277.8	12	91.7
ž	272.2	12	133.3
r	252.8	13	41.7
ŋ	250.0	12	80.6
l	233.3	16	77.8
g	216.7	12	61.1
n	211.1	203	66.7
m	197.2	23	66.7
f θ s š	758.3	46	255.6
p k	575.0	36	225.0
p k + č	564.8	48	207.2
p t k	363.9	176	211.1
b d g	308.3	45	113.9
b d g + ǰ	302.3	57	110.8
b g	286.1	23	136.1
b g + ǰ	286.0	35	124.1
v ð z ž	297.2	47	100.0
l r	242.0	29	63.9
m n ŋ	211.1	238	66.7

In coda position a major sonority reversal for both genders is that voiceless fricatives have higher U_t values than voiceless stops. This is possibly due to a glottalization of the voiceless stops syllable-finally. Even if they were not glottalized, they were still likely to be unaspirated and/or unreleased, so the glottis was not opened very widely. This would lead to relatively low U_g and U_o values. On the other hand, the glottis should remain fully spread for voiceless fricatives, even in coda position. For the males (table 4.69), the voiced obstruents are inverted as well. In both cases /č/ and /ǰ/ pattern as stops. Among the sonorants, /l/ again has lower U_t than /r/. The female values continue to be lower than those of the males.

Table 4.71: Air flow of vowels for English males (in ml/sec)

segment	mean	*n*	sd
ʊ	438.9	12	122.2
ɪ	419.4	157	163.9
ʌ	408.3	24	116.7
u	380.6	48	63.9
æ	377.8	226	94.4
ɛ	372.2	36	75.0
e	369.4	128	77.8
ə	366.7	87	88.9
i	358.3	36	69.4
o	347.2	98	75.0
ɔ	319.4	76	94.4
a	311.1	65	69.4
i ɪ u ʊ	405.6	253	138.9
æ a	361.1	291	91.7
e ɛ ʌ o ɔ	355.6	362	86.1
e ɛ ʌ o ɔ + ə	358.3	449	86.1

Table 4.72: Air flow of vowels for English females (in ml/sec)

segment	mean	*n*	sd
ʊ	316.7	12	108.3
ʌ	258.3	24	88.9
ɛ	238.9	36	88.9
o	233.3	94	69.4
ɪ	225.0	147	83.3
e	219.4	125	61.1
u	213.9	48	86.1
æ	213.9	219	58.3
ə	211.1	85	75.0
i	188.9	36	58.3
ɔ	188.9	77	66.7
a	188.9	61	63.9
i ɪ u ʊ	222.2	243	86.1
e ɛ ʌ o ɔ	219.4	356	72.2
e ɛ ʌ o ɔ + ə	218.7	441	72.6
æ a	208.3	280	61.1

The vowel natural classes generally follow the sonority hierarchy very well, again in a negative direction. Nevertheless, the differences between the pooled natural class means are mostly quite small. For both genders [ə] patterns with the mid vowels. Similarly to P_o, the U_t values of the higher vowels overlap with those of many sonorant consonants, as noted above.

Table 4.73: Correlations between English U_t data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	–.71	–.72	–.76	–.64	–.71
by natural classes	–.70	–.74	–.83	–.70	–.74

A tendency in table 4.73 is that correlating by natural classes yields stronger *r* values than correlating by individual segments. The overall mean correlations (–.71 and –.74) are much weaker than those of English P_o measurements from table 4.31 (–.88 and –.85).

It would also be worthwhile to correlate all of the U_t data with the corresponding P_o results. The following table lists these values for all of the English speakers. The overall means indicate a fairly good match between the different sets:

Table 4.74: Correlations between English P_o and U_t data

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.75	.70	.88	.68	.75
by natural classes	.71	.70	.88	.70	.75

In table 4.74 the correlations are consistently higher for the males than for the females.

4.3.4.3 Spanish U_t measurements

I now present the air flow results for Spanish:

Table 4.75: Air flow of onset consonants for Spanish males (in ml/sec)

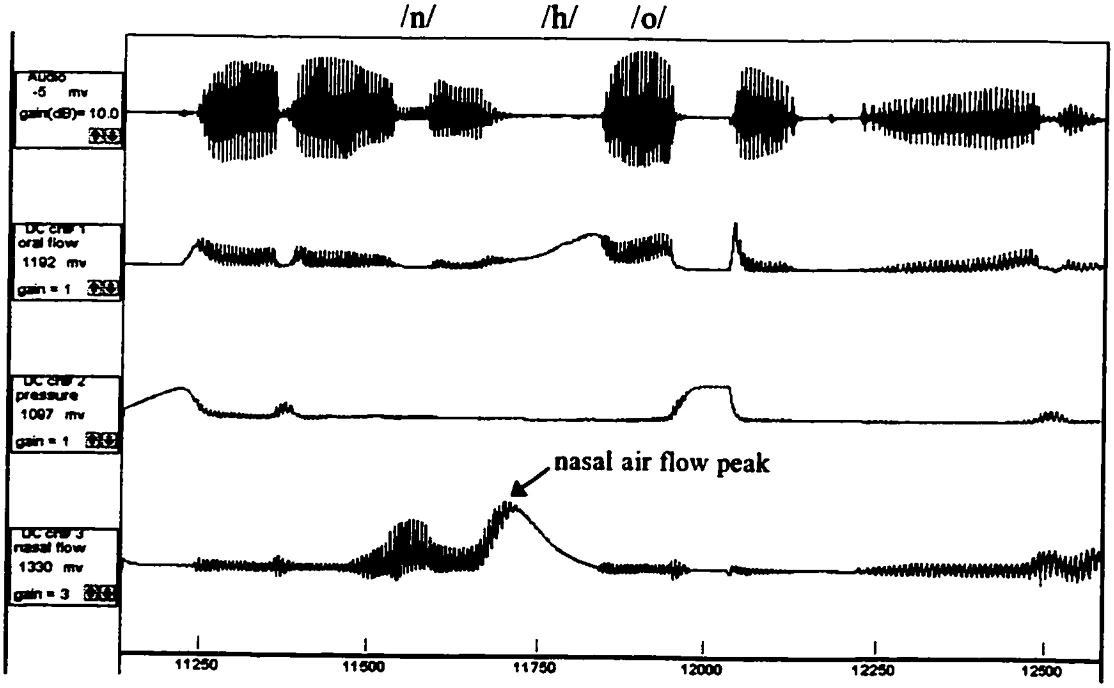
segment	mean	*n*	sd
č	1289.8	12	442.6
s	1060.8	12	471.2
h	870.6	12	250.5
t	833.0	24	365.8
p	644.2	120	242.5
d	638.2	13	279.5
r̄	595.8	12	203.3
f	587.0	12	262.4
k	565.1	48	185.4
g	506.0	13	172.2
b	478.9	13	134.4
ř	432.8	11	98.8
ð	421.1	11	211.3
ǰ	409.4	24	162.2
m	325.4	12	132.9
ñ	315.2	12	112.3
n	300.3	12	86.7
β	286.2	21	113.7
w	269.4	12	64.4
l	268.8	24	42.7
γ	264.3	11	79.5
f s	823.9	24	444.6
f s + h	839.5	36	387.5
p t k	648.0	192	259.4
b d g	541.0	39	211.5
β ð γ	315.1	43	149.4
m n ñ	313.6	36	109.5

Table 4.76: Air flow of onset consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
č	938.7	12	274.7
h	658.4	12	328.0
f	523.9	11	169.0
p	414.2	117	166.6
s	404.7	11	241.3
k	401.8	43	163.3
t	373.9	23	116.0
d	352.8	12	190.5
r̄	300.9	12	108.8
b	286.7	13	147.1
ǰ	272.3	24	102.6
ð	262.3	12	116.9
ř	246.2	12	94.6
ñ	241.1	12	54.2
g	239.0	12	111.3
n	236.2	12	59.1
m	203.7	12	77.9
β	193.5	23	87.3
w	185.8	12	54.7
l	174.4	24	56.6
γ	156.6	12	68.7
f s	464.3	22	212.2
p t k	406.2	183	160.1
b d g	292.7	37	155.8
b d g + ǰ	284.6	61	136.7
m n ñ	227.0	36	64.9
β ð γ	201.6	47	97.8

In the onset tables above, the higher U_t of voiceless fricatives relative to voiceless stops is a major sonority reversal for both sexes. Also, for the females (table 4.76), the voiced fricatives have lower U_t than the nasals, indicating that the former are strongly lenited. For the females, /ǰ/ groups with the voiced stops. For both sexes /r̃/ and /ř/ pattern mainly as obstruents, and /č/ at the top of the scales beats out all other segments by a wide margin. Another segment which is relatively high in U_t for both sexes is /h/. As explained in §4.3.4.1, this is often due to complete nasal coupling, which is permitted when articulating [h] since the soft palate does not need to be raised. (By the way, this confirms that the point of articulation of this phoneme truly is glottal, not velar.) In the following display of the utterance *Quiero una jota ahora* 'I want a jot or bit now,' the peak U_n of the /h/ of *jota* (587 ml/sec) is in fact higher than that of the *n* of *una* since the glottis is abducted and U_g is very high. Because of this, /h/ patterns as a voiceless fricative in the male data (table 4.75):

Figure 4.5: PCquirer display of the sentence
Quiero una jota ahora by a male speaker



I now consider U_t for Spanish consonants in syllable-final position:

Table 4.77: Air flow of coda consonants for Spanish males (in ml/sec)

segment	mean	*n*	sd
s	751.4	72	383.8
f	651.7	11	378.3
ř	506.1	24	167.2
h	493.0	9	257.2
k	444.6	12	243.3
ŋ	441.0	12	136.4
n	426.3	47	145.4
m	384.4	12	134.8
ñ	355.8	24	120.4
γ	322.9	12	132.9
l	310.2	36	76.5
t	301.8	12	177.7
ð	291.0	10	77.0
β	275.0	11	60.1
p	229.7	10	38.8
f s	738.2	83	382.3
m n ñ ŋ	405.0	95	138.8
p t k	331.0	34	196.9
β ð γ	297.2	33	96.4

Table 4.78: Air flow of coda consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
f	469.3	12	291.6
s	414.6	72	198.8
h	386.1	12	271.1
k	376.9	11	102.6
ř	305.2	23	98.8
n	270.8	48	94.4
ŋ	250.8	12	73.4
ñ	247.1	24	87.0
m	229.8	12	88.4
l	223.3	36	79.7
γ	199.9	11	89.8
ð	179.3	12	91.6
t	173.4	12	94.4
p	154.5	12	53.6
β	142.8	11	52.0
f s	422.4	84	213.2
f s + h	417.9	96	219.9
m n ñ ŋ	257.3	96	89.4
p t k	230.9	35	130.5
β ð γ	174.2	34	81.4

The two coda tables above involve several major sonority reversals among natural classes, but at least they do so in a consistent way: voiceless fricatives are highest of all, and the nasals are next highest. /ř/ is also relatively high in both lists. /h/ clearly patterns as an obstruent rather than a sonorant. The fact that we get relatively low values for the (voiceless) stops undoubtedly reflects the absence of any release for these consonants in this position. Indeed, it is surprising that we observe any appreciable U_o for these segments at all.

Table 4.79: Air flow of vowels for Spanish males (in ml/sec)

segment	mean	*n*	sd
u	403.6	48	134.0
o	367.3	250	126.5
e	340.4	48	113.5
a	326.9	144	107.8
i	300.8	55	93.6
e o	362.9	298	124.7
i u	348.7	103	124.8

Table 4.80: Air flow of vowels for Spanish females (in ml/sec)

segment	mean	*n*	sd
e	210.7	48	69.4
o	200.6	251	66.3
u	198.3	48	90.7
a	187.3	143	63.7
i	180.1	60	54.2
e o	202.2	299	66.8
i u	188.2	108	72.9

For both sexes the mid vowels have higher U_t than high vowels, unlike their English counterparts. An extremely strong tendency throughout all the Spanish U_t data is that men have much higher values than women. For some segments the male averages are twice those of the females.

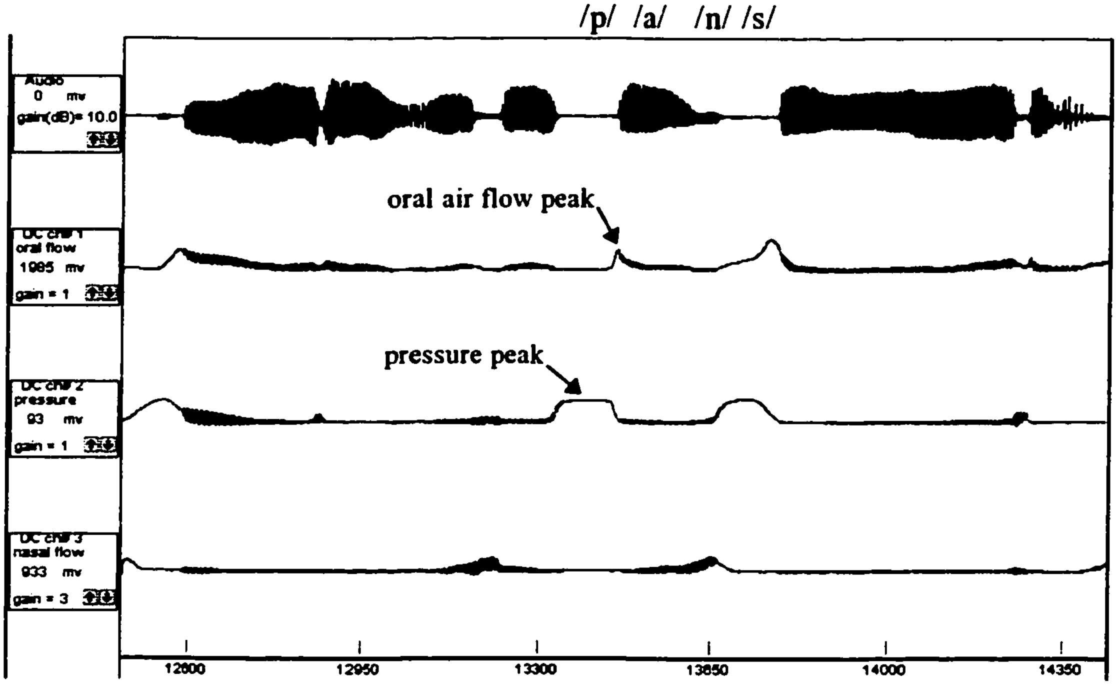
Table 4.81: Correlations between Spanish U_t data and sonority indices

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	–.62	–.70	–.24	–.42	–.50
by natural classes	–.68	–.77	–.39	–.51	–.59

The correlations in table 4.81 are quite a bit weaker than those of English (table 4.73). This shows up in a drastic way with coda consonants due to the major sonority reversals there. The females overall do better than the males, and correlating with natural classes is stronger than with individual segments.

I now present the correlations between U_t and P_o data for Spanish. The following figure illustrates the interaction between pressure buildup during occlusion and air flow upon release. For the /p/ of *panza* 'belly', the U_o peak (446 ml/sec) occurs right after the pressure plateau at 6.8 cm H_2O. A similar relationship is evident for the /s/ later in the target word:

Figure 4.6: PCquirer display of the sentence
Quiero una panza ahora by a female speaker



Correlations between U_t and P_o for Spanish are summarized below:

Table 4.82: Correlations between Spanish P_o and U_t data

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.75	.71	.39	.72	.64
by natural classes	.87	.73	.56	.77	.73

In table 4.82, the overall mean correlations are slightly lower than those of English (.75 in table 4.74). It is obvious that most of this difference is caused by the Spanish male U_t data for consonants in coda position (table 4.81). The corresponding correlations between P_o results and sonority indices (table 4.38) are the strongest of that table. The overall picture which very consistently emerges then is that P_o is a much stronger (negative) correlate of sonority than U_t is.

4.3.5 Duration

4.3.5.1 Background

In this section I explore absolute segmental duration as a physical correlate of the sonority hierarchy. This relationship is proposed by Allen (1973), Donegan (1978), Nathan (1989), Beckman *et al.* (1992), Kenstowicz (1996), and Lavoie (2000). The strong consensus which emerges from these works is that sonority is correlated with consonant durations in a negative direction, and with vowel durations in a positive direction. Consequently, when duration measurements for vowels and consonants together on a unitary scale are paired with relative sonority indices, the resulting correlations are very weak (compared with the other four phonetic parameters already analyzed). However, when we calculate duration × sonority correlations for vowels and consonants separately, the results improve dramatically. Therefore, in this case there is a logical *a priori* reason for distinguishing the vowel and consonant scales when comparing them with sonority indices. Later the two correlation coefficients (for vowels and consonants) can be averaged together for each group to give us an idea of the larger picture, e.g., for comparing duration with the other four physical studies. It is not implausible that listeners and speakers evaluate phonetic measures of sonority differently for consonants and vowels when it comes to properties such as duration, since the scales run in opposite directions.

One relatively large scale study on the duration of English consonants is reported by Lavoie (2000). Below I highlight her findings, based on 5 repetitions of each segment by each of 5 male speakers:

Table 4.83: Summary of a previous experiment on duration in English

author	date	duration scale	*r*	*p*
Lavoie	2000	č š t s p k f θ ǰ ž z r b g l d v m ð n ř	–.75	.000

The duration scale above lists the segments analyzed, from longest to shortest (left to right). A minor drawback of Lavoie's experiment is that she does not include data on the phonemes /y w h/. I remedy this in my results, to be presented shortly. I also measure vowels at the same time as consonants, for both men and women, so my study is more exhaustive. In Lavoie's (2000) discussion she compares her data with those of a number of other experiments on consonantal duration. Her overall findings are that (1) most previous studies do not include data on as many consonants as she does, so they are less helpful in this respect. (2) Nevertheless, insofar as her data overlap with those of other experiments, the results are comparable, i.e., they lead to the same conclusions.

Specifically, (3) voiceless obstruents are longer than their voiced counterparts, and (4) consonant durations are longer in stressed and word-initial syllables than they are elsewhere. Since my concern here is not with lenition (unlike Lavoie), I do not pursue the lengthening effects in different prosodic environments. Nevertheless, my results do coincide with these earlier studies in that voiceless segments tend to be longer than voiced ones. Furthermore, one specific advantage of my experiment is that I acquired data on all phonemes — vowels and consonants alike — from the same set of speakers, so the relative sonority of all speech sounds can now be simultaneously assessed.

My criteria for positing segmental boundaries are spelled out in detail in §4.2.5, so I do not repeat them here. I do reiterate, however, that for those types of speech sounds whose acoustic properties are not sharply discontinuous from flanking segments (i.e., liquids, glides, and vowels), a major landmark for pinpointing the beginnings and ends of junctures was F_2 (either the presence vs. absence of a clearly discernible F_2, or the location of a significant F_2 transition).

4.3.5.2 English duration measurements

I begin with English onset consonants:

Table 4.84: Duration of onset consonants for English males (in ms)

segment	mean	*n*	sd
č	206.6	12	29.2
š	193.3	12	42.3
f	185.6	12	51.7
s	183.6	35	36.8
p	181.3	36	32.1
k	177.7	129	34.4
t	172.3	21	35.4
θ	170.4	22	29.2
ǰ	146.4	36	24.6
b	135.0	153	26.6
d	134.1	13	26.1
z	133.9	12	25.2
h	130.6	60	28.1
g	122.1	23	25.4
n	118.4	83	31.0
ð	113.8	12	27.5
v	110.7	24	24.1
m	107.7	119	20.0
l	105.7	69	24.1
ž	101.2	11	30.9
w	99.6	12	29.3
y	95.0	12	25.6
r	94.7	45	24.4
ʔ	86.9	30	20.5
f θ s š	181.8	81	38.4
p t k	177.8	186	34.0
b d g	133.3	189	26.7
v ð z ž	114.3	59	27.9
m n	112.1	202	25.6
l r	101.4	114	24.7
y w	97.3	24	27.0

Table 4.85: Duration of onset consonants for English females (in ms)

segment	mean	*n*	sd
č	199.9	12	20.7
š	180.8	12	21.2
p	180.1	36	22.6
k	180.0	132	28.7
t	170.0	24	22.9
f	158.2	12	20.6
s	157.7	35	22.7
θ	151.4	24	19.8
ǰ	148.3	36	23.0
h	130.5	60	26.2
g	128.9	24	24.0
b	126.4	148	16.7
d	118.8	12	21.0
z	114.3	12	15.7
ð	112.3	12	19.3
w	109.3	12	20.3
n	106.2	84	15.5
v	104.9	24	21.2
y	103.8	9	11.0
m	102.4	120	12.8
l	99.6	69	17.1
ž	95.7	12	9.2
r	93.2	41	19.2
ʔ	90.2	31	15.8
p t k	178.7	192	27.1
f θ s š	159.3	83	23.0
b d g	126.2	184	18.1
y w	107.0	21	16.8
v ð z ž	106.4	60	18.7
m n	104.0	204	14.1
l r	97.2	110	18.1

For the males (table 4.84), voiceless fricatives are slightly longer than voiceless stops, but this sonority reversal is not observed for the females (table 4.85). The rest of the male natural classes follow the sonority hierarchy well, although /r/ is shorter than the glides (but the difference is negligible). For the females the glides are just slightly longer than we would hypothesize, i.e., longer than other sonorant consonants and voiced fricatives, but the liquids follow the expected order. For both sexes /č/ is the longest consonant. This is not surprising since affricates are complex segments (cf. §3.2.5.3). For both sexes /h/ patterns as an obstruent but [ʔ] is the shortest of all segments and thus falls among the sonorants.

Table 4.86: Duration of coda consonants for English males (in ms)

segment	mean	*n*	sd
č	141.0	12	16.0
s	138.6	13	18.0
š	136.9	12	25.5
f	123.9	12	16.4
θ	114.1	12	19.5
k	110.8	23	15.1
p	110.2	11	16.4
ǰ	98.3	12	10.2
r	96.6	15	23.3
ž	91.1	12	14.5
ð	88.0	12	12.7
l	85.7	17	21.1
z	84.8	12	14.9
g	83.7	12	14.7
m	81.3	24	11.7
ŋ	78.0	12	16.7
b	77.4	12	20.8
v	72.0	9	16.6
t	65.8	136	28.4
n	54.8	213	12.1
d	49.7	23	17.2

(cont. next page)

Table 4.87: Duration of coda consonants for English females (in ms)

segment	mean	*n*	sd
č	160.7	12	22.7
š	154.3	12	15.8
s	145.0	12	16.1
f	135.7	10	19.5
θ	135.5	12	27.9
k	121.3	23	18.3
p	114.9	12	11.4
ž	101.0	12	23.4
ǰ	100.9	12	11.7
t	94.8	141	39.8
r	90.2	13	11.8
ð	88.6	12	10.8
g	83.3	12	15.8
z	82.8	12	9.7
b	82.3	11	17.3
v	82.1	11	18.7
l	81.6	16	15.6
ŋ	78.6	12	11.6
m	77.7	23	10.0
n	60.1	202	11.3
d	49.9	22	9.7

(cont. next page)

(Table 4.86 cont.)

f θ s š	128.6	49	21.9
p k	110.6	34	15.3
l r	90.8	32	22.5
v ð z ž	84.8	45	15.6
b g	80.5	24	17.9
p t k	74.7	170	31.8
b d g	65.4	47	23.4
m n ŋ	58.4	249	15.2

(Table 4.87 cont.)

f θ s š	143.0	46	21.3
p k	119.1	35	16.4
p t k	99.7	176	37.6
v ð z ž	88.8	47	17.8
l r	85.4	29	14.5
b g	82.8	23	16.1
b d g	66.7	45	21.3
m n ŋ	62.8	237	12.9

In coda position /t/ and /d/ are relatively short for both genders due to the flapping mentioned in §4.3.1.2. In both tables fricative natural classes are longer than their stop counterparts. Another reversal involves the sonorants, which are completely backwards (in duration) from what the sonority hypothesis would predict: *r* > *l* > nasals. However, it is well-known that English liquids are vocalized in codas; this undoubtedly contributes to their increased length in this position. For this reason Sproat and Fujimura (1993) use duration as one diagnostic of /l/ vocalization.

Table 4.88: Duration of vowels for English males (in ms)

segment	mean	*n*	sd
e	158.0	48	22.8
æ	155.2	223	28.7
ɔ	152.0	32	35.3
u	145.4	24	34.0
a	140.4	18	33.1
o	139.5	63	31.8
ɛ	111.5	36	19.0
i	105.3	12	19.3
ʌ	97.0	23	26.5

(cont. next page)

Table 4.89: Duration of vowels for English females (in ms)

segment	mean	*n*	sd
æ	157.2	219	25.7
e	150.0	46	24.1
ɔ	148.1	26	25.0
a	145.7	19	36.5
u	138.2	24	31.4
o	129.2	63	24.8
i	107.2	12	19.8
ɛ	106.3	36	19.6
ʌ	91.0	24	13.0

(cont. next page)

(Table 4.88 cont.)

ɪ	77.9	157	20.1
ʊ	65.3	12	9.9
ə	55.7	87	17.1
æ a	154.1	241	29.2
e ɛ ʌ o ɔ	136.1	202	34.7
i ɪ u ʊ	86.6	205	31.3

(Table 4.89 cont.)

ɪ	71.5	147	21.0
ə	62.0	85	16.9
ʊ	45.7	12	13.4
æ a	156.3	238	26.8
e ɛ ʌ o ɔ	127.7	195	30.4
i ɪ u ʊ	80.4	195	32.7

The vowel duration data follow the sonority hierarchy more consistently than the consonant results do, i.e., there are fewer sonority reversals. All of the natural class groupings pattern as expected, and [ə] is at or near the bottom of both scales, confirming its classification as the least sonorous of all vowels.

Table 4.90: Correlations between English duration data and sonority indices

	onset consonants (without vowels)		coda consonants (without vowels)		vowels	
	males	females	males	females	m	f
by individual segments	–.86	–.82	–.63	–.72	.72	.72
by natural classes	–.91	–.86	–.51	–.66	.99	.99

Table 4.90 is unlike previous correlation summaries in this chapter in that vowels and consonants were ***not*** combined when computing *r* values. (We shall do this, however, in just a moment.) A very striking pattern in table 4.90 is that correlations for onset consonants are all stronger than those of codas. There are two factors which contribute to this effect: (1) in coda position, several fewer consonant segments were measured than in onsets, and (2) there are several major sonority reversals in codas. Among the vowels, the correlations

are identical for males and females, and the results for natural classes are virtually perfect.

In order to fully compare the duration data with the other four phonetic parameters (a task we shall soon undertake), it would be helpful to combine the consonant and vowel correlations into a single *r* value for each group. Based on the discussion in §4.3.5.1, one logical way to do this is to simply average together the corresponding correlations for vowels and consonants in each set of data. For example, for the male onset consonants in table 4.90 (by individual segments), $r = -.86$. The male vowel segments have a correlation of .72 with sonority indices. The mean of these two numbers is .79 (here I ignore the signs of these correlations since we are only interested in their relative size, not their actual direction). In joining together two correlations in this way, there are two potential concerns: (1) *r* values are not in themselves raw data but rather statistics derived from raw data, and (2) the sets of consonants and vowels have different numbers of members, so we are not dealing with the same numbers of correlated data points. Nevertheless, looking ahead to chapter 5, we will see that even with this adjustment, duration is clearly the weakest of the five physical parameters studied in terms of overall match ups with sonority. Consequently, these duration data will not play any role in developing a formal model of sonority in that chapter. Rather, our primary focus there will be on intensity, whose correlations with sonority indices in §4.3.1 were not adjusted in any way. With respect to my fivefold exploration of phonetic measurements of sonority, duration clearly comes in last place (in spite of the help we are giving it), so no harm is done. If we somehow manipulated the duration results so that they were then superior to those of intensity, that would clearly be a questionable move. As it stands, averaging together the vowel and consonant correlations for duration will serve a very benign purpose only: to allow us to simultaneously compare them with the other four sets of correlations so as to demonstrate that duration is in fact a relatively poor indicator of sonority ranks. Having clarified this point, I now present the combined correlations for English duration measurements, calculated by averaging together the vowel and consonant *r* values from table 4.90:

Table 4.91: Adjusted correlations between English duration data and sonority indices, derived from table 4.90

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.79	.77	.68	.72	.74
by natural classes	.95	.93	.75	.83	.87

In the averaged correlations in table 4.91 above, there are two strong trends. First, correlations in onset position continue to be higher than those in codas. This is obviously due to the correlations for consonants alone (without vowels) from table 4.90, since the same vowel correlations are factored into all of the *r* values here in table 4.91. Second, correlating by natural classes clearly yields stronger results than correlating by individual segments in table 4.91. This too can be ascribed to the much higher correlations for vowel natural classes as opposed to individual vowel phonemes.

4.3.5.3 Spanish duration measurements

Below I review the results of a previous study on duration measurements for Spanish consonants, based on 4 male speakers and 5 repetitions of each segment:

Table 4.92: Summary of a previous experiment on duration in Spanish

author	date	duration scale	*r*	*p*
Lavoie	2000	x p č t f s k ǰ ñ m n r̄ β γ l v ð ř	–.75	.002

In table 4.92, the correlation of Spanish consonant durations with sonority indices (–.75) is comparable to that obtained with Lavoie's (2000) English durations (table 4.83), although the sample sizes and therefore the *p* values are obviously different. I now present my own Spanish results:

Table 4.93: Duration of onset consonants for Spanish males (in ms)

segment	mean	*n*	sd
č	150.6	12	30.0
f	140.0	12	19.3
k	135.0	48	29.9
s	129.6	12	21.3
r̄	123.9	12	26.6
t	123.5	24	26.7
p	121.9	120	22.1
h	121.1	12	31.5
ñ	107.4	12	17.8
m	104.5	12	22.0
w	91.3	12	26.1
l	83.7	24	21.3
ǰ	79.4	24	24.4

(cont. next page)

Table 4.94: Duration of onset consonants for Spanish females (in ms)

segment	mean	*n*	sd
č	167.9	12	23.6
f	143.5	12	27.1
h	136.3	12	47.7
s	133.5	11	24.0
k	132.5	48	23.8
t	125.8	24	21.5
p	124.1	119	27.7
r̄	122.0	12	29.1
w	111.7	12	22.2
m	109.5	12	15.5
ñ	100.1	12	19.5
γ	97.4	12	17.3
l	95.8	24	16.2

(cont. next page)

(Table 4.93 cont.)

n	78.6	12	21.7
γ	77.7	11	21.6
β	69.7	21	30.9
g	66.2	13	19.8
b	63.2	13	29.6
ð	60.3	11	29.5
d	57.8	13	27.6
ř	43.9	11	9.03
f s	134.8	24	20.6
f s + č	140.1	36	24.9
p t k	125.4	192	25.3
m n ñ	96.8	36	23.9
β ð γ	69.3	43	28.5
β ð γ + ǰ	72.9	67	27.4
b d g	62.4	39	25.6

(Table 4.94 cont.)

n	92.3	12	11.9
β	87.2	23	26.1
ǰ	84.5	24	26.6
ð	73.5	12	20.0
g	60.7	12	16.5
b	55.1	13	16.3
d	53.9	12	25.4
ř	34.7	12	10.0
f s	138.7	23	25.6
f s + h	137.9	35	34.1
p t k	126.4	191	26.2
m n ñ	100.6	36	17.0
β ð γ	86.3	47	23.9
β ð γ + ǰ	85.7	71	24.6
b d g	56.0	37	19.5

In the tables above, fricatives are longer than their corresponding stops for both sexes. /ǰ/ patterns as a fricative in both sets of data. For the men (table 4.93), /č/ groups with the voiceless fricatives, whereas for the women (table 4.94), it is /h/ which is indistinct from /f s/. For both sexes the nasals fall between the voiceless obstruents and their voiced counterparts.

Table 4.95: Duration of coda consonants for Spanish males (in ms)

segment	mean	*n*	sd
h	129.6	9	35.8
s	114.8	72	38.7
γ	113.3	11	39.2
t	94.4	11	36.7
β	89.7	10	31.9
k	89.5	12	27.9

(cont. next page)

Table 4.96: Duration of coda consonants for Spanish females (in ms)

segment	mean	*n*	sd
h	111.3	11	31.9
s	110.8	72	35.1
γ	88.4	10	37.7
l	88.2	36	15.3
ŋ	85.2	12	23.6
n	84.8	48	23.1

(cont. next page)

(Table 4.95 cont.)

f	88.6	10	16.6
n	81.0	47	18.6
ŋ	73.5	12	17.0
ð	72.5	9	19.1
l	71.5	36	16.1
m	69.8	12	6.1
ř	69.6	24	19.2
ñ	61.3	24	10.8
p	57.9	9	22.6
f s	111.6	82	37.6
f s + h	113.4	91	37.6
β ð γ	93.2	30	35.1
p t k	82.3	32	33.0
m n ñ ŋ	73.6	95	17.4

(Table 4.96 cont.)

t	82.6	10	22.4
ř	80.5	24	25.3
f	80.0	12	16.3
m	74.4	12	9.4
ð	73.5	9	10.2
β	71.2	11	24.6
k	70.8	10	17.8
ñ	66.1	24	16.2
p	65.2	8	22.9
f s	106.4	84	34.7
f s + h	107.0	95	34.3
m n ñ ŋ	78.9	96	21.7
β ð γ	77.6	30	27.2
p t k	73.4	28	21.5

In coda position, /h/ patterns with the other voiceless fricatives for both sexes. Voiceless stops are very short because they tend to be lenited syllable-finally in Spanish. /l/ is relatively long for the females (table 4.96).

Table 4.97: Duration of vowels (in open syllables) for Spanish males (in ms)

segment	mean	*n*	sd
i	92.0	12	10.1
e	94.0	12	10.4
u	96.2	24	22.6
o	102.4	155	17.9
a	107.2	24	16.5
i u	94.8	36	19.3
e o	101.8	167	17.5

Table 4.98: Duration of vowels (in open syllables) for Spanish females (in ms)

segment	mean	*n*	sd
u	131.2	24	23.3
i	136.9	12	14.5
o	148.1	154	22.4
e	150.0	12	17.4
a	166.7	24	23.4
i u	133.1	36	20.7
e o	148.3	166	22.1

The Spanish vowel duration results are separated according to whether they occurred in open or closed syllables. Recall that all English vowel durations were measured in closed syllables only. Neither of the two tables above is remarkably different from expectations. However, the female durations (table 4.98) are noticeably longer than those of the males (table 4.97). This effect is probably related to the fact that the women tended to speak more slowly than the men (in Spanish but not in English). For some reason this difference seems to affect the vowels much more than the consonants.

Table 4.99: Duration of vowels (in closed syllables) for Spanish males (in ms)

segment	mean	*n*	sd
i	75.8	41	23.3
e	82.4	36	16.5
a	87.0	116	21.6
u	87.2	24	17.8
o	114.5	94	33.0
i u	80.0	65	22.0
e o	105.6	130	32.7

Table 4.100: Duration of vowels (in closed syllables) for Spanish females (in ms)

segment	mean	*n*	sd
i	95.5	47	41.4
e	112.6	36	20.7
u	116.1	24	20.0
a	124.6	114	25.4
o	158.5	96	44.0
i u	102.5	71	36.8
e o	146.0	132	44.0

Most of the Spanish vowels in closed syllables are shorter than their counterparts in open syllables, as we would expect since there is less time in which to articulate the vowel when it is checked by a coda consonant. One anomaly in closed syllables is that /a/ is not the longest vowel for either gender. This is unexpected since duration is known to be strongly correlated with degree of jaw and tongue lowering. For both sexes the longest vowel in closed syllables is in fact /o/, by a rather large margin. It is not clear to me why this should be so. Since /o/ is the most common vowel in the list of words I used to elicit Spanish data, perhaps the speakers emphasized it in order to better contrast the consonants. However, if this is true, the vowel /o/ should show the same pattern in open syllables as well, but it doesn't.

For the correlations between mean durations and sonority indices in Spanish, the data for vowels in closed syllables (rather than open syllables) are used. The reasons for this are twofold: (1) so that the conditions are as consistent as possible with those of English, and (2) because all of the coda consonants obviously occurred in closed syllables only, and many of the onset consonants did as well.

Table 4.101: Correlations between Spanish duration data and sonority indices

	onset consonants (without vowels)		coda consonants (without vowels)		vowels	
	males	females	males	females	m	f
by individual segments	–.44	–.34	–.42	–.06	.27	.44
by natural classes	–.42	–.26	–.68	–.08	.26	.51

In table 4.101, the correlations overall are much weaker than those of English (table 4.90). For Spanish the male results are stronger than those of the females. The female values are extremely weak in coda position due to many sonority reversals there. I now present the corresponding table for vowel plus consonant correlations averaged together:

Table 4.102: Adjusted correlations between Spanish duration data and sonority indices, derived from table 4.101

	onset consonants plus vowels		coda consonants plus vowels		
	males	females	males	females	means
by individual segments	.36	.39	.35	.25	.34
by natural classes	.34	.39	.47	.30	.38

In Spanish the consonant correlations are not helped by the vowels (when averaging the two together) nearly as much as they are in English. Consequently, the means for each row of four correlations (in the rightmost column in table 4.102) are considerably weaker than those of their English counterparts (table 4.91). This is the primary reason why duration "loses" to the other four phonetic parameters discussed in this chapter (cf. table 5.1).

4.3.6 Reliability checks

Approximately one year after I made the measurements discussed in this chapter, I went back to the recorded files and measured some of the same tokens again. The purpose for this was to see how close I would come to my original values, and thus gain an idea of the reliability of these initial measurements. Without consulting the previously noted values, I looked at a few randomized segments from 2 groups: the English-speaking men, and the Spanish-speaking women. The phonemes examined in this restudy were, for English, the vowels /i æ ʊ/, the onset consonants /p b m l w/, and the coda consonants /s ǰ/. For Spanish I checked the vowels /i a u/, the onset consonants /p b ñ l w/, and the coda consonant /s/. For each of these segments I remeasured one token from each of the 4 speakers from the 2 groups. All of these values (within each phonetic parameter) were pooled together for all 8 speakers combined. The results are presented below:

Table 4.103: Summary of the differences between the original phonetic measurements and the reanalyzed values one year later

parameter	*n*	mean difference	mean % error
intensity	99	.21 dB	1.94
pressure	72	.043 cm H_2O	4.12
F_1	75	9.89 Hz	1.61
flow	100	1.98 ml/sec	1.85
duration	98	1.01 ms	.75

In the table above, the 5 physical parameters end up with different numbers of tokens reanalyzed. This is because not all of the original segments lent themselves to all five types of phonetic measurements (for various and idiosyncratic reasons). The column labeled "mean difference" indicates the average overall discrepancy between the original tokens (pooled together) and the same segments when reanalyzed, also pooled together. For example, the "mean difference" in intensity is listed as .21 dB. This signifies that, on average, the intensity value for each remeasured segment differed by .21 dB from the intensity value for the same segment as originally analyzed. To illustrate this, suppose that for one specific instance of the vowel /a/ I initially recorded its peak intensity as 30 dB, and one year later when remeasuring it I obtained a value of 28 dB. This would then be counted as a difference of 2 dB for that token. When all of these intensity difference scores for the 99 reanalyzed tokens are pooled together, their mean value is .21 dB.

The column labeled "mean % error" indicates the proportional difference, on average, between each remeasurement and its original value. For example, suppose that for one token of the segment /w/ I recorded its original duration as 100 ms. Suppose further that on reanalysis I measured this same segment as 103 ms in duration. This would count as an error of 3%. When all of these percentage values are pooled together for the 98 duration tokens I checked, they average out to .75%. This value then corresponds roughly to a mean difference score of 1.01 ms for all duration comparisons, as indicated in table 4.103. (The virtue of stating the discrepancies as a percentage of the initial amount is that we can then directly compare across the 5 physical correlates.) The largest value in the "mean % error" column is 4.12 for P_o. Consequently, we can reasonably conclude that the physical values reported throughout this chapter (i.e., as I originally measured them) are all very likely to be accurate to a degree of at least 95%, assuming of course that my measurement techniques were valid to begin with.

4.4 Conclusion

The instrumental results presented in this chapter strongly confirm the physical reality of the sonority hierarchy. The five parameters studied are correlated with typical phonological sonority scales in the following order (from strongest to weakest): intensity, intraoral air pressure, F_1 frequency, total air flow, and duration. Compared with most previous experiments, this one is more exhaustive in that it provides data on the complete inventory of phonemes, in both onset and coda positions, for both male and female speakers, from two different languages. Consequently, it gives us a very good indication of which phonetic measures will lead to a characterization of sonority which is complete, precise, and potentially universal. This topic is a major focus of the next chapter.

CHAPTER 5

DISCUSSION AND APPLICATION OF PHONETIC RESULTS

5.1 Introduction

In this chapter I summarize and discuss the most important implications of the instrumental data presented in chapter 4. My goal is to apply those results to the development of an exact and phonetically-based definition of sonority. This chapter is organized as follows. In §5.2 I carry out a detailed statistical analysis of the summary correlations from chapter 4. In §5.3 I then return to the intensity data in order to formalize a precise definition of sonority. In §5.4 I highlight the fact that air flow and air pressure (especially the latter) also closely mirror the sonority hierarchy (albeit in a negative direction). Beginning in §5.5 I then reconsider — in light of my data — a number of segments and natural classes whose relative sonority rank needs to be clarified. These are glottal consonants, voiceless fricatives vs. voiced stops, affricates, liquids, and [ə]. I close in §5.10 by positing a single, universal sonority hierarchy based on all of the statistical findings as a whole.

5.2 Statistical analysis of correlations

In this section I summarize all of the correlation tables from chapter 4 by means of five single-factor ANOVA's. The five variables are (1) phonetic parameter (intensity vs. P_o vs. F_1 frequency vs. U_t vs. segmental duration), (2) language (English vs. Spanish), (3) method of correlation (by individual segments vs. by natural classes), (4) prosodic position (onset consonants plus vowels vs. coda consonants plus vowels), and (5) sex (males vs. females). The F_1 correlations used here are those calculated with consonants adjacent to /æ/ and /a/ (tables 4.52 and 4.64 respectively), not those with the vowel /i/ (tables 4.47 and 4.59). There are three reasons which justify this choice: (1) F_1 values for consonants measured next to low vowels result in higher overall correlations than those measured next to /i/; (2) the 16 F_1 correlations with /æ/ and /a/ exhibit less variability (a smaller standard deviation) than those with /i/; and (3) there is more room for the consonants to spread out underneath the F_1 values for low vowels (vs. /i/) since the range is less compressed, as discussed in §4.3.3.1. These three facts converge on the decision to select the F_1 data with /æ/ and /a/ as the best correlates of sonority to include here. Except for this principled exclusion of F_1 correlations with /i/, the following table is otherwise exhaustive. For duration, the correlations reported in table 5.1 below are those calculated by averaging together the separate *r* values for consonants and vowels for each group. That is, they come from tables 4.91 and 4.102.

Table 5.1: Summary of correlations between phonetic data and sonority indices

			prosodic position				
			onset C's plus vowels		coda C's plus vowels		
parameter	method	language	males	females	males	females	grand means
intensity	segments	English	.97	.98	.94	.96	.97
		Spanish	.96	.99	.99	.98	
	classes	English	.97	.96	.89	.92	.96
		Spanish	.97	.99	.99	.98	
pressure	segments	English	–.89	–.91	–.84	–.87	–.83
		Spanish	–.77	–.82	–.83	–.70	
	classes	English	–.83	–.87	–.85	–.86	–.84
		Spanish	–.79	–.85	–.89	–.80	
F_1	segments	English	.82	.77	.77	.77	.76
		Spanish	.76	.64	.73	.79	
	classes	English	.80	.75	.79	.80	.77
		Spanish	.77	.69	.75	.81	
flow	segments	English	–.71	–.72	–.76	–.64	–.60
		Spanish	–.62	–.70	–.24	–.42	
	classes	English	–.70	–.74	–.83	–.70	–.67
		Spanish	–.68	–.77	–.39	–.51	
duration	segments	English	.79	.77	.68	.72	.54
		Spanish	.36	.39	.35	.25	
	classes	English	.95	.93	.75	.83	.62
		Spanish	.34	.39	.47	.30	

In table 5.1 above, the rightmost column lists the overall mean correlation (of 8 *r* values) for each of the five physical parameters, separated by method of correlation (individual segments vs. natural classes). As noted in §4.3.1.2, it would not be appropriate to average together across the two methods of correlation since the instrumental values for segments are partially subsumed under the pooled natural class means, i.e., they largely overlap. Consequently, for the inferential statistics that I will soon carry out, I always calculate two sets of results — one for correlations by segments, and a second one for correlations by classes. A cursory inspection of table 5.1 suggests that the main effect of the variable *(phonetic) parameter* is highly significant since the grand means are fairly well spread out across the table and there is relatively little variability within each parameter. Later in this section, after I present the ANOVA's, I will focus in more detail on the contrasts between the five physical parameters and quantify these tendencies. This factor (phonetic parameter) is obviously the most important and relevant one for understanding sonority. Before carrying out further statistical analyses on table 5.1, however, two modifications need to be made. First, in testing these correlations, the negative signs for P_o and U_t will be dropped because we are only interested in the relative strength of *r*, not its absolute direction (positive or negative). Without this adjustment the calculations would be artificially biased in favor of contrasts having opposite signs. Second, since there are many very high values in table 5.1, the correlations will be normalized (unskewed) by means of the Fisher *Z* transformation (Myers and Well 1995). This procedure uses a natural logarithm to smooth out a set of correlations containing many high values, which would otherwise be too compressed at the top end. After these two adjustments are made, the Fisher *Z* chart corresponding to table 5.1 is the following:

Table 5.2: Values of Fisher's *Z* for the correlations of table 5.1

			prosodic position				
			onset C's plus vowels		coda C's plus vowels		grand means
parameter	method	language	males	females	males	females	
intensity	segments	English	2.09	2.30	1.74	1.95	2.20
		Spanish	1.95	2.65	2.65	2.30	
	classes	English	2.09	1.95	1.42	1.59	2.09
		Spanish	2.09	2.65	2.65	2.30	
pressure	segments	English	1.42	1.53	1.22	1.33	1.22
		Spanish	1.02	1.16	1.19	.87	
	classes	English	1.19	1.33	1.26	1.29	1.24
		Spanish	1.07	1.26	1.42	1.10	
F_1	segments	English	1.16	1.02	1.02	1.02	1.00
		Spanish	1.00	.76	.93	1.07	
	classes	English	1.10	.97	1.07	1.10	1.03
		Spanish	1.02	.85	.97	1.13	
flow	segments	English	.89	.91	1.00	.76	.73
		Spanish	.73	.87	.24	.45	
	classes	English	.87	.95	1.19	.87	.84
		Spanish	.83	1.02	.41	.56	
duration	segments	English	1.07	1.02	.83	.91	.66
		Spanish	.38	.41	.37	.26	
	classes	English	1.83	1.66	.97	1.19	.90
		Spanish	.35	.41	.51	.31	

In the upcoming tables and discussion I will present group means in terms of both *r* and *Z*, but the obtained *F* statistics are all based on *Z* values only (from table 5.2). A glance at tables 5.1 and 5.2 suggests that there may not be a significant effect for method of correlation (segments vs. classes). This is confirmed by the following ANOVA:

Table 5.3: Results of ANOVA on the Z values of table 5.2 for the factor ***method (of correlation)***

source of variance	options	mean r	mean Z	degrees of freedom	F	p
Method	segments classes	.74 .77	1.16 1.22	1, 78	.194	.661

As table 5.3 demonstrates, there is no significant difference between the correlations based on the *method* of correlation. Consequently, when the remaining four variables are separated by segments and classes for the other statistical tests below, the two sets always lead to analogous conclusions. Let us now deal with these other four main factors in table 5.2, beginning with the correlations for segments:

Table 5.4: Results of ANOVA on the ***segment*** values of table 5.2

source of variance	options	mean r	mean Z	degrees of freedom	F	p
Position	onset coda	.77 .71	1.22 1.10	1, 38	.319	.576
Language	English Spanish	.81 .66	1.26 1.06	1, 38	1.026	.317
Gender	males females	.74 .74	1.14 1.18	1, 38	.027	.871
Parameter	(later)	(later)	(later)	4, 35	44.903	.000 (s)

In the ANOVA results in table 5.4 (for correlations by segments), only one F value is significant (highly so): the Parameter main effect. There is no other significant difference for the remaining variables. A second ANOVA, this time with the natural class correlations, follows exactly the same pattern, i.e., only Parameter is significant:

Table 5.5: Results of ANOVA on the *class* values of table 5.2

source of variance	options	mean *r*	mean *Z*	degrees of freedom	*F*	*p*
Position	onset coda	.79 .76	1.27 1.17	1, 38	.355	.555
Language	English Spanish	.84 .71	1.29 1.15	1, 38	.665	.420
Gender	males females	.77 .77	1.22 1.22	1, 38	.002	.966
Parameter	(later)	(later)	(later)	4, 35	16.078	.000 (s)

The conclusions to be drawn from tables 5.4 and 5.5 are as follows. In the experiment discussed in chapter 4, the five physical correlates of sonority (intensity, P_o, etc.) reliably differ in magnitude from one another. Otherwise, overall correlations with sonority indices do not vary in terms of Method, Prosodic Position, Language, or Sex. The failure to detect a difference in "sonority" based on language and gender is a positive result since it supports the hypothesis that sonority is universal. Similarly, sonority patterns the same way regardless of whether it is calculated for individual segments or for natural classes. Finally, it is reassuring that sonority relationships among speech sounds are equally stable in onset and coda positions. Nevertheless, the most important and significant result in tables 5.4 and 5.5 is the very strong difference between the five acoustic and aerodynamic parameters. The ramifications of this fact will be exploited throughout the remainder of this chapter. In the remainder of this section I now focus in more detail on the contrasts between the five physical measurements (one compared with another) to show that some of them are in fact reliably distinct. I begin by displaying the mean values and their relative spread from tables 5.1 and 5.2:

Table 5.6: Means and standard deviations of the five phonetic parameters from tables 5.1 (*r*) and 5.2 (*Z*) (by ***segments***)

parameter	mean *r*	sd *r*	mean *Z*	sd *Z*
intensity	.97	.02	2.20	.33
pressure	–.83	.07	1.22	.21
F_1	.76	.05	1.00	.12
flow	–.60	.18	.73	.26
duration	.54	.22	.66	.33

Table 5.7: Means and standard deviations of the five phonetic parameters from tables 5.1 (*r*) and 5.2 (*Z*) (by ***classes***)

parameter	mean *r*	sd *r*	mean *Z*	sd *Z*
intensity	.96	.04	2.09	.45
pressure	–.84	.03	1.24	.12
F_1	.77	.04	1.03	.09
flow	–.67	.14	.84	.25
duration	.62	.27	.90	.61

In tables 5.6 and 5.7 the standard deviations for the *r* values in particular are quite small, indicating that there is relatively little variability within each parameter. For example, in table 5.1 the lowest correlation for intensity is .89, while the strongest correlation for P_o is only –.91. This general lack of overlap between parameters obviously contributes greatly to the high significance of this main effect. The standard deviations for the corresponding *Z* values in tables 5.6 and 5.7 are elevated somewhat due to the stretching effect of this transformation, especially for the topmost correlations. Nevertheless, a one-way contrast between the two strongest correlates (intensity and P_o) is still significant (for both *r* and *Z* and for both segments and classes) using paired *t* tests:

Table 5.8: Pairwise contrasts between phonetic measures in terms of overall correlation with sonority, based on the *r* values of table 5.1 (by ***segments***)

parameters	*t*	df	*p* (one-tail)
intensity vs. pressure	5.62	7	.0004
pressure vs. F_1	2.48	7	.0212
F_1 vs. flow	2.37	7	.0248
flow vs. duration	1.06	7	.1624

Table 5.9: Pairwise contrasts between phonetic measures in terms of overall correlation with sonority, based on the *Z* values of table 5.2 (by ***segments***)

parameters	*t*	df	*p* (one-tail)
intensity vs. pressure	6.80	7	.0001
pressure vs. F_1	2.80	7	.0132
F_1 vs. flow	2.73	7	.0146
flow vs. duration	.85	7	.2120

Table 5.10: Pairwise contrasts between phonetic measures in terms of overall correlation with sonority, based on the *r* values of table 5.1 (by ***classes***)

parameters	*t*	df	*p* (one-tail)
intensity vs. pressure	6.28	7	.0002
pressure vs. F_1	3.36	7	.0061
F_1 vs. flow	1.92	7	.0482
flow vs. duration	.52	7	.3089

Table 5.11: Pairwise contrasts between phonetic measures in terms of overall correlation with sonority, based on the *Z* values of table 5.2 (by ***classes***)

parameters	*t*	df	*p* (one-tail)
intensity vs. pressure	5.35	7	.0005
pressure vs. F_1	3.42	7	.0055
F_1 vs. flow	1.92	7	.0479
flow vs. duration	–.33	7	.3744

In tables 5.8-5.11 above, I pair up each phonetic correlate or measure with the one which is next strongest relative to it, to test for significant separations between the parameters. In other words, I contrast all adjacent pairs from the leftmost column of tables 5.1 and 5.2. For the purposes of interpreting the results in tables 5.8-5.11 above, it would be judicious to invoke a Bonferroni adjustment and test each contrast at a one-tail α level of .0125. When we do this, only the intensity vs. P_o comparison is significant in all four cases. In addition, in tables 5.10 and 5.11 only, P_o is also reliably stronger than F_1 as a correlate of sonority. A striking pattern in all four tables is that as we go from top to bottom, the obtained *t* values always decrease and, accordingly, the *p* values consistently increase. In other words, the farther down we go in the list of the five physical parameters measured, the less reliably they differ from one another. (The absolute *t* and *p* values differ between the four tables, but the relative degree of significance between the four pairs is exactly the same throughout.) Specifically, in all four tables the most robust contrast is that between intensity and P_o (the highest two parameters). Consequently, we can now draw the following conclusions. The five physical correlates of sonority examined in chapter 4 do differ from one another in terms of their relative match ups with sonority indices (per the ANOVA's), but to varying degrees of confidence (per the *t* tests). Furthermore, intensity is consistently superior to the other four measures in three crucial respects: (1) it yields the highest overall correlations, (2) its *r* values have the smallest overall standard deviations, and (3) its *r* and *Z* values separate it the most from its immediate neighbor (P_o) —

more than any other pair of adjacent physical parameters are distinguished. These facts strongly indicate that intensity is the best phonetic correlate of sonority from which to derive a precise and potentially universal definition of sonority, a topic to which I now turn.

5.3 Intensity revisited: towards a universal definition of sonority

In this section I return to the intensity results from chapter 4 and show how we can develop them into an exact and nonarbitrary definition of sonority. Tables 5.12 and 5.13 below highlight the data for female speakers of Spanish and male speakers of English, respectively. These two groups are chosen since (1) their mean intensity values follow the sonority hierarchy the most closely; (2) as a consequence of (1), they have the highest correlations; and (3) we end up with one set from each gender and each language. Furthermore, onset consonants are selected (rather than codas) so as to maximize the number of language-specific phonemes included. The two tables below list the natural class and segmental intensity means as well as their corresponding sonority indices (from (4.11) and (4.9)). In tables 5.12 and 5.13 all pairs of adjacent means are significantly distinct (by separate variance *t* tests at a one-tail α level of .05) except those specifically annotated with the label *ns* (off to the right side of the columns):

Table 5.12: Summary of intensity data for Spanish females (in dB) with consonants in onset position (from tables 4.16 and 4.20)

segments	sonority index	mean	
e o	11	15.81	
a	12	14.85	
i u	10	13.99	
w	9	10.83	} ns
l	8	9.04	
ř	7	6.33	
r̄	6	2.92	
m n ñ	5	–.50	
β ð γ	4	–2.62	} ns
b d g	3	–4.03	
ǰ		–5.75	
h		–8.17	
f s	2	–10.70	
p t k č	1	–12.07	

$r = .99$

Table 5.13: Summary of intensity data for English males (in dB) with consonants in onset position (from tables 4.5 and 4.9)

segments	sonority index	mean	
i ɪ u ʊ	10	10.65	} ns
e ɛ ʌ o ɔ	11	10.21	
æ a	12	9.62	
ə	9	5.73	
y w	8	3.92	} ns
r	7	2.53	} ns
l	6	2.51	
m n	5	–4.16	
h		–6.05	} ns
v ð z ž	4	–6.30	
ʔ		–11.10	} ns
f θ s š	3	–11.96	} ns
b d g ǰ	2	–12.41	
p t k č	1	–13.75	

$r = .97$

In the two tables above, no sonority index is listed for [h] and [ʔ] since there is little *a priori* agreement about their relative sonority (cf. §3.2.5.1). Furthermore, Spanish [ǰ] is also unindexed since it is significantly less intense than the voiced stops. These three segments are all left out of the correlation calculations given below each table (and in figure 5.1 as well). For the Spanish females (table 5.12), only two contrasts fail to reach significance: /w/ vs. /l/ and [β ð γ] vs. [b d g]. The latter pair of groups are not phonemically distinct anyway, so this result is not a major problem. In this case the outcome (lack of contrast) is due to the very high standard deviation of the voiced fricatives (7.34

from table 4.16). Recall that these fluctuate with approximant-like articulations due to lenition. However, it is worth noting that in both cases ([b d g] vs. [β ð ɣ] and /l/ vs. /w/) all four mean values clearly do go in the right direction, even if this is only a trend. This is ultimately a matter of statistical power; presumably with enough tokens we could eventually attain reliable separations. Among the remaining Spanish data, all adjacent pairwise contrasts are significant, and the only clear sonority reversal involves /a/ vs. /e o/. In other words, except for non-high vowels, all of the Spanish segmental and group intensity means are ranked exactly in the same order as their corresponding sonority indices. Consequently, the correlation is nearly perfect (r = .99). The following picture illustrates this match up quite well. Each data point corresponds to the overall mean intensity for one segment (minus [ʝ] and [h]), not an entire natural class. Nevertheless, these are precisely the individual values on which the groups in table 5.12 are based:

Figure 5.1: Scatterplot of Spanish female intensity data (vowels plus onset consonants) from tables 4.16 and 4.20 ($n = 24$)

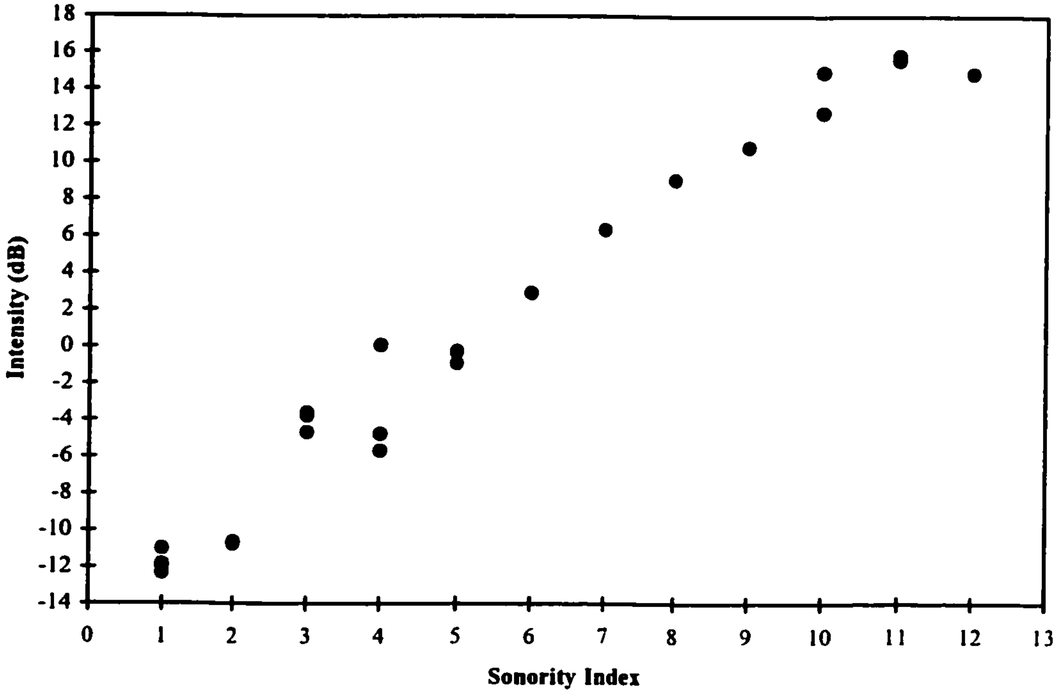


Figure 5.1 speaks for itself; the very strong linear relationship is striking ($r^2 = .97$). We can now state unequivocally that the single factor *Sonority* or *Sonority Index* accounts for (predicts) 97% of the systematic variability in the Spanish female intensity data. While this is not a perfect fit, it is extremely doubtful that any set of acoustic or aerodynamic measurements could ever correlate with a phonological feature to a degree that is significantly higher than that of intensity and sonority. In the interface between linguistic theory and data, no phenomenon discovered so far has "behaved" much better than this. This is especially true when dealing with aspects of neuromotor implementation that must vary in slight but insignificant ways across speakers, genders, and languages simply because we all have different bodies. In other words, we can

now be confident that the sonority scales we have been using ((4.9) and (4.11)) are in fact phonetically motivated in a very straightforward way because they are highly correlated with a single acoustic measure (intensity).

I now return to the English male intensity data (table 5.13) to make a few summary observations. This time I will not depict the correlation with a visual figure since this would be very similar to that of Spanish. In table 5.13 the absolute value of voiceless fricatives is higher than that of voiced stops plus /ǰ/ (unlike Spanish), but in English this contrast is not significant. Next we see that the mean value for [ʔ] is not distinct from that of the voiceless fricatives. This is not a concern since we have no reason to worry about keeping these groups separate in the first place. Similarly, the lack of contrast between /h/ and /v ð z ž/ is of no consequence. The fact that English /h/ is higher in the intensity scale than its Spanish counterpart is probably because Spanish /h/ is derived from /x/ (a velar fricative), at least historically, and, in many dialects, synchronically as well. Consequently, we would expect /h/ to pattern like an obstruent in Spanish, but not necessarily in English. In other words, the intensity value (and relative ranking) for /h/ may be more typical of a true glottal fricative (and/or a voiceless vowel) in English than in Spanish. In English, [ʔ] clearly falls among the obstruents, but /h/ only marginally does so since it lies between the voiced fricatives and the nasals. Nevertheless, /h/ is statistically distinct from /m n/ but not from /v ð z ž/. All of these facts suggest that it is probably most appropriate to classify English /h/ as an obstruent, at least insofar as intensity is concerned. This conclusion is further confirmed by the fact that for the English females (table 4.6), the intensity of /h/ is more firmly entrenched among the obstruents than it is for the males. We will return to this issue in §5.5. Moving up the scale in table 5.13, we find that for English males, /l/, /r/, and /y w/ are not distinguishable, although the trend in their absolute values does follow the predictions of the sonority hierarchy. Finally, the three vowel height natural classes (excluding [ə]) are completely reversed in terms of the sonority hierarchy, as noted in §4.3.1.2. However, this problem is mitigated somewhat by the fact that the high and mid vowels are not statistically distinct.

At this point a useful application would be to plot linear regression equations for the intensity data from each of the four groups of speakers. These formulas can then be used to further compare the intensity results and approximate a very precise definition of sonority. When the sonority indices assumed thus far are regressed with the mean intensity values for natural classes reported in chapter 4 (vowels plus onset consonants combined), the results are as follows:

Table 5.14: Coefficients of linear regression analyses on the intensity data of chapter 4 (for natural class values)

group	intercept	slope	r^2	p
English males	6.61	.39	.95	.0000
English females	6.60	.37	.93	.0000
Spanish males	5.14	.35	.94	.0000
Spanish females	5.16	.37	.97	.0000

In table 5.14 the two intercepts within each language are remarkably similar. A generalization is that the English subjects spoke about 1.5 dB louder than their Spanish counterparts. There is also remarkable similarity among the slopes, which range between .35 and .39 only. Consequently, not only can we conclude that sonority and intensity are very highly correlated, but we can now go one step further and also specify the exact nature of the relationship between them: for every dB by which intensity is increased, the corresponding sonority rank or index increases by about .37 units (the mean slope from table 5.14). Another way of stating this same fact is that there is an average difference of about 2.7 dB's worth of intensity between successive ranks on the sonority scale ($2.7 = 1 \div .37$). This of course assumes that the steps or intervals between natural classes on the sonority hierarchy are all of the same size. This issue arose in §3.2.5.6 and 3.3, where I argued that there is no need for overly precise sonority indices since these do not benefit actual phonological analyses in any tangible way. As I foreshadowed in those sections, I could very easily apply the regression equations from table 5.14 to my intensity data and "tweak" the sonority indices so that there would then be a perfect fit (i.e., r^2 would equal 1.0). However, there is no advantage I can see in such added precision, and the resulting indices would also be subject to the problem of changing from one phonetic sample of data to the next. Consequently, I continue to maintain that sonority indices are expressed in whole integers only, i.e., the entire scale is quantal.

Having established this point, I now digress and note that if we did wish to pursue the hypothesis that not all sonority distances are equal, my intensity data could be straightforwardly adapted for this purpose. What makes this exercise possible is the fact that the intensity values for natural class means follow the sonority hierarchy with so little discrepancy. For example, let us take the Spanish female values from table 5.12 and calculate the differences in dB between each successive pair of classes:

Table 5.15: Differences in intensity values between adjacent natural classes for Spanish females (in dB), based on table 5.12

i u	
	3.16 dB
w	
	1.79
l	
	2.71
ř	
	3.41
r̄	
	3.42
m n ñ	
	2.12
β ð γ	
	1.41
b d g	
	6.67
f s	
	1.37
p t k č	

In adapting table 5.15 from table 5.12, I have dropped out the data for the mid vowels and /a/ since these constitute a sonority reversal in this case. Similarly, I have not included the values for /h/ and /ĵ/ since these two segments do not pattern with any predetermined natural classes (in this set of data). While the absolute intensity values for a list of segmental classes will always vary from sample to sample, we can nevertheless expect that the proportional ratios between them might remain more or less stable. To the extent that this is true, the technique illustrated in table 5.15 allows us to make some reasonable generalizations. To begin with I note that the difference in dB between voiceless stops and voiceless fricatives (1.37) is the smallest of this table. Conversely, the difference between voiceless fricatives and voiced stops (6.67) is the largest in this data set. What these facts indicate is that in absolute physical terms, there are some significant discontinuities in the phonetic scale which mirrors the phonological sonority hierarchy. This finding confirms a prediction observed in one of the quotes from Selkirk (1984) in §3.2.5.6. The remaining intensity differences in table 5.15 average somewhere between 2-3 dB. We can also observe that among the sonorant consonants, the smallest interval is that between /w/ and /l/ (1.79 dB). Furthermore, the gap between /r̆/ and /r̄/ (3.41 dB) is almost exactly the same as that between /r̄/ and the nasals (3.42 dB). Nevertheless, as I have concluded on previous occasions in this dissertation, it remains to be demonstrated how this degree of precision can be exploited to give us a better model of phonology.

To summarize this section, we have established that sonority is best characterized as a function of intensity. Furthermore, we have seen that it is possible to specify in rather concrete terms exactly what type of function this is. Any one of the regression equations encapsulated in table 5.14 could now be used as an approximate definition of the substance of sonority. For example, for the Spanish-speaking females we could posit the following equation:

(5.1) $$\boxed{sonority = 5.16 + .37 \times dB}$$

However, it must be emphasized that nothing crucially can depend on the exact values of these regression coefficients; they are for expository purposes only and must be considered somewhat tentative since they are sample-specific. There is certainly nothing universal about the intercept value in particular since it strongly depends on the nature of the segment used for comparing intensity measurements (a nasal in this case). On the other hand, having calculated an average slope of .37, we can now claim that we are getting very close to a cross-linguistic statement of the relationship between sonority and intensity. This is because this value derives from an exhaustive study of all phonemes as pronounced by both genders in two different languages. Consequently, a formula like (5.1) could now potentially be used to predict the relative sonority index for certain ambiguous segments, such as /h/, once we have produced an intensity measurement for them. For example, for the Spanish females in table 5.12, /h/ has a mean intensity value of –8.17 dB. When this number is plugged into equation (5.1), the predicted sonority index is 2.14. Consequently, we have empirically established that the most appropriate sonority rank for Spanish /h/ is *2*, i.e., it patterns as a voiceless fricative (at least for the females).

In conclusion, compared with virtually all previous accounts of sonority, the "definition" in (5.1) has the following advantages: (1) it is less arbitrary,

(2) it is completely grounded in a phonetic parameter shared by all humans, (3) it is based on measurements which can be empirically verified and replicated, (4) it has been shown to be relatively stable across speakers, genders, and languages, and (5) it is theory-neutral. We have therefore made great progress in our effort to quantify sonority. Later in this chapter, after we reconsider a number of segments and classes whose relative sonority rank is disputable, we will be in a position to combine the Spanish and English results into one exhaustive and universal sonority hierarchy.

5.4 Further confirmation of the sonority hierarchy

In this section I briefly review two other sets of data from chapter 4 which provide additional evidence for the physical reality of sonority. In this case we will examine two parameters which are correlated with sonority in a negative direction: P_o and U_t. Below I highlight one hierarchy from each of these areas — the sets of results which parallel relative sonority rankings to the greatest extent, i.e., with fewest reversals. My ultimate goal is to arrive at an idealized sonority hierarchy derived from all of these findings as a whole.

Table 5.16: Summary of pressure data for English females (in cm H_2O) with consonants in onset position (from tables 4.26 and 4.30)

segments	sonority index	mean
æ a	12	.88
e ɛ ʌ o ɔ ə	11	.94
i ɪ u ʊ	10	1.11
l	6	1.22
r	7	1.27
y w	8	1.29
m n	5	1.37
v ð z ž	4	4.16
b d g	3	5.75
f θ s š	2	5.82
p t k	1	6.00

$r = -.86$

Table 5.17: Summary of air flow data for English males (in ml/sec) with consonants in onset position (from tables 4.67 and 4.71)

segments	sonority index	mean
y w	8	222.2
l	6	247.2
r	7	261.1
m n	5	341.7
e ɛ ʌ o ɔ ə	11	358.3
æ a	12	361.1
i ɪ u ʊ	10	405.6
v ð z ž ǰ	4	547.2
b d g	3	680.6
f θ s š	2	738.9
p t k	1	1325.0

$r = -.69$

For tables 5.16 and 5.17 I will not contrast all adjacent pairs of mean values since no further phonological applications will be based on these results. Thus the comments I make here reflect only the trends in the data without implying that all of them are necessarily significant. Furthermore, to simplify matters I have left out most instances of the segments /č/, /ǰ/, /h/, and [ʔ] in these two summary tables. The English female P_o values (table 5.16) follow the sonority hierarchy quite well and thus have a relatively strong overall correlation ($r = -.86, p = .0007$). (This increases slightly to −.87 when [ə] is correlated with its own separate sonority index rather than grouped with the other mid vowels.) In this case even the vowel natural classes pattern exactly as desired, as do all the obstruents and the nasals. The only sonority reversals involve the liquids: /l/ and /r/ are "backwards" (although this particular contrast is not statistically significant; see table 5.25) and they also have lower pressure than the glides. Except for this one detail the hierarchy matches the sonority scale exactly. Furthermore, we can categorically state without exception that all obstruents have higher mean P_o values than all sonorant consonants, and all sonorant consonants are higher than all vowels. Consequently, these results are potentially as promising as those of intensity in many important aspects. I conclude that table 5.16 strongly confirms the physical reality of the sonority hierarchy by providing empirical data from a realm other than intensity whose correlation with sonority consistently runs in a negative direction. Nevertheless, the overall correlation between sonority and P_o across all data sets was demonstrated to be less robust than that of intensity, so I will not use this table to pursue an exact definition of sonority. However, it should be clear from the previous section that this could easily be done and that it would also yield equally nice, analogous results.

The English male U_t data in table 5.17 also show a fairly good fit with the sonority hierarchy. The glaring mismatch is that vowels fall between obstruents and sonorant consonants. Furthermore, within the vowels the low and mid classes are reversed. However, the glides are now (correctly) lowest of all consonants (outranking the liquids in this case), even though /l/ and /r/ themselves are still inverted (but not significantly so; cf. table 5.25). The overall correlation for this set of data is moderately strong ($r = -.69$, $p = .0179$) and is clearly pulled down the most by the fact that the vowel means are interspersed among those of the consonants. This is a strong and consistent trend among all of the U_t data sets and even holds true for most of the P_o results as well, except for table 5.16. Nevertheless, if we were to calculate correlations with sonority for vowels and consonants separately, the fit of table 5.17 would significantly improve. Consequently, I have included it here as an example of a third phonetic parameter which matches the sonority hierarchy reasonably well.

The conclusion to be drawn from this section and the previous one is that the phonological feature *sonority* exhibits strong phonetic correlates in more than one physical domain. Intensity is still the "winner" since it follows the sonority hierarchy most closely overall, but P_o is not far behind. Similarly, U_t provides additional confirmation that sonority is linguistically real. Intensity is the best correlate discovered to date since all of the vowel measurements are clearly separated from those of the consonants, i.e., the scale increases monotonically across these two major classes. However, within the vowels themselves, the natural class rankings corresponding to the P_o and U_t results sometimes do better than those of intensity. This overlap is not a problem for my approach to characterizing sonority; on the contrary, it is somewhat of an advantage since it demonstrates that, like most other phonological features, sonority has multiple physical manifestations which can be recovered from the actual speech signal itself. This is a very satisfying outcome because it shows that we can rely on the convergence of more than one phonetic parameter to give us a better idea of what the universal sonority hierarchy looks like. This topic will be the focus of the remainder of this chapter.

5.5 On the relative sonority of glottal consonants revisited

In the next five sections of this chapter I return to several of the segments and classes whose relative sonority rank is debatable, as indicated originally in chapter 3. We can now re-examine these issues in light of the experimental findings of chapter 4. We will successively consider /h/ and /ʔ/ (in this section), then voiceless fricatives vs. voiced stops, affricates, liquids, and [ə]. In all cases we will give the most weight to the relative ranking of these segments in terms of ***intensity*** since this parameter is the best overall indicator of sonority. Nevertheless, I will also comment on the results of the other four instrumental measures to confirm and further elucidate the patterns when appropriate.

The following table summarizes the behavior of /h/ in the experimental results of chapter 4. Cells containing the notation "= f s" indicate that, for that category, /h/ is statistically indistinct from the (language-specific) set of voiceless fricatives. Otherwise I report whether /h/ groups primarily with the obstruents (*O*) or with the sonorant consonants (*S*). A long dash (—) in a cell means that /h/ does not occur in the data corresponding to that category, e.g., coda position in English words.

Table 5.18: Summary of the relative sonority of /h/

		onset position		coda position	
		males	females	males	females
intensity	English	O	O	—	—
	Spanish	O	O	O	= s
pressure	English	S/O	S/O	—	—
	Spanish	S/O	S/O	O	O
F_1	English	S	S	—	—
	Spanish	S	S	—	—
flow	English	O	O	—	—
	Spanish	= f s	O	O	= f s
duration	English	O	O	—	—
	Spanish	O	= f s	= f s	= f s

In table 5.18 we see that /h/ invariably patterns as an obstruent in terms of intensity, U_t, and duration. The notation "S/O" for P_o cells in onset position signifies that in these four data sets, the value for /h/ falls between that of sonorant consonants and obstruents, but is somewhat closer to the former. Only in the case of F_1 measurements does /h/ invariably fall more towards the end of the scale that is most typical of sonorants (a relatively high F_1 value). An explanation for this is that during the articulation of /h/, there is no physiological incentive for the mouth to be more closed than it is for adjacent vowels. In 6 of the cells (all of them corresponding to Spanish speakers) /h/ groups statistically with /f s/. In 14 other cases, on the other hand, /h/ is unambiguously an obstruent yet distinct from the other voiceless fricatives. All of these facts lead to the conclusion that phonetically speaking, /h/ is best classified as an obstruent rather than a sonorant, but should not necessarily be lumped together with /f θ s š/. Furthermore, as noted in §5.3, English /h/

probably yields values which are more indicative of a true glottal consonant than its Spanish counterpart.

Table 5.19: Summary of the relative sonority of [ʔ] in English

	onset position	
	males	females
intensity	O	O
pressure	S	S
flow	S	S
duration	S	S

As table 5.19 shows, the [ʔ] in the English words *uh-oh* and *Latin* expectedly patterns as an obstruent in terms of intensity since it is a very weak sound. Nevertheless, for the other three parameters [ʔ] behaves as the most sonorous of all segments (no F_1 measurements of [ʔ] were made). Given this very contradictory situation, I will refrain from taking a firm stance with respect to where /ʔ/ should be placed in the universal sonority hierarchy. This is especially appropriate since [ʔ] is not a true consonant phoneme of English. In keeping with this fact, it is noteworthy that [ʔ] never groups with the genuine voiceless stops /p t k/ in any of my data sets. To resolve this issue more conclusively it would be best to study a language in which /ʔ/ is fully contrastive and productive. In summary, the patterns reviewed in this section help explain why the phonological behavior of laryngeal consonants is so variable across languages: their aerodynamic characteristics are quite mixed. Both of them have traits in common with obstruents and sonorants, unlike most other consonants which are clearly one or the other. In other words, a mixed which are clearly one or the other. In other words, a mixed physical signal leads to ambiguity in terms of the phonological classification of these segments.

5.6 On the relative sonority of voiceless fricatives vs. voiced stops revisited

In this section I reconsider the relative sonority of voiceless fricatives (as a natural class) vs. voiced stops, returning to the issue raised in §3.2.5.2. Recall that the phonological evidence for their ranking is scant and not entirely conclusive. The following chart highlights the overall results in my data:

Table 5.20: Summary of the relative sonority of voiceless fricatives vs. voiced stops

		onset position		coda position	
		males	females	males	females
intensity	English	bdgǰ = fθsš	bdgǰ > fθsš	bgǰ > fθsš	bgǰ > fθsš
	Spanish	bdg > fs	bdg > fsč	—	—
pressure	English	bdg > fθsšč	bdg = fθsš	bg > fθsš	bg > fθsš
	Spanish	bdg > fs	bdg > fs	—	—
F_1	English	fθsšč > bdg	fθsš > bdg	fθsšč > bdg	fθsšč > bdg
	Spanish	fs > bdg	fs > bdg	—	—
flow	English	bdg > fθsš	bdg > fθsš	bdgǰ > fθsš	bgǰ > fθsš
	Spanish	bdg > fsh	bdgǰ > fs	—	—
duration	English	bdg > fθsš	bdg > fθsš	bg > fθsš	bg > fθsš
	Spanish	bdg > fsč	bdg > fsh	—	—

In the table above the class of segments to the left of an arrow patterns as significantly more "sonorous" than the group to the right of the same arrow. For example, for the English female speakers, the intensity of /b d g ǰ/ as a group in onset position is greater than that of /f θ s š/ in the same data set. Since table 5.20 is rather hard to read when skimming for overall trends, the following chart presents the same information in a simplified format:

(5.2) Legend for table 5.21

stop = voiced stops (plus /ǰ/, when appropriate) fall more towards the high sonority end of the scale than voiceless fricatives (plus /č/ or /h/, when appropriate)

fric = voiceless fricatives fall more towards the high sonority end of the scale than voiced stops

equal = the difference in mean values between voiceless fricatives and voiced stops is not significant

Table 5.21: Summary of the relative sonority of voiceless fricatives vs. voiced stops, simplified from table 5.20

		onset position		coda position	
		males	females	males	females
intensity	English	equal	stop	stop	stop
	Spanish	stop	stop	—	—
pressure	English	stop	equal	stop	stop
	Spanish	stop	stop	—	—
F_1	English	fric	fric	fric	fric
	Spanish	fric	fric	—	—
flow	English	stop	stop	stop	stop
	Spanish	stop	stop	—	—
duration	English	stop	stop	stop	stop
	Spanish	stop	stop	—	—

In tables 5.20 and 5.21, only two contrasts fail to attain significance. Setting these cells aside, there are two very strong trends in the tables: (1) in terms of F_1, voiceless fricatives consistently pattern as more sonorous than voiced stops, and (2) for the other four phonetic parameters, voiced stops always outrank voiceless fricatives on the respective sonority scales. The "anomalous" F_1 results may be due to the effects of voicing, as discussed in §4.3.3. (For this reason F_1 is a relatively poor indicator of sonority among consonants, or at least among obstruents.) The most logical conclusion, i.e., the one which accords with the majority of the instrumental data, is that, based on the phonetic evidence alone, voiced stops pattern as higher in sonority than voiceless fricatives. However, in chapters 1 and 3 we reviewed phonological data indicating that in some languages, voiceless fricatives need to outrank voiced stops. Consequently, I will ultimately conclude that the sonority rank between these two natural classes is not universally fixed. Nevertheless, we can at least posit that the ranking *voiced stops > voiceless fricatives* is the most likely default cross-linguistically.

5.7 On the relative sonority of affricates revisited

In this section I summarize the statistical results of chapter 4 with respect to affricates. This topic was originally examined in §3.2.5.3. The following table summarizes the data concerning /č/:

Table 5.22: Summary of the relative sonority of /č/

		onset position		coda position	
		males	females	males	females
intensity	English	= ptk	= ptk	= pk	= pk
	Spanish	= ptk	= ptk, = fs	—	—
pressure	English	= fθsš	< ptk	= pk	< pk
	Spanish	< ptk	< ptk	—	—
F_1	English	= fθsš	< ptk	= ptk, = fθsš	= fθsš
	Spanish	< ptk	= ptk	—	—
flow	English	> ptk	= ptk	= pk	= pk
	Spanish	< ptk	< ptk	—	—
duration	English	< ptk	< ptk	< pk	< pk
	Spanish	= fs	< ptk	—	—

In table 5.22, /č/ patterns as statistically indistinct from the voiceless stops in 12 cases (= *ptk*); it is less "sonorous" than /p t k/ in 13 instances (symbolized by " < "); it is higher in sonority than voiceless stops in one data set; and it is equivalent to voiceless fricatives in 6 cells. These results suggest that /č/ should be classified as either equivalent in sonority to, or less sonorous than, canonical voiceless stops. (The " < " result has a very slight edge.) In this case we will decide in accordance with the intensity data, in which /č/ is consistently equivalent to /p t k/. (This is expected since /č/ is partially composed of a phone similar to [t], which should logically be as weak in intensity as any other voiceless plosive.) Consequently, with respect to the universal sonority hierarchy, I posit that voiceless affricates should be grouped together with stops. A phonological phenomenon of English which supports this conclusion is the fact that /č/ is allophonically aspirated in exactly the same environments as /p t k/.

I now present the analogous data for /ǰ/:

Table 5.23: Summary of the relative sonority of /ǰ/

		onset position		coda position	
		males	females	males	females
intensity	English	= bdg	= bdg	= bg	= bg
	Spanish	< bdg	< bdg	—	—
pressure	English	< bdg	< bdg	< bg	< bg
	Spanish	< bdg	< bdg	—	—
F_1	English	= vðz	< bdg	< bdg	= vðz
	Spanish	< bdg	< bdg	—	—
flow	English	= vðzž	> bdg	= bdg	= bdg
	Spanish	> bdg	= bdg	—	—
duration	English	< bdg	< bdg	< bg	< bg
	Spanish	= βðγ	= βðγ	—	—

In table 5.23, /ǰ/ patterns as a voiced stop 7 times, as lower in sonority than /b d g/ 16 times, as more sonorous than voiced stops twice, and as a voiced fricative in 5 cases. Unlike /č/, the overall phonetic evidence for /ǰ/ favors its classification as less sonorous than /b d g/. In this case even the intensity results are divided (across languages). For /č/ there is no problem even if it does pattern as lower in sonority than voiceless stops, since there are no other sounds that low on the scale for it to compete against. With /ǰ/, however, this is not the case. The fact that it patterns as lower in sonority than /b d g/ in so many data sets (16) suggests that it may potentially conflict with the voiceless fricatives. Consequently, for these 16 cells (and only these) I explicitly compare /ǰ/ with the language-specific set of voiceless fricatives as well. The results are as follows:

Table 5.24: Statistical comparisons of /ǰ/ vs. voiceless fricatives

		onset position		coda position	
		males	females	males	females
intensity	English				
	Spanish	ǰ > fs	ǰ > fsč		
pressure	English	ǰ > fθsšč	fθsš > ǰ	ǰ = fθsš	fθsš > ǰ
	Spanish	ǰ = fs	ǰ > fs		
F_1	English		fθsš > ǰ	fθsšč > ǰ	
	Spanish	fs > ǰ	fs > ǰ		
flow	English				
	Spanish				
duration	English	ǰ > fθsš	ǰ > fθsš	ǰ > fθsš	ǰ > fθsš
	Spanish				

In table 5.24, /ǰ/ patterns as more sonorous than the class of voiceless fricatives on 8 occasions. In 6 other cases it is less sonorous than they are, and it ties with them twice. (I did not test the remaining data sets since /ǰ/ is clearly distinct from the voiceless fricatives there.) Overall, then, it is reasonable to conclude that /ǰ/ can probably be separated from voiceless fricatives on the phonetic sonority scale. (Their contrast in voicing further confirms this.) This would place /ǰ/ just below voiced stops and just above voiceless fricatives. However, since /ǰ/ is equivalent to the voiced stops in all four English intensity data sets, and since /č/ was counted as a voiceless stop above, the conclusion which is most consistent for affricates as a whole is to place /ǰ/ together with /b d g/ on the ***phonological*** sonority scale. That is, I will eventually argue that the sonority hierarchy needed for actual phonological analyses may differ in minor yet principled ways from the scale which emerges from my phonetic results.

This claim and its ramifications will be fully fleshed out in §5.10 at the end of this chapter.

5.8 On the relative sonority of liquids

In this section I consider how liquids pattern in terms of the results of chapter 4. We might expect the relative sonority of these segments to differ between Spanish and English since their phonetic qualities are rather distinct. This in fact will be the case.

Table 5.25: Summary of the relative sonority of liquids in English

	onset position		coda position	
	males	females	males	females
intensity	r = l	r = l	r = l	r = l
pressure	r = l	r = l	r = l	r = l
F_1	l > r	l > r	l > r	l > r
flow	r = l	l > r	r = l	r = l
duration	r > l	r > l	r = l	r = l

In English, /r/ and /l/ are statistically equivalent in 13 out of 20 comparisons (65%). In 2 instances /r/ patterns as more "sonorous" than /l/, while the reverse is true 5 times, 4 of which are in terms of F_1. It is noteworthy that for the two strongest correlates of sonority (intensity and P_o), /r/ and /l/ are indistinct all 8 times. Consequently, I conclude that the overall results of my acoustic and aerodynamic experiment do not confirm a reliable separation between /r/ and /l/ in English. We can therefore posit that they have the same ranking in the phonetic sonority hierarchy (which I will discuss further at the end of this chapter). This claim is of course based on the physical data alone. In

§3.2.5.9 I presented several pieces of phonological evidence from English indicating that /r/ is more sonorous than /l/. Consequently, I will eventually argue that it is appropriate to separate these two segments in the phonological sonority hierarchy. However, I know of no other language having an /r/ which is articulatorily identical to that of English (a rounded retroflexed rhotic approximant), so additional (cross-linguistic) evidence for the relative sonority of this segment unfortunately does not seem to exist.

Table 5.26: Summary of the relative sonority of liquids in Spanish

	onset position		coda position	
	males	females	males	females
intensity	l > ř > r̄	l > ř > r̄	l = ř	l > ř
pressure	l = ř > r̄	l = ř > r̄	l > ř	l > ř
F_1	l = ř > r̄	l > ř > r̄	l = ř	ř > l
flow	l > ř > r̄	l > ř = r̄	l > ř	l > ř
duration	ř > l > r̄	ř > l > r̄	l = ř	l = ř

The phonetic data on the three Spanish liquids in table 5.26 distinguish between them much more conclusively than those of English. Specifically, /l/ patterns as more sonorous than the flap /ř/ 10 times, as equivalent 7 times, and as less sonorous in 3 cases. The flap /ř/ in turn outranks the trill /r̄/ 9 times and ties with it only once. There is not a single instance in which the mean value for /r̄/ is significantly more "sonorous" than that of /ř/. I therefore posit that these three natural classes are universally ranked in the order *laterals* > *flaps* > *trills* within the sonority hierarchy (both phonetically and phonologically). This claim is strongly substantiated by the Spanish intensity results in particular.

Furthermore, this finding retroactively confirms the tentative scale I initially posited in (4.11) for calculating correlations between sonority indices and the Spanish instrumental data.

5.9 On the relative sonority of [ə]

In this section I examine the physical data relevant to the vowel [ə] in English. In particular, we are interested in whether or not it patterns statistically with the five non-reduced mid vowel phonemes /e ɛ ʌ o ɔ/. The following chart summarizes the results:

Table 5.27: Summary of the relative sonority of [ə] in English

	males	females
intensity	< mid	< mid
pressure	> mid	= mid
flow	= mid	= mid
duration	< mid	< mid

Unfortunately, I did not include tokens of [ə] in the word list used to elicit F_1 data, but previous studies have shown that [ə] has an F_1 value comparable to that of other mid vowels. For both intensity and duration, [ə] patterns as the least "sonorous" of all English vowels. With respect to the U_t and female P_o data it behaves like a normal mid vowel. Given the strong intensity and duration findings, it is justifiable to treat [ə] as less sonorous than all other vowels, even the high ones. I will therefore make use of the vowel sonority hierarchy from (1.9) posited by Bianco (1996), Kenstowicz (1996), and de Lacy (1997, 2002). However, it must be borne in mind that the intensity and duration measurements of [ə] are obviously affected to a large degree by the fact that in English this vowel occurs only in unstressed (reduced) syllables. That is, [ə] is the product of reducing full vowels in unstressed positions. Because of this (the allophonic status of [ə] in English), my conclusions about its relative sonority are only tentatively confirmed by my phonetic results. Ideally it would be best to have unbiased data on [ə] from a language in which it is not limited to stressless positions, in order to resolve this issue more conclusively. It is possible that there are really two kinds of [ə]: a brief mid central vowel like that occurring in English, and a full length mid central variety which occurs wherever any other vowel can (in other languages).

5.10 A universal sonority hierarchy

In this section I bring together the results of all the statistical analyses presented throughout this chapter in order to posit a unified and inclusive sonority scale. Let us begin with what we have been able to deduce from the phonetic data alone (later I will discuss the phonological evidence as well). Based on the conclusions above (drawing on the convergence of the five acoustic and aerodynamic measures), the hierarchy which is most consistent with the overall picture given by the phonetic results is the following:

(5.3) Universal sonority hierarchy (preliminary, phonetic version)

low vowels
mid vowels
high vowels
  /ə/
glides
laterals and /r/
flaps
trills
nasals
  /h/
voiced fricatives
voiced stops
  /j̆/
voiceless fricatives
voiceless stops and affricates

Several details of the scale in (5.3) need clarification. First, the separation of all vowels except [ə] into one of three natural classes based on height is motivated primarily by the F_1 and duration results. As we saw in §4.3.3, high vowels as a group have the lowest overall F_1 values, then mid vowels, and low vowels exhibit the highest F_1 values. Similarly, high vowels are shortest in duration, and low vowels are the longest. With respect to these two parameters (F_1 and duration), my results are entirely consistent with each other and also with many other previous studies (Ladefoged 1962, 1993; Kent and Read 1992; Stevens 1998). However, as we saw in §4.3.1, this particular subset of the ranking (*low vowels > mid > high*) is not as neatly confirmed by the intensity data as I would have liked. This again raises the issue of whether the phonetic realization of sonority is different in vowels and consonants. I would like to claim that it is not; hopefully future research will help resolve this problem.

Moving on, the classification of [ə] as the least sonorous of all vowels was established by the results of intensity and duration in §5.9 (it is relatively soft and short). Concerning liquids, I was forced to conclude from my overall findings that English /r/ and /l/ were not separated phonetically. (Perhaps there is some other physical parameter which distinguishes them better than my five measures could.) Next, the relative position of /h/ in (5.3) is tentative since it is based mainly on just one data set: English male (onset) intensities (table 5.13). (Recall that for English female intensities (table 4.6), /h/ falls between the voiced fricatives and the voiced stops.) Given the discussion in §5.5, all that I would venture to claim categorically about /h/ is that it is probably best to consider it an obstruent of some kind. Nevertheless, placing it right below the nasals may help account for why it often behaves as a sonorant (cf. chapter 6). Finally, among the obstruents, the overall convergence of the statistical results motivates the default ranking *voiced stops > voiceless fricatives*, and /ǰ/ falls between these two groups phonetically speaking (§5.7).

The preceding paragraph summarizes the relative placement of speech sounds in the universal sonority hierarchy insofar as we can establish this based on my phonetic data only. At this point we should now ask ourselves, what does the phonological evidence tell us? Given the nature of the interface between phonetics and phonology, it would not be surprising if the scales given to us by the two domains were slightly different (cf. Clements 1990:291; de Lacy

1997:128). At the same time this would not be a major setback for my model of sonority since the mapping from abstract phonological intentions to motor implementations is somewhat gradient and blurred for other categorical distinctive features as well (i.e., phonological contrasts and features are rarely phonetically invariant). Consequently, in order to arrive at a phonological hierarchy suitable for capturing all sonority-based generalizations (cf. chapter 1), it would be appropriate to make a few modifications to the phonetic scale from (5.3) so as to produce the most efficient sonority hierarchy possible. As we will see, the four adjustments I argue for are all logical and principled.

First, we should add the segment /ɨ/ as the least sonorous of all vowels. This is based on the phonological evidence from the weight and stress hierarchies reviewed in §1.2.5 (primarily the facts of Kobon stress). This move obviously does not contradict any of my phonetic data since I did not elicit any tokens of /ɨ/. Consequently, this is simply an addition to the phonetic scale which does not change any of the pre-established rankings in any way.

Second, the phonological evidence outlined in §3.2.5.9 requires that we rank English /r/ above /l/ in the sonority hierarchy (see that section for four concrete arguments). In separating /r/ from /l/ in terms of sonority we are adding a rank that the phonetic data do not directly support. However, there is ample phonological motivation for this and it does not contravene the phonetic results; these were simply inconclusive in establishing this distinction.

Third, based on the discussion in §5.7, it would be judicious to make /ǰ/ equivalent to the voiced stops in the phonological sonority hierarchy. The co-ranking of /č/ and the voiceless stops establishes a precedent for this adjustment (pattern congruity), and once again we are not reversing any phonetic ranks but only collapsing two of them together.

Finally, as I have argued in §3.2.5.2, 5.6, and elsewhere, the ranking between voiced stops and voiceless fricatives is not fixed. In §3.2.5.2 I presented evidence from the operation of the SSP in Imdlawn Tashlhiyt Berber that in this language, voiceless fricatives pattern as more sonorous than voiced stops. Also, as I will demonstrate in the next chapter, results of a psycholinguistic experiment on reduplicative rhyming forms motivate the ranking /f θ s š/ > /b d g ǰ/ for English as well. It is beyond the scope of this dissertation to illustrate how the effect of permuting these two natural classes can be formally achieved in a language-specific OT grammar. However, I refer the reader to de Lacy (2002) for a cogent discussion of this issue, as well as other matters related to phonological scales such as the sonority hierarchy. I do reiterate, nevertheless, that my phonetic results in §5.6 above suggest that voiced stops are probably higher in sonority than voiceless fricatives in the unmarked case, all else being equal.

I have just proposed four modifications to the phonetic sonority scale from (5.3), for phonological reasons. All of these are logical and restrictive in that they are limited to segments and/or natural classes which are immediately adjacent in the hierarchy. The final, comprehensive sonority scale which we ultimately derive is thus the following:

Table 5.28: Universal sonority hierarchy
(final, exhaustive, phonological version)

low vowels	16
mid vowels (except /ə/)	15
high vowels (except /ɨ/)	14
/ə/	13
/ɨ/	12
glides	11
/r/	10
laterals	9
flaps	8
trills	7
nasals	6
/h/	5
voiced fricatives	4
voiced stops and affricates / voiceless fricatives	3
voiceless fricatives / voiced stops and affricates	2
voiceless stops and affricates	1

My claim is that the phonological sonority scale in table 5.28 is universal: it forms part of UG, and the constraints in CON can and do access its rankings, and perhaps its indices as well. Probably no language invokes the distinction between all 16 of these sonority classes, but they are always potentially available. Furthermore, there are no other natural class divisions in the sonority hierarchy, with the possible exception of more exotic types of segments such as ejectives, clicks, etc., about which I have nothing else to say. Most languages in fact conflate the scale in the sense that they do not systematically exploit all 16 intervals. This is because they either lack the respective phoneme(s) entirely, or else they collapse together two or more adjacent ranks and thus do not distinguish them in terms of their phonological processes (see de Lacy 2002 for a formal account of this type of situation).

There are three large natural classes which can be compressed in this way: vowels, liquids, and obstruents. If a particular language (such as Spanish, for example) chooses not to differentiate between any of the segments within these three groups (in terms of sonority), it is in effect utilizing the minimal hierarchy V > G > L > N > O discussed in §3.2.5 (Baertsch 1998). However, no language may permute (reverse) any of the 16 classes in table 5.28, except for voiced stops and voiceless fricatives. (I also concede that /h/ might fit better somewhere else in the scale.) In this sense the rankings are universally fixed, so apparent counterexamples are just that: apparent. Such exceptions must be explained by some other mechanism (constraint) which probably has nothing to do with sonority at all.

I now move on to highlight the virtues of the universal sonority hierarchy in table 5.28. Compared with nearly all other scales proposed in the literature, this one is the most complete in that it encompasses the largest number of different types of segments and natural classes. In particular, we have made progress by establishing the most likely sonority rank of flaps, trills, affricates, and /h/. Most treatments of sonority avoid these segments because of their inherent difficulty and controversy. Next, my scale is based on extensive, systematic acoustic and aerodynamic data from both genders in two languages. Consequently, it is thoroughly grounded in the physical properties of the speech signal. (This is mainly true of the phonetic scale, but by transitivity this argument extends to the phonological scale as well.) Finally, we are also now a step closer to being able to claim that this hierarchy truly is cross-linguistically valid.

5.11 Summary

This chapter has significantly advanced our understanding of what sonority is as well as the mathematical values which characterize it. We have tested the statistical reliability of five physical correlates of sonority and have found that intensity consistently gives us the most favorable results. Consequently, we have established that sonority can and should be defined as a function of intensity and, furthermore, we have been able to precisely quantify what this function is. In the face of this evidence, the claim that sonority lacks a reliable phonetic basis can no longer be maintained.

CHAPTER 6

A PSYCHOLINGUISTIC EXPERIMENT AND ITS RESULTS

6.1 Introduction

In this chapter I discuss a psycholinguistic experiment which I carried out using rhyming nonce forms in English. As mentioned briefly in §1.3.4, doublets such as *namby-pamby* tend to have a higher sonority onset consonant in their first half than in the second half. Using 99 contrived pairs of words, I tested this sonority hypothesis with 332 native speakers of English. The results strongly confirm the role of sonority in predicting the preferred order in such cases. Two alternative explanations (alphabetic order and lexical frequency) are also considered and shown to yield lower overall power in accounting for the observed statistical patterns.

The principal goal of this chapter therefore is to provide empirical data showing that the sonority hierarchy is psychologically real to native speakers of English. As a consequence of this finding, in my formal analysis of the *roly-poly* phenomenon at the end of the chapter, I will posit that a "low level" phonological constraint such as the Syllable Contact Law can actually affect the linear order of morphemes. The organization of the chapter is as follows. I first review previous literature on the topic and discuss the general phenomena, in §6.2. In §6.3 I then summarize two prior experiments very similar to my own and conclude that new input in this area would be welcome. In §6.4 I describe the design and methodology of my experiment. In §6.5 I present the results, analyze them, and discuss their theoretical significance. In §6.6 I consider and reject the two alternative hypotheses. Finally, in §6.7 I propose an OT account of the pattern analyzed throughout the chapter.

6.2 Background

A number of studies have examined codified expressions such as *salt and pepper*. A recurring question is, how and why the does order of the two elements get fixed in its most common form? That is, why do we naturally prefer to say *salt and pepper* rather than *pepper and salt*? My goal in this section is to briefly review the literature on this subject, focusing especially on the details most relevant to sonority.

Phrases such as *salt and pepper*, *roly-poly*, etc. are variously known as freezes, irreversible or formulaic binomials, rime pairs, binary phrases, frozen sequences, paired words, phraseological doublets, *and* phrases, rime combinations, set or frozen expressions, parallels, irreversible conjoined phrases, binomial coordinate compounds, and fixed reduplicatives. The elements which make them up are often called "kernels" or "conjuncts." A sample of the references on this subject includes Scott (1913), Morawski (1927), Bentley and Varon (1933), Newman (1933), Abraham (1950), Brown *et al.* (1955), Malkiel (1959, 1968), Bolinger (1962), Thun (1963), Marchand (1969), Brown (1970), Cooper and Ross (1975), Campbell and Anderson (1976), Drachman (1977), Pinker and Birdsong (1979), Cardona (1988), and Ourn and Haiman (2000). Several of these authors propose a series of "laws" to explain the tendencies observed in the order of the two conjuncts. These generalizations are rooted in both semantic and phonological factors. The most important of the semantic laws is summarized by Cooper and Ross (1975) as "Me First:" "First conjuncts refer to those factors which describe the prototypical speaker." (p. 67) These features are relevant, for example, in deictic references such as *here and there* (not **there and here*), *now and then*, etc., as well as in expressions dealing with age (*man and boy*), number (*singular and plural*), animacy (*people and things*), spatial orientation (*front and back*), etc. I will have little more to say about this semantic constraint. More relevant for our purposes are the phonological features which help predict the order of the two parts of frozen binomials. At least seven different phonological laws have been proposed in the literature. The following chart, adapted from Pinker and Birdsong (1979), summarizes the list of generalizations identified by Cooper and Ross (1975), where A = first conjunct and B = second conjunct:

Table 6.1: Phonological patterns in fixed expressions (from Cooper and Ross 1975 and Pinker and Birdsong 1979)

	law	*A* prefers	*B* prefers	examples
1	number of syllables	fewer σ's	more σ's	*salt and pepper* *male and female* *ladies and gentlemen* *vim and vigor* *rough and ready*
2	vowel length	shorter V's	longer V's	*stress and strain* *trick or treat*
3	number of initial C's	fewer C's	more C's	*itsy-bitsy* *harum-scarum* *fair and square*
4	sonority of initial C	more sonorous	less sonorous	*lovey-dovey* *mumble-jumble* *razzle-dazzle* *walkie-talkie* *willy-nilly*
5	F_2 of V (or backness)	higher F_2	lower F_2	*ding dong* *tic tac toe* *cats and dogs*
6	number of final C's	more C's	fewer C's	*betwixt and between* *wax and wane* *sink or swim*
7	sonority of final C	less sonorous	more sonorous	*rock 'n roll* *thick and thin* *kith and kin* *push and pull*

In the table above, the first law (number of vowels or syllables) and the third law (number of initial consonants) were originally formulated by Pāṇini since they tend to be obeyed in Sanskrit dvandva compounds (Cooper and Ross 1975, Pinker and Birdsong 1979, Cardona 1988). Most statistical studies confirm the productivity of these generalizations, at least in English. (They tend not to be followed in most other languages, so they must be learned rather than universally given.) For example, in Scott's (1913) list of 276 *and* phrases, 160

(58%) fulfill Pāṇini's first law and 116 (42%) do not. Similarly, in a psycholinguistic test carried out by Bolinger (1962) with nonfrozen examples such as *frank and candid statement* vs. *candid and frank statement*, 17 undergraduate students followed this law in preferring conjunct *A* to have fewer syllables than *B* 91% of the time (277 responses vs. 28). These facts concur with the hypothesis that the 7 phonological laws are ranked in relative strength or importance as listed in table 6.1 (Cooper and Ross 1975; Pinker and Birdsong 1979). That is, in the case of a conflict between two generalizations, a law higher in the table will tend to take precedence over a lower law. For example, in *bread and butter*, law 1 beats out law 3. This principle is obviously a predecessor of OT, and it predicts that the number of attested exceptions to any given law should be proportional to its rank in table 6.1. As far as I can determine, this does generally seem to be the case.

As noted by several authors, the overall effect of the 7 phonological tendencies can be summarized as a pressure to reduce or shorten the phonetic content of conjunct *A vis-à-vis* conjunct *B* (Malkiel 1959, 1968, Cooper and Ross 1975). Abraham (1950:282) calls this the "law of the increasing members." Campbell and Anderson (1976) and Pinker and Birdsong (1979) claim that it may perform the psychological function of aiding speech perception by reducing the strain of decoding at the beginning of prosodic units, similar to heavy NP shift. On the other hand, there may be a metrical explanation as well, at least for law 1: since the word *and* naturally tends to reduce and group prosodically with conjunct A, we end up with a nice, even, trochaic parse: */vim and vigor/* → *(vím'n)* *(vígor)* (Campbell and Anderson 1976). Marchand (1969) notes that rhyming expressions are found very far back in the history of the Indo-European family, and date from the 1300's in English. Consequently, diachronic evidence can be found in support of many of the laws. For example, the fourth law (sonority of the initial consonant) apparently motivated the change from *tag and rag* (16th-17th centuries) to *tagrag* and eventually to the modern form *ragtag* (Campbell and Anderson 1976). A few accounts suggest that sound symbolism also plays a role in these patterns. For example, Marchand (1969) describes their impressionistic effect as "playful," "facetious," "childish," "babyish," "sentimentalizing," and "appealing." Similarly, Campbell and Anderson (1976:76) state, "Together with the evidence on consonant patterning, this makes us suspect that nursery rhymes actually teach important parts of the sound system to young children, a system which they will use throughout the rest of their life."

At the same time, however, most authors freely acknowledge the existence of numerous (and at times very strong) counterexamples to all 7 of the phonological laws. Some of these can be explained by the pressure of a semantic factor outweighing a phonological one (Pinker and Birdsong 1979). For example, *fingers and toes* (**toes and fingers*) obeys an UP ⟩⟩ DOWN semantic preference at the expense of Pāṇini's (first) law (Cooper and Ross 1975). Other exceptions are attributed to ideophonic reasons. For example, it is very common for an initial labial consonant to be attracted to conjunct *B*, even if this leads to a violation of the 4th law, e.g., *nitwit*, *silly-willy*, *teenie-weenie* (Marchand

1969, Cooper and Ross 1975, Campbell and Anderson 1976, Drachman 1977). It is in fact possible to test the statistical robustness of many of the phonological laws using resources such as Thun's (1963) exhaustive corpus of about 2000 fixed expressions. For example, with respect to the predicted higher sonority of conjunct *A*'s initial consonant (law 4), I counted about 154 "regular" forms and 200 counterexamples in Thun (1963). This "reversal" seems to cast doubt on the validity of the pattern, but the psycholinguistic test of Pinker and Birdsong (1979, to be reviewed shortly) confirms law 4, as does my own experiment discussed later in this chapter.

Another quirk is that initial /h/'s occur almost exclusively in conjunct *A* (Morawski 1927, Abraham 1950, Marchand 1969, Campbell and Anderson 1976). This is apparently the reason why Cooper and Ross (1975) and Pinker and Birdsong (1979) classify /h/ as the most sonorous (English) consonant in their respective sonority hierarchies. Indeed, Marchand (1969) claims that about one-third of all freezes begin with /h/, while Campbell and Anderson (1976) put their frequency at as high as 50% of all cases. In my own results later in this chapter, the overwhelming tendency of /h/ to beat out all other initial segments in conjunct *A* (even vowels!) is also confirmed. (In §6.5 I will suggest that this may be due to an alignment constraint specific to /h/.) The database of Thun (1963) mentioned above corroborates these numbers as well; of 240 rhymes involving /h/, the /h/ begins conjunct *A* 224 times and conjunct *B* only 16 times. The few cases in which /h/ occurs second may be partially explained by stress; whereas trochees are the norm in fixed rhymes (to avoid a final stressed syllable), we find iambic stress, for example, in some people's pronunciation of *boo-hoo* (cf. *húb-bub*) (Marchand 1969, Campbell and Anderson 1976). Finally, the third law in table 6.1 (number of initial consonants) is also strongly confirmed by Thun's (1963) corpus; in pairs involving a vowel-initial conjunct, this occurs first in 41 cases and second only 4 times.

To summarize this section, 2 of the 7 phonological laws governing frozen expressions directly implicate sonority (nos. 4 and 7). In addition, the law preferring fewer initial consonants in conjunct *A* (no. 3) can also be ascribed to sonority in that vowels are more sonorous initial segments than consonants (law 4) and a one-segment onset beats out a cluster by the Sonority Dispersion Principle (§1.2.4). In fact, looking at things in a slightly different light, laws 3 and 4 actually reduce to just special cases of the Syllable Contact Law (§1.2.3). (However, the preference for a less sonorous final consonant in conjunct A (law 7) would seem to conflict with this.) Consequently, these laws are especially relevant to this dissertation, so they will now be examined in more detail. In particular, the final consonant sonority law (no. 7) was tested by Bolinger (1962) and will be reviewed next. In addition, the initial consonant sonority law (no. 4) was tested by Pinker and Birdsong (1979). Although their overall result is positive, their manner of reporting the data is not very informative. Consequently, I follow up their experiment with a much more elaborate one of my own later in this chapter.

6.3 Two previous experiments

I now discuss two earlier experiments which test the importance of sonority in laws governing reduplicative rhymes in English. They are presented in chronological order and serve as a basis for and introduction to my own study in §6.4 and 6.5.

6.3.1 Bolinger (1962)

In one experiment Bolinger (1962) probed the final consonant sonority law, according to which conjunct *B* prefers to end with a higher sonority consonant than conjunct *A*. He devised a list of 30 minimal pairs of hypothetical adjectives differing only in their final consonant. These were presented in random order in sentential contexts in which all other words were normal, such as *He lives in a plap and plam house* vs. *He lives in a plam and plap house*. In 11 of the nonce pairs one member ended in a consonant and the other did not, e.g., *sprea and spreak* vs. *spreak and sprea*. The reasonable prediction in these latter cases is that the vowel-final word should preferentially occur in conjunct *B* by virtue of having a higher sonority terminal segment. This is especially true given the independent convergence of law 6 (number of final consonants). The test stimuli were administered in written form on sheets containing these instructions: "Say the expressions over to yourself and then put a check mark beside one out of each pair, the one that seems to sound better to you." (p. 37) The subjects consisted of three groups differing in age: 28 seventh graders, 27 college undergraduates, and 5 graduate students.

Of the 30 pairs of words tested, 21 have an overall response total confirming the predicted order (e.g., *plap and plam > plam and plap*). However, because of the relatively low number of subjects ($n = 60$), only 9 of these 21 correct "winners" attain a p value of less than .05 (which I calculated using the binomial cumulative distribution). In other words, 12 of the 21 pairs confirming the final consonant sonority law are in fact not statistically reliable, and all 9 of the pairs reversing the predicted order are also nonsignificant. However, by pooling the responses for all 30 pairs of test items together, an overall significant result emerges: 992 responses (55%) affirming the law vs. 801 responses (45%) against ($p = .000$). The following chart breaks down the response totals by age groups:

Table 6.2: Results of Bolinger's (1962) test on the final consonant sonority law

group	responses in favor	%	responses against	%	*p*
7th grade	444	53	390	47	.033
undergraduate	455	56	354	44	.000
graduate	93	62	57	38	.002

As table 6.2 shows, the percentage of responses which affirm the expected conjunct order increases with age. However, the data which Bolinger (1962) presents are not sufficient to determine whether the contrast between these three groups is significant. Nevertheless, for the sake of argument let us assume that the age effect is real. This naturally raises the question, why should this be so? Bolinger speculates that it may be due to "maturity," but we might *a priori* expect that native speaker intuition and competence should be fully developed by the 7th grade. On the other hand, in defense of Bolinger's hypothesis, older people should have more experience with this phenomenon, both in terms of the number of tokens and their types, and therefore have a firmer basis on which to respond (analogically) to these nonce forms. As an aside, Newman (1933) also obtained more consistent results from subjects older than 15 on a similar semantic task, but his outcome was later shown to be spurious by Bentley and Varon (1933). Nevertheless, because of these results, one of the tests I carry out with my own data in §6.5 is whether responses reliably differ by age group, and the answer is no.

In conclusion, Bolinger's (1962) test of the final consonant sonority law as a whole is successful and encouraging. However, it is worth reiterating that, of the 7 phonological tendencies listed in table 6.1, this one is generally thought to be the weakest (§6.2). Consequently, it would certainly be worthwhile to carry out a similar experiment with the initial consonant sonority law. If the relative ranking in table 6.1 is correct, the prediction is that law 4 should give us a more robust outcome than law 7. Furthermore, if we use many more subjects than Bolinger did, we can expect to have a larger number of significant pairwise results. Nevertheless, before I get to my own data, it would be relevant to first review a previous experiment that has already explored initial consonant sonority patterns.

6.3.2 Pinker and Birdsong (1979)

In a series of experiments similar to those of Bolinger (1962), Pinker and Birdsong (1979) also tested several of the phonological laws on freezes from table 6.1. One of these was law 4 (initial consonant sonority); they did not test law 7. Their subjects consisted of 48 adults, of whom 16 were native speakers of English and 32 were at different stages in their acquisition of English as a second language. The purpose of using non-native speakers, they explain, is to probe for the universality of the phonological laws. Ten contrived pairs of nonsense rhymes were used in which the two conjuncts differed only in their initial consonants, and were phonotactically licit English words. These were randomly scattered throughout a list with 40 additional items testing 4 of the other laws, and the order of presentation was counterbalanced. The words were carefully chosen so as not to sound like commonly-known extant freezes. Five of the test pairs were embedded at the ends of otherwise natural English sentences (like those of Bolinger 1962), and the other 5 were presented in isolation. Subjects were instructed to listen to a native speaker's pronunciation of the test items (pre-recorded) while they read along silently on their questionnaires. They responded to each pair of utterances by placing a mark on a 5-point scale. Extreme responses (1 and 5) indicated the strongest preference for the respective contrasting (opposite) orders, while 3 indicated no preference whatsoever for either order.

The overall mean rating of the 10 pairs confirms the initial consonant sonority law in that it is significantly greater than chance (i.e., larger than a value of 3) in the predicted direction. However, this is true only for native speakers; the results for the other 32 subjects indicate no preference for either conjunct order. From this result Pinker and Birdsong (1979) conclude that this law is psychologically real for native speakers of English but probably should not be considered universal (cf. Cooper and Ross 1975). The following quote summarizes their thinking and highlights the potential contribution of psycholinguistic tests of this nature:

> "These findings suggest that ratings of minimally contrasting nonsense pairs are an ideal form of evidence for assessing the potency of principles of frozen word order in those cases where the linguistic evidence is equivocal owing to a lack of unconfounded examples. It also supports the notion that the formation and maintenance of freezes (and perhaps of other idioms) are mediated by speakers' intuitions that certain word combinations sound better than others. If indeed there exist among speakers certain selection pressures which work to preserve some word combinations and to weed out others, it is evident from our study that speaker intuitions do act discriminatingly to conform to the phonological principles which uphold, rather than violate, the linguistic status quo." (Pinker and Birdsong 1979:506)

Notwithstanding the success of this experiment, Pinker and Birdsong's (1979) presentation of their results is not as thorough as it could have been. From reading their article one can glean little more about their data than what I encapsulate above. Specifically, it would be helpful to know the following details, none of which are recoverable from their exposition: (1) What are the 10 specific pairs of words they used to test the 4th law? (While 4 of these items are listed in their discussion, the other 6 are not.) (2) How do the results break down for each of the 10 pairs individually? That is, which ones follow the law and which ones, if any, reverse it? And how significant are each of the 10 pairwise scores? (3) For which particular items, if any, do the non-native speakers tend to do especially better or worse? For example, does the relative sonority distance between the two onsets make any difference in their responses? (4) And what exactly is the overall mean rating for the 10 test items as a group? (From their figure 1 we can deduce only that it is between 3.5 and 3.75.)

In conclusion, Pinker and Birdsong's (1979) study is an important empirical confirmation of the role of sonority in reduplicative freezes in English. Nevertheless, for the purposes of this dissertation, it would be desirable to have much more explicit information. Consequently, I designed a similar experiment in which I simultaneously probe 99 different pairwise sonority contrasts and present the results of each one individually (as Bolinger 1962 does). The summary statistics which I then carry out on all the data as a whole are quite interesting and relevant to the elaboration of a complete sonority hierarchy.

6.4 Design, methodology, and subjects

I now discuss my own experiment, focusing in this section on the preparation and administration of the test items as well as a general sketch of the participants who took part. The list of words I devised was carefully selected to contain at least one member from every natural class of potential English onset consonants, and to contrast all groups with each other as far as possible. To this end the use of non-occurring but hypothetically real forms, i.e., accidental gaps, is both ideal and probably unavoidable. Nonce forms have the advantage of completely neutralizing all semantic pressures which otherwise might bias the results. Furthermore, contrived words free us from having to rely on attested morphemes only. Of course, a difficulty inherent in certain combinations is that they sound highly reminiscent of actual English words. This problem is hard to negotiate, especially in a list as big as mine (99 words = 198 conjuncts). Nevertheless, I tried to reduce the influence of lexically similar items as much as these constraints would allow me. The complete list of words I used is given in the next section, where I present the results for each pair. About three-fourths of the words are disyllabic and intended to have trochaic stress; the remaining one-fourth are monosyllabic. Unlike Bolinger (1962) and Pinker and Birdsong (1979), I included pairs having equally sonorous onsets as a control (e.g., *boce-goce*, *wog-yog*). The prediction in these cases is that neither order should be preferred, i.e., the choice between them should not differ from chance. I also used a few pairs in which one of the two conjuncts began with a vowel rather than a consonant, e.g., *esh-tesh*. Before deciding on the final list of test items, I circulated a number of pilot studies to weed out problems such as spelling ambiguities, similarities to actual lexical items, etc.

The 99 test items were presented to each subject in written form. In order to keep the task manageable, word pairs appeared in isolation rather than in sentential context. I emphasized to the participants that there was no time limit on how long they could take to complete the experiment, and even encouraged them to take one or more short breaks during the task to allow their minds a chance to rest. The instructions informed the readers that I would like to get their intuitive judgements about which of the "made-up" words sound the most "natural" to them. Accordingly, they were asked to decide which order sounds the most like it ***could*** or ***would*** be an actual, real word of English if they had to choose only one of the two options. It was suggested that they say each word out loud first to see how it "feels" in their mouth. They were also told to assume that all letters are pronounced according to their most common and obvious English spellings. In addition to choosing one conjunct order over the opposite order for each pair, subjects were also instructed to indicate how confident they felt about their choice of preferred order by noting in each case whether their judgement was relatively strong, weak, or in-between. These techniques have the advantage of forcing the respondents to choose one order or the other (like Bolinger 1962) while simultaneously obtaining more gradient impressions as in Pinker and Birdsong (1979). Test items were thus presented in the following format:

	strong preference: relatively sure and certain		weak preference: relatively unsure and uncertain
1. weeby-leeby ***OR*** leeby-weeby	3	2	1

Subjects were asked to underline or circle their preferred word order on the left, and circle one of the three numbers on the right side of each row. The instructions said, "If you feel it was fairly easy to choose your preferred order in a given case, circle *3*. If you had a very difficult time deciding on the order, circle *1*. For judgements that fall somewhere in-between, circle *2*." Response items which did not follow the instructions completely are not included in the calculation of results. Most misunderstandings involved failing to provide one of the two pieces of information requested for each pair — either the preferred conjunct order or the strength of judgement. The frequency of such mistakes was relatively low, but this accounts for why the response totals for some items do not add up to 332 (the number of subjects). On the last page of the questionnaire the subjects were requested to provide some personal data and answer a few questions. This information included age and sex and whether they were a native speaker of English (non-native responses were not analyzed). They were also asked to invent (make up) one new nonsense word of English and state which order they preferred for it. Finally, they were asked whether they could see any general pattern to which orders they preferred for the beginning consonants in the experimental list, or whether it seemed completely random. The responses to these last two tasks are discussed in the following two sections.

Because of the strong possibility of responses being influenced by the patterns of nearby items (especially on such a long list), the order of presentation of the test pairs was controlled for by counterbalancing. A total of 18 different versions of the experiment were distributed and collected. Each one contained the same list of 99 words in a different randomized order. The order was counterbalanced both horizontally (within rows) and vertically. That is, subjects were equally likely to encounter the prompt "*hidgy-widgy **OR** widgy-hidgy*" as they were to find "*widgy-hidgy **OR** hidgy-widgy.*" They were also equally likely to encounter this pair listed as item no. 1, 7, 18, 34, ..., 99, etc. (insofar as this is possible using 18 different forms). Each of the 332 subjects was randomly assigned to one of the 18 versions of the word list, resulting in the following distribution among those sheets which were actually turned in and analyzed: mean number of subjects per form = 18.4, low = 14, high = 30, median = 17, mode = 17, sd = 3.8.

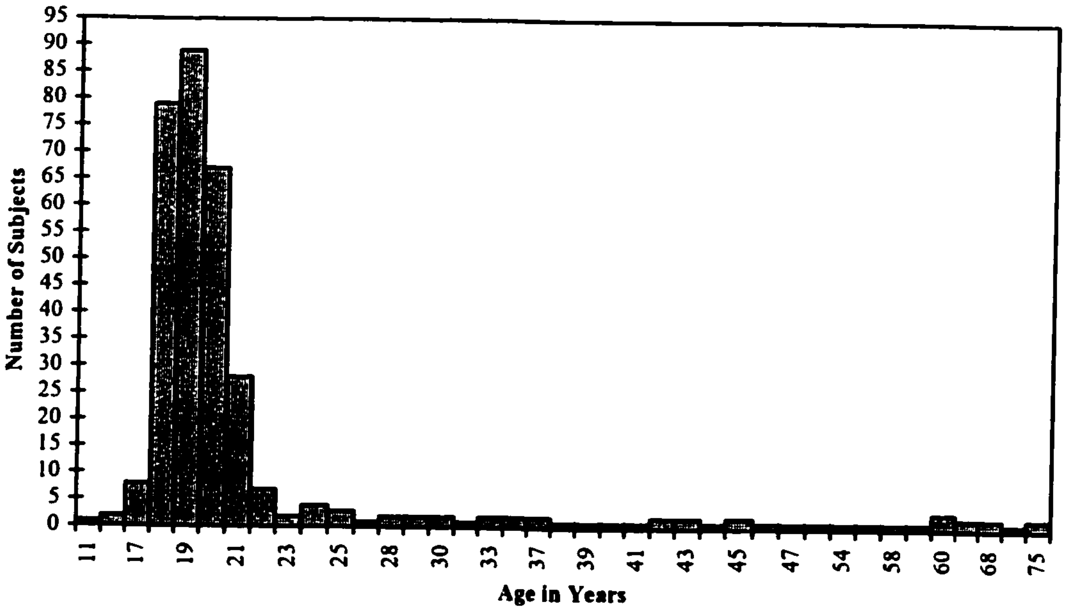
The 332 subjects who participated in the experiment were all native speakers of English. Most of these were current undergraduate students in an introductory linguistics class at U. Mass. (school year 2000-2001). No one was paid for their collaboration but most of the students were assigned to do it as a homework, while a few received extra credit. The breakdown of the subjects by age and gender is summarized in the following chart:

Table 6.3: Statistical analysis of the subjects participating in the psycholinguistic experiment

	males	females	combined
n	103	229	332
mean age	23.7	22.2	22.7
youngest	17	11	11
oldest	75	75	75
median	20	19	19
mode	19	18	19
sd	10.9	10.2	10.4
skewness	3.06	3.33	3.21
kurtosis	9.62	10.85	10.22

In the table above, the large preponderance in the number of female subjects (vs. males) was not intentional but rather reflects the typical makeup of undergraduate linguistics courses at U. Mass. At any rate there are enough males to do a comparative analysis of the results, and the overall effect of gender is highly insignificant anyway (§6.5). The following figure shows quite graphically that the great majority of all subjects were of college age. As I will demonstrate in the next section, a contrast of the results by age is also far from significant, so the heavy skewness on this variable is not a problem.

Figure 6.1: Distribution of the experimental subjects by age (both genders combined)



6.5 Results and discussion

In this section I present the item-by-item results and carry out a number of tests on their overall statistical reliability and goodness of fit with the sonority hierarchy. We will see that sonority plays a decisive role in predicting conjunct order, confirming law 4 of table 6.1. In §6.6 I then consider two alternative explanations for the data and show that each of them is weaker than the sonority hypothesis. In anticipation of the results, I first present the sonority hierarchy which I assume is in effect for English and will therefore guide us in analyzing the data:

(6.1)	vowels	10
	h	9
	y, w	8
	r	7
	l	6
	m, n	5
	v, ð, z, ž	4
	f, θ, s, š	3
	b, d, g, ǰ	2
	p, t, k, č	1

The scale in (6.1) above is derived (simplified) from the universal sonority hierarchy which I posited in table 5.28. The two scales differ in a few details, which will be discussed and fully justified after we see the results of the experiment. The responses of all 332 participants for the 99 test pairs were tabulated and sorted by significance. In the exhaustive table below, the items are ranked in decreasing order of the preference for one conjunct sequence over the reverse sequence. The null hypothesis being tested for each pair (with the binomial function) is that the most frequently preferred conjunct order is due to chance. When the *p* value for a given pair is small enough to reject the null hypothesis (discussed further below), this means that the preference for the most frequent conjunct order is extreme enough in the data to be significant.

The null hypothesis assumes a predicted probability of .5 for any given conjunct order, i.e., it denies any pairwise preference whatsoever based on an effect of the initial consonant sonority law. Given equal numbers of total responses for each test item (which I come close to but do not always have), the pairwise *p* values then are inversely proportional to the difference in percentage between the winning and losing orders.

In table 6.4 below, the leftmost column displays the two conjunct orders for each word, with the preferred order first (i.e., the one receiving the most "votes"). The second column lists the total number of responses in favor of each order (out of a theoretical maximum *n* of 332), regardless of judgement strength (1, 2, or 3). The third column gives the corresponding percentage value for each of the two orders of every pair, derived directly from the total *n*'s. Next come the binomial *p* values, rounded off to four decimal places and increasing monotonically. The column labeled *mean* refers to the overall average judgement strength (from 1-3) for each selected order among all the responses. Finally, the rightmost column displays the standard deviation for each mean judgement rating. In order to control for the effects of multiple comparisons (type 1 statistical errors), the α level for significance testing is set at .0005 for each test word since there are nearly 100 pairs of items. Given this criterion, the first 51 pairs of items listed in table 6.4 achieve significance whereas the last 48 pairs do not. Those winning orders marked with an asterisk to the left of their row in the table are reversals of the sonority hierarchy posited in (6.1) above. That is, they counterexemplify the law governing the sonority of initial consonants (from table 6.1). Non-parenthesized *'s are used for reversed results which are significant, and sonority reversals which are not significant are marked as "(*)":

Table 6.4: Overall pairwise results of the psycholinguistic experiment on reduplicative rhyming forms in English

	word	*n*	%	*p*	mean	sd
	hidgy-widgy	262	79	.0000	2.47	0.68
	widgy-hidgy	69	21		2.28	0.75
	hicey-kicey	259	78	.0000	2.40	0.73
	kicey-hicey	73	22		2.10	0.77
	roshy-toshy	247	76	.0000	2.44	0.66
	toshy-roshy	77	24		2.06	0.75
	rowly-zowly	252	76	.0000	2.46	0.65
	zowly-rowly	80	24		2.13	0.74
	hommy-zommy	251	76	.0000	2.37	0.67
	zommy-hommy	80	24		2.15	0.71
	hoozy-goozy	249	75	.0000	2.62	0.56
	goozy-hoozy	83	25		2.25	0.71
	ob-chob	245	74	.0000	2.44	0.72
	chob-ob	87	26		2.00	0.82
	esh-tesh	243	73	.0000	2.43	0.72
	tesh-esh	88	27		2.28	0.74
	hofey-jofey	241	73	.0000	2.37	0.70
	jofey-hofey	88	27		2.08	0.76
	heemie-yeemie	238	73	.0000	2.45	0.67
	yeemie-heemie	90	27		2.14	0.80
	sifey-difey	236	72	.0000	2.35	0.68
	difey-sifey	94	28		2.12	0.75
	hessy-fessy	235	71	.0000	2.47	0.65
	fessy-hessy	95	29		2.26	0.75
*	moudy-woudy	235	71	.0000	2.51	0.64
	woudy-moudy	96	29		2.07	0.78
	heffy-leffy	206	73	.0000	2.36	0.71
	leffy-heffy	78	27		2.17	0.75
	suddy-juddy	229	70	.0000	2.27	0.70
	juddy-suddy	98	30		2.19	0.73

(cont. next page)

(Table 6.4 cont.)

word	*n*	%	*p*	mean	sd
hifey-chifey	231	70	.0000	2.36	0.68
chifey-hifey	100	30		2.12	0.76
huppy-ruppy	228	69	.0000	2.38	0.64
ruppy-huppy	102	31		2.17	0.75
ut-yut	228	69	.0000	2.42	0.76
yut-ut	104	31		2.13	0.81
loddy-joddy	225	69	.0000	2.48	0.68
joddy-loddy	102	31		2.33	0.67
* siggy-liggy	225	68	.0000	2.43	0.65
liggy-siggy	106	32		2.20	0.74
yatter-jatter	222	67	.0000	2.43	0.68
jatter-yatter	109	33		2.23	0.79
rofe-dofe	222	67	.0000	2.09	0.73
dofe-rofe	109	33		1.99	0.71
* cheggy-deggy	217	66	.0000	2.29	0.71
deggy-cheggy	111	34		2.14	0.78
fissy-bissy	218	66	.0000	2.44	0.66
bissy-fissy	112	34		2.13	0.74
* chuffy-guffy	218	66	.0000	2.29	0.73
guffy-chuffy	112	34		2.17	0.76
moggy-voggy	218	66	.0000	2.16	0.76
voggy-moggy	112	34		2.09	0.75
pog-tog	218	66	.0000	2.25	0.73
tog-pog	113	34		2.02	0.80
shibby-jibby	216	65	.0000	2.50	0.63
jibby-shibby	116	35		2.15	0.76
* mapey-lapey	216	65	.0000	2.28	0.69
lapey-mapey	116	35		2.16	0.72
ot-zot	210	64	.0000	2.36	0.71
zot-ot	120	36		2.28	0.78
semmy-temmy	209	64	.0000	2.29	0.69
temmy-semmy	120	36		2.10	0.74
* chebby-jebby	208	63	.0000	2.22	0.76
jebby-chebby	121	37		2.17	0.80
vooly-booly	209	63	.0000	2.50	0.67
booly-vooly	123	37		2.37	0.73
* thubby-zubby	205	62	.0000	2.34	0.71
zubby-thubby	124	38		2.22	0.75

(cont. next page)

(Table 6.4 cont.)

	word	*n*	%	*p*	mean	sd
	nafey-dafey	204	62	.0000	2.36	0.66
	dafey-nafey	125	38		2.26	0.72
	kep-tep	204	62	.0000	2.05	0.79
	tep-kep	126	38		2.02	0.74
	reecy-jeecy	203	62	.0000	2.37	0.65
	jeecy-reecy	126	38		2.35	0.70
	yaff-naff	203	62	.0000	2.04	0.75
	naff-yaff	126	38		2.14	0.79
*	chirey-zirey	204	62	.0000	2.19	0.71
	zirey-chirey	127	38		2.13	0.76
*	chelly-relly	202	61	.0000	2.49	0.65
	relly-chelly	128	39		2.35	0.62
	affle-naffle	203	61	.0000	2.44	0.70
	naffle-affle	129	39		2.34	0.78
	ubby-gubby	201	61	.0000	2.43	0.67
	gubby-ubby	129	39		2.40	0.70
	jassy-tassy	202	61	.0000	2.35	0.69
	tassy-jassy	130	39		2.22	0.67
	een-reen	200	61	.0001	2.17	0.79
	reen-een	129	39		2.08	0.85
	boke-doke	200	61	.0001	1.98	0.78
	doke-boke	130	39		1.88	0.80
	hudgy-sudgy	200	60	.0001	2.21	0.74
	sudgy-hudgy	131	40		2.02	0.75
	shoomy-goomy	199	60	.0001	2.33	0.68
	goomy-shoomy	132	40		2.24	0.66
*	cazzy-gazzy	199	60	.0001	2.20	0.76
	gazzy-cazzy	132	40		2.11	0.72
	ladgy-tadgy	198	60	.0002	2.27	0.68
	tadgy-ladgy	132	40		2.12	0.74
*	teeshy-deeshy	197	60	.0003	2.16	0.72
	deeshy-teeshy	134	40		2.06	0.79
	rezzy-nezzy	196	59	.00047	2.37	0.71
	nezzy-rezzy	135	41		2.24	0.71

↑
significant

hassy-nassy	195	59	.0006	2.28	0.71
nassy-hassy	135	41		2.25	0.73

not
significant
↓

(cont. next page)

(Table 6.4 cont.)

	word	*n*	%	*p*	mean	sd
	yusser-tusser	195	59	.0006	2.23	0.76
	tusser-yusser	135	41		2.05	0.69
	weeby-leeby	195	59	.0007	2.34	0.69
	leeby-weeby	136	41		2.29	0.65
	luspy-duspy	194	58	.0012	2.28	0.74
	duspy-luspy	138	42		2.12	0.74
	lokey-zokey	193	58	.0018	2.33	0.66
	zokey-lokey	139	42		2.24	0.74
(*)	chooly-nooly	190	58	.0029	2.38	0.63
	nooly-chooly	139	42		2.27	0.73
	gome-jome	190	58	.0034	1.92	0.79
	jome-gome	140	42		1.94	0.78
	suke-shuke	191	58	.0035	1.97	0.82
	shuke-suke	141	42		1.96	0.77
	yom-gom	190	57	.0041	2.20	0.75
	gom-yom	141	43		2.00	0.76
	ite-jite	189	57	.0048	2.27	0.78
	jite-ite	141	43		2.16	0.78
	zopey-topey	188	57	.0055	2.28	0.72
	topey-zopey	141	43		2.19	0.76
(*)	hoony-oony	189	57	.0057	2.43	0.70
	oony-hoony	142	43		2.24	0.73
(*)	jizzy-nizzy	185	56	.0117	2.38	0.66
	nizzy-jizzy	143	44		2.40	0.68
	nabey-tabey	186	56	.0119	2.30	0.71
	tabey-nabey	144	44		2.24	0.73
	moke-noke	184	56	.0134	2.00	0.78
	noke-moke	143	44		1.90	0.78
	sheppy-keppy	184	56	.0180	2.35	0.65
	keppy-sheppy	145	44		2.15	0.72
(*)	fammy-vammy	184	56	.0180	2.18	0.71
	vammy-fammy	145	44		2.09	0.75
	ocey-locey	185	56	.0211	2.34	0.71
	locey-ocey	147	44		2.38	0.73
	pess-kess	183	56	.0235	2.09	0.77
	kess-pess	146	44		1.98	0.75
	seevy-cheevy	184	56	.0238	2.32	0.72
	cheevy-seevy	147	44		2.20	0.78

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(Table 6.4 cont.)

	word	*n*	%	*p*	mean	sd
	yeebie-reebie	183	55	.0269	2.32	0.73
	reebie-yeebie	147	45		2.33	0.72
(*)	choundy-loundy	181	55	.0341	2.16	0.72
	loundy-choundy	147	45		2.17	0.74
	chiff-kiff	182	55	.0346	2.08	0.78
	kiff-chiff	148	45		2.03	0.73
	yeck-zeck	181	55	.0439	2.14	0.75
	zeck-yeck	149	45		2.02	0.74
	vake-zake	179	55	.0485	1.96	0.73
	zake-vake	148	45		1.93	0.77
(*)	jimey-zimey	180	55	.0490	2.14	0.72
	zimey-jimey	149	45		2.28	0.64
	nally-zally	181	55	.0495	2.24	0.73
	zally-nally	150	45		2.24	0.67
	yoop-choop	181	55	.0557	2.10	0.76
	choop-yoop	151	45		2.07	0.76
	fimey-pimey	179	54	.0613	2.15	0.76
	pimey-fimey	150	46		2.07	0.73
	chope-tope	179	54	.0613	2.07	0.75
	tope-chope	150	46		2.07	0.74
	deef-jeef	178	54	.0758	2.01	0.76
	jeef-deef	151	46		1.88	0.82
	ribe-libe	178	54	.0843	1.87	0.83
	libe-ribe	152	46		2.04	0.73
(*)	rissy-wissy	178	54	.0935	2.40	0.65
	wissy-rissy	153	46		2.18	0.73
	zoofy-doofy	177	53	.1133	2.43	0.69
	doofy-zoofy	154	47		2.30	0.68
	jossy-cossy	174	53	.1471	2.21	0.66
	cossy-jossy	154	47		2.28	0.72
(*)	chiggy-shiggy	175	53	.1612	2.11	0.78
	shiggy-chiggy	156	47		2.21	0.73
	rabe-sabe	174	53	.1747	1.91	0.77
	sabe-rabe	156	47		2.04	0.73
	gobe-dobe	170	52	.2718	2.04	0.81
	dobe-gobe	158	48		2.15	0.73
	feg-seg	171	52	.3107	1.96	0.78
	seg-feg	161	48		2.12	0.77

(cont. next page)

(Table 6.4 cont.)

	word	*n*	%	*p*	mean	sd
	wog-yog	171	52	.3107	1.94	0.73
	yog-wog	161	48		2.11	0.77
	yubbie-lubbie	170	51	.3301	2.28	0.75
	lubbie-yubbie	161	49		2.39	0.71
(*)	narpy-larpy	169	51	.3500	2.39	0.67
	larpy-narpy	161	49		2.29	0.73
(*)	seppy-neppy	169	51	.3500	2.21	0.67
	neppy-seppy	161	49		2.11	0.72
	yote-sote	168	51	.3704	1.90	0.76
	sote-yote	161	49		2.01	0.81
	eedy-sheedy	168	51	.3916	2.40	0.68
	sheedy-eedy	162	49		2.41	0.65
	goce-boce	167	51	.4344	1.94	0.69
	boce-goce	163	49		2.01	0.82
	bimmy-pimmy	166	50	.4561	2.08	0.74
	pimmy-bimmy	163	50		2.21	0.80
	jiney-biney	165	50	.5000	2.21	0.76
	biney-jiney	164	50		2.15	0.76

In analyzing the results of table 6.4, it is convenient to focus initially on the 51 significant pairs only. Among these, the winning and losing initial segments are summarized below (preferred onsets for conjunct A are to the left of the arrows). For the moment we will not be concerned about whether each pair confirms or reverses the sonority law; this detail will be examined shortly.

(6.2) significant phoneme pairwise comparisons (*n* = 51)

h > w k z g ǰ y f l č r s
r > t z d ǰ n
vowels > č t y z n g r
s > d ǰ l t
m > w v l
l > ǰ t
y > ǰ n
č > d g ǰ z r

f > b
p > t
š > ǰ g
v > b
θ > z
n > d
k > t g
ǰ > t
b > d
t > d

In the list above, the order of presentation simply follows the *p* value rankings from table 6.4. Otherwise it is random and no importance should be attached to it. An important detail in this list is that there are no violations of ranking transitivity. That is, there are no cases in which *x* > *y* and *y* > *z* but *z* > *x*. Among the 51 significant pairs in (6.2), it is noteworthy that /h/ and the vowels win every one of their respective encounters. (For our purposes here there is little point in distinguishing among vowels based on height or any other feature since I did not test or control for this quality.) I now divide the data from (6.2) according to relative sonority relationships:

(6.3) winning pairs which confirm the sonority hypothesis (n = 37)

h > w k z g ǰ y f l č r s
r > t z d ǰ n
vowels > č t y z n g r
s > d ǰ t
m > v
l > ǰ t
y > ǰ n
f > b
š > ǰ g
v > b
n > d
ǰ > t

(6.4) winning pairs which reverse the sonority hypothesis (n = 11)

s> l
m > w l
č > d g ǰ z r
θ > z
k > g
t > d

(6.5) pairs equal in sonority but one member unexpectedly wins (n = 3)

p > t
k > t
b > d

In (6.3) and (6.4) above I list the statistically significant pairwise results which confirm and reverse the initial consonant sonority law, respectively. This determination is crucially based on the sonority scale posited in (6.1) above. This hierarchy differs in a few details from the universal scale in table 5.28, and merits clarification. First, since /h/ consistently beats out all other contenders for conjunct A, it seems reasonable to treat it as the most sonorous consonant for the purposes of this experiment. Recall from the discussion in §5.10 that the placement of /h/ (and /ʔ/) in the sonority hierarchy is more difficult to establish than any other ranking. At least four previously proposed sonority scales assign glottal consonants a position right below the vowels, i.e., higher than all other consonants (Parker 1989, Larson 1990, Gnanadesikan 1997, and de Lacy 2002). Consequently, there is a clear precedent for this move. If we did not make this adjustment, the results would be artificially biased against the sonority hypothesis. Second, in (6.1) I have collapsed all the vowels into just one natural class. This is also appropriate since I am not directly comparing one vowel quality with another, and law 4 is primarily concerned with consonants. Third, I have dropped the segments /r̄/ and /r̆/ (which English does not have) and have realigned the remaining sonority indices accordingly. Finally, given the fact that all 5 encounters between voiceless fricatives and voiced stops/affricates come out in favor of the former (and are statistically significant), I posit that the nondefault ranking of these two natural classes is appropriate for English. These four modifications to the universal sonority hierarchy are all logical and benign in this context.

Let us now examine the results in (6.3) - (6.5) more closely. In (6.4) /č/ is especially prolific as a reversed winner (5 cases). In (6.5) there are 3 pairs equal in sonority but where one member nevertheless wins (against the prediction). All three of these involve a noncoronal beating out a coronal. In all there are 37 pairs in (6.3) which obey the prediction of the sonority law while only 11 pairs in (6.4) violate it. Leaving aside the 3 pairs in (6.5), a winning ratio of 37 pairs in favor vs. 11 pairs against is highly significant; the binomial p value for an outcome this extreme is .0001. Even if we count the three "false" winners in (6.5) as a negative result and add these pairs to the 11 reversals in (6.4), we still end up with a winning ratio of 37:14 (p = .0009). Furthermore, if we insisted (for the sake of argument) that the unmarked ranking /b d g ǰ/ > /f θ s š/ is universally fixed and therefore has to be followed at all costs, we would still end up with a felicitous 32:16 or 2:1 ratio in favor of the sonority law (p = .0147). I conclude that, given the adjusted sonority hierarchy in (6.1), the results of the 51 significant pairwise conflicts strongly confirm the hypothesis that initial consonants which are higher in sonority prefer conjunct A over conjunct B. Even if we adopted the two stringent conditions just mentioned, we would still end up with a significant outcome.

We can now consider the last 48 pairs of table 6.4, keeping in mind that they are statistically less reliable than those we have just analyzed. Taking into account all 99 contrasts as a whole, the comprehensive, "idealized" sonority hierarchy which best fits the observed data (in a post hoc fashion) is the following:

(6.6)	h	18
	vowels	17
	y	16
	m	15
	s	14
	č	13
	r	12
	w	11
	l	10
	š, f	9
	p, v	8
	k	7
	g	6
	ǰ, θ	5
	n	4
	z	3
	t, b	2
	d	1

The exhaustive scale above is completely consistent with the 51 significant pairwise results, i.e., it does not contradict any winning sequences. It is also designed so as to maximize the match with the nonsignificant pairs as well. It thus follows the trend of 41 of the 48 insignificant pairs, and only reverses 7 of them. It is not possible to perfectly fit my results with a single hierarchical scale which simultaneously obeys all 99 pairs of results, i.e., significant as well as nonsignificant ones. In other words, there are a few differences in the rank orders obtained from the nonsignificant pairs as compared to the significant ones. In such cases I naturally follow the rankings of the significant outcomes. In the above scale there is more than one way to arrange the rankings so as to obey all 51 significant results. In particular, the phonemes /m v θ/ can be placed at several different locations in this hierarchy. The procedure I follow in such cases is to place them as close as possible to their actual ranking in the (English) scale of (6.1). To determine how well the idealized hierarchy in (6.6) lines up with the final universal scale we posited in table 5.28, I correlated the sonority indices from the two scales (for individual segments, and with the ranking *voiceless fricatives* > *voiced stops*). The outcome indicates a moderate overlap between the two hierarchies: $r = .54$, $p = .0091$. From this fact I conclude that the sonority scale we arrived at based on the phonetic evidence (table 5.28) does significantly help to account for the observed psycholinguistic results.

Focusing now on scale (6.6) in particular, several of the outcomes from table 6.4 are noteworthy. First, as mentioned previously, /h/ wins every single one of its encounters, beating out even the one vowel-initial conjunct it was tested against (*hoony-oony* (57%) > *oony-hoony* (43%), $p = .0057$). This might be taken as strong psychophonological evidence that English /h/ is extremely high in relative sonority, a hypothesis already discussed several times (§3.2.5.1 and 5.5). As I noted in §5.10, the evidence for the placement of /h/ in the final sonority hierarchy in table 5.28 is not as conclusive as that of most other segments. Consequently, it is not out of the question that /h/ should really be located much higher in the scale. One fact which confirms this is that several works classify /h/ and /ʔ/ as [+son] and [–cons] (Halle and Clements 1983, Durand 1990). This places them in the same major class as oral glides. On the other hand, /h/ might be especially favored in conjunct A for a reason that has nothing to do with sonority: alignment. It is well-known that English /h/ is normally maintained at the beginning of prosodic domains (intonational phrases and stressed syllables), but tends to delete otherwise (cf. *vehícular* vs. *véhicle*). For this reason Davis (1999) posits two left alignment constraints specific to the feature [spread glottis]. If these are ranked high enough in the grammar, they will automatically pull /h/ towards conjunct A regardless of its true sonority rank. However, since I am not focusing in this section on a formal analysis of the *roly-poly* phenomenon (much less its details), I will not pursue this issue further.

Returning to the scale in (6.6), vowel-initial conjuncts also win every contrast against all consonants (except /h/), as we would expect. Among the remaining (consonant) segments, we can make the generalization that most sonorants outrank most obstruents in (6.6). There are only three exceptions to this tendency: the segments /s/, /č/, and /n/. For some reason /s/ and /č/ pattern as high in sonority, and /n/ as relatively low. The claim that /s/ merits a special status as a high sonority consonant is made by Hooper (1976), Vogel (1977), Selkirk (1984), and Scheer (1998), *inter alios*. This may have an acoustic explanation: the high stridency of /s/ makes it perceptually very salient (the same is true of /č/). I am less sure what to say about /n/. Another strong tendency in (6.6) is that labials and dorsals outrank their coronal counterparts. However, as mentioned in §3.2.5.4, I do not believe we should make systematic sonority distinctions among consonants based on place of articulation alone, so I do not ascribe much relevance to this pattern.

In the remainder of this section I carry out five other types of statistical analyses on the results of table 6.4. Each one examines the data in a different way to give us a better idea of the whole picture. Furthermore, all five confirm the crucial role of sonority to one degree or another in explaining the *roly-poly* phenomenon. First I simply add up all the scores for all test items simultaneously to determine the overall margin of "victory." Among the 99 pairs of items tested, 16 involve onsets having the same degree of sonority (from the scales in table 5.28 and (6.1)), e.g., *feg-seg* vs. *seg-feg*. This leaves 83 potentially conflicting pairs in which the sonority law predicts a certain conjunct order. When the responses from all 332 subjects are pooled together for these 83 crucial pairs, the overall result total is 15,599 individual item scores confirming the sonority hypothesis against 11,758 responses in the "wrong" direction, a winning ratio of 57.0% vs. 43.0%. The p value for an outcome this extreme (57.0% vs. 43.0% = a difference of 3841 votes) consistent with this large a sample size is exceedingly small ($< 10 \times 10^{-n}$, where n is the limit of Excel's resolution). I conclude that this result also supports the sonority law. A skeptic might quibble that a percentage of 57.0% votes in favor is not a very big effect size. However, given the large number of subjects, this translates into a total differential of 3841 scores, which is hardly trivial.

The second line of analysis I will employ is to convert all the responses for each subject into an overall % value which measures how well each participant follows the sonority hypothesis. This is done by adding up the number of test items for which a subject prefers the predicted order and dividing that by the total number of pairs responded to by that subject (among the 83 conflicting encounters). Having done this, the overall results are as follows: grand mean of 332 percentage scores = 57.0, lowest individual = 28, highest individual = 92, sd = 9.0. We can now further contrast these individual percentage scores by age and gender. First, a correlation between raw age (in years) and percentage score for all 332 subjects combined yields an insignificant result: $r = .06, p = .29$. Next, all subjects are assigned to one of two age groups: (1) 21 years and younger, or (2) 22 years and older. Given the low number of subjects younger than college age ($n = 3$), there is no point in establishing a separate category for them. Similarly, it makes sense to lump all subjects above college age into just one group so as to have sample sizes large enough to be meaningful. The following chart indicates the number of persons in each group resulting from this simplification:

Table 6.5: Breakdown of the numbers of subjects by groups

	males	females	totals
age 11-21	79	195	274
age 22-75	24	34	58
totals	103	229	332

The overall mean percentage scores for the separate categories in the table above are displayed below. What is striking is how little variability there is within the data:

Table 6.6: Mean "sonority law" percentage scores for individuals, by groups

	males	females	totals
age 11-21	57.1	56.5	56.7
age 22-75	57.9	59.2	58.7
totals	57.3	56.9	57.0

Not surprisingly, a two-factor ANOVA on the individual values comprising table 6.6 fails to detect any significant effects:

Table 6.7: Results of the ANOVA on the 332 individual percentage scores

source of variance	degrees of freedom	F	p
gender	1, 328	.058	.810
age	1, 328	1.720	.191
gender × age	1, 328	.487	.486

The results of this test strongly indicate that the intuitions of native speakers of English concerning the initial consonant sonority law do not depend on either age or sex. While this may just be due to similar linguistic experiences among the sample of subjects, a more likely explanation is that this task truly does tap into their linguistic competence in some way.

A third statistical hypothesis we can pursue is whether the distance between the sonority indices of the initial segments of the two conjuncts influences the outcomes. A natural hypothesis is that the greater the relative sonority between the two onset segments, the more likely that pair is to obey the sonority law. Furthermore, a greater sonority difference might be expected to correlate with a higher margin (%) of victory as well. The following table summarizes the 83 conflicting pairs, broken down by direction and size of sonority differences. In this table I do not include the 16 pairs in which the initial segments of the two conjuncts are equal in sonority since neither order is *a priori* predicted to win in such cases. The differences below are calculated by simply subtracting the sonority index of the initial segment of conjunct B from that of the onset of conjunct A, for each preferred order. Consequently, a positive differential value corresponds to a result in which the sonority law is obeyed, while a negative value indicates a reversal of the hypothesis. For example, the winning pair *hicey-kicey* is counted here as *8* in the leftmost column because the index of /h/ is *9* and that of /k/ is *1*, based on scale (6.1). In the rightmost column of this row I have then indicated this specific pair as "h > k".

Table 6.8: Summary of the sonority distances between the conjunct-initial segments for the 83 conflicting pairs from table 6.4

difference between sonority indices	number of pairs	specific pairs
9	2	vowel > č, vowel > t
8	4	h > k, h > č, vowel > g, vowel > ǰ
7	5	h > g, h > ǰ, y > t, y > č, vowel > š
6	6	r > t, h > f, y > ǰ, vowel > z, h > s, y > g
5	6	h > z, r > d, r > ǰ, vowel > n, l > t, y > s
4	7	l > ǰ, h > n, l > d, n > t, vowel > l, y > z, r > s
3	6	r > z, h > l, n > d, y > n, vowel > r, z > t
2	12	h > r, vowel > y, s > t, v > b, r > n, w > l, l > z, š > k, s > č, f > p, z > d, y > l
1	14	h > w, h > y, s > d, s > ǰ, f > b, m > v, š > ǰ, ǰ > t, š > g, y > r, n > z, r > l, ǰ > k, b > p
–1	11	č > d, č > g, m > l, č > ǰ, θ > z, k > g, t > d, h > vowel, f > v, r > w, n > l
–2	3	ǰ > z, č > š, s > n
–3	4	m > w, s > l, č > z, ǰ > n
–4	1	č > n
–5	1	č > l
–6	1	č > r
–7	0	
–8	0	
–9	0	

As the table above shows, no sonority reversals occur in which the difference between the sonority indices of the onset segments is *–9*, *–8*, or *–7*. In other words, a total of 11 pairs of forms were tested in which the difference in sonority rank between the two initial segments has an absolute value between |7| and |9| inclusively, and all 11 of these cases came out in favor of the sonority law. This outcome in itself is a positive result since it means that sonority reversals are possible (in my data) only when the onset differential is equal to *6* or less. Furthermore, all 3 cases of reversals in which the difference is between *–4* and *–6* involve an initial /č/ in conjunct A. Earlier in this section we noted that this may be due to the high stridency of this segment. The remaining 18 reversals (those not involving /č/) all have a negative sonority distance of *3* or less. Another striking pattern in table 6.8 is that for all contrasts involving the same absolute sonority distance but opposite signs (e.g., *6* vs. *–6*), the number of attested pairs which confirm the sonority law is invariably greater than the number of pairs which reverse it. For example, for the distances *6* and *–6* there are 6 pairs vs. 1, respectively. This is also a nice confirmation of the hypothesis. This match up is easier to see in the following table, in which I pair each positive differential with its corresponding negative having the same absolute value (e.g., *9* and *–9*):

Table 6.9: Overall results for 83 pairs of test items based on the relative sonority distance between the initial phonemes

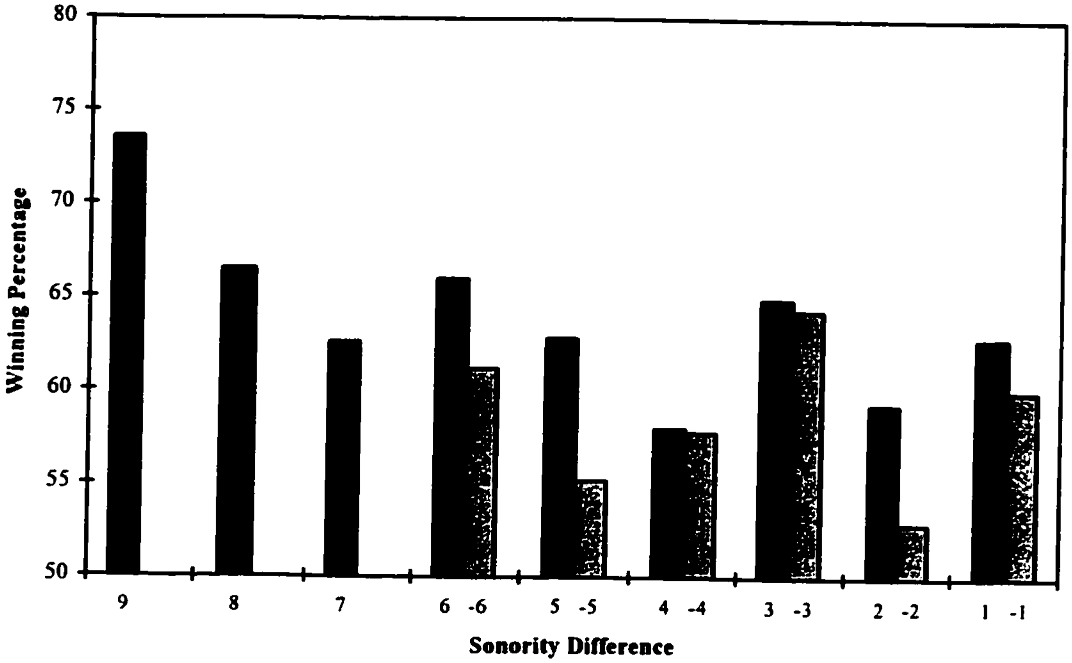
difference between sonority indices	number of pairs	votes in favor	votes against	percentage of votes in favor
9	2	488	175	73.6%
–9	0	–	–	–
8	4	880	443	66.5
–8	0	–	–	–
7	5	1034	619	62.6
–7	0	–	–	–
6	6	1304	673	66.0
–6	1	202	128	61.2
5	6	1245	737	62.8
–5	1	181	147	55.2
4	7	1340	971	58.0
–4	1	190	139	57.8
3	6	1253	679	64.9
–3	4	849	472	64.3
2	12	2352	1616	59.3
–2	3	524	466	52.9
1	14	2900	1719	62.8
–1	11	2180	1451	60.0

In table 6.9 above, I sum up the total number of responses for all winning conjunct orders having the same sonority distance and sign. For example, in table 6.4 *hicey-kicey* received 259 votes, while *kicey-hicey* got 73. These two numbers are included in table 6.9 in the columns labeled "votes in favor" and "votes against", respectively, in the row corresponding to a sonority difference of *8* (in the positive direction). The rightmost column in table 6.9 indicates the percentage of total votes in favor of the winning conjunct orders subsumed in each row (the second column lists how many pairs of test items are factored into each of these totals). For example, for the row involving a sonority distance of

–1, the percentage of total votes in favor (60.0%) is calculated by dividing 2180 by the sum of (2180 + 1451).

A noteworthy feature of table 6.9 is that for each contrast (pair of adjacent rows) having the same absolute difference but opposite signs (e.g., *3* and *–3*), the percentage of total votes in favor of the winning order is always greater for the positive differential value than it is for the negative one. For example, in the case of the 12 pairs involving a distance of *2*, the overall margin of victory is 59.3%, but for the 3 pairs at *–2* it is only 52.9% Consequently, the total percentage of votes in favor of the winning conjunct orders is 62.6% overall for the 62 pairs which obey the sonority law but only 59.5% for the 21 pairs which violate it. All of these facts point towards the same general conclusion, namely, that the preferred orders which confirm the sonority law tend to have a greater margin of victory than those pairs which reverse it. The following figure summarizes the results displayed in table 6.9:

Figure 6.2: Relationships between direction and amount of sonority difference and responses in favor of the preferred orders, in percents, taken from table 6.9



The figure above graphically illustrates the fact that pairs which obey the sonority hypothesis (black columns) always have a larger winning percentage than the corresponding reversals (gray columns). Furthermore, as the absolute sonority difference decreases (from left to right), there is a general tendency for the winning percentage values to even out. Thus the trend in the height of the black columns very gradually drops downward from left to right, while the height of the gray columns tends to rise slightly. What these data indicate is that the relative amount of distance between the sonority indices of the two initial segments (plus their direction) does have some impact on the overall outcomes of the test pairs, as well as on their robustness.

In spite of the above results, however, the correlations between sonority differences (plus direction) and two other potential predictor variables are rather low. For the 48 significant pairs which conflict (from (6.3) and (6.4)), the correlation between the relative sonority distance and the percentage value (margin of victory) of the winning conjunct order is .34 ($p = .0181$). When sonority difference is correlated with the mean judgement strength of the winning order (on a scale of 1 to 3), $r = .18, p = .22$. These latter two tests show that the individual percentage values of the winning conjunct orders as well as their mean confidence of judgement ratings are in general not very strong predictors of the observed outcomes, when compared with relative sonority distances.

This last point brings us to the topic of judgement ratings — how confident the respondents were about their choice of preferred conjunct order for each test pair. This is the fourth area in which additional statistics would be beneficial. A striking pattern in table 6.4 is that the mean judgement score for the winning order in each case is usually higher than that of the losing order. Among the first 51 pairs (those whose *p* value is significant), this tendency holds true 50 times and is reversed only once. Among the last 48 pairs in the table (the nonsignificant ones), the mean judgement strength for the preferred order is higher 28 times, that of the loser is higher 18 times, and for 2 pairs they are equal. Additional tests with mean judgement ratings can probe their correlations with the percentage values of the different conjunct orders: (1) for all 99 pairs, using both the winning percentage (the higher of the two) and the losing order's percentage (the lower of each pair), $r = .45, p = .0000$; (2) for all 99 pairs, using only the winning percentages, $r = .58, p = .0000$; (3) for only the 51 significant pairs, using both the winners' and losers' percentages, $r = .63, p = .0000$; and (4) for only the 51 significant pairs, using only the winning percentage values, $r = .49, p = .0003$. Finally, I wanted to see how well the mean judgement strengths correlate with the overall outcome for each pair, i.e., whether it confirms or violates the sonority law. Accordingly, I assigned the value *2* to pairs which obey the sonority hypothesis and *1* to reversals. When the mean judgement strength of the winning conjunct order for the 48 significant conflicting pairs is correlated with this index (*1* or *2*) for the pair's general result, $r = .21, p = .14$. The conclusions to be drawn from these facts are that overall, the confidence ratings are higher for the 51 significant pairs than for the other 48, and they tend to be higher for the preferred conjunct orders than for their counterparts. All of these generalizations are logical and unsurprising.

As a fifth and last indication of the function of sonority in reduplicative rhyming expressions, the instructions on the questionnaire asked each subject to invent one new pair of their own choosing (cf. §6.4). The purpose for this was to test the sonority law with spontaneous data created by other native speakers. Not all respondents performed the task correctly. Furthermore, even some of those who did so gave conjunct pairs in which the onsets were equal in sonority. Nevertheless, of a total of 227 conflicting pairs, 138 confirm the sonority hypothesis while 89 do not. This outcome is highly significant (60.8% vs. 39.2%, $p = .0007$), and further authenticates my results and claims.

To recap the statistical analysis of the psycholinguistic experiment discussed in this section, the role of sonority in predicting preferred conjunct orders is strongly confirmed, in many different ways. The best indicator of the result for each pair of test items is simply which conjunct begins with a more sonorous segment. After this effect is factored out, the relative amount of sonority distance between the two initial segments helps to further explain the outcomes. Finally, the mean judgement ratings also account for some of the systematic variability in the data, but their importance is more limited. Since a number of different tests and approaches to understanding the results have been employed in this section, it would be helpful to summarize them by means of a table:

Table 6.10: Summary of the statistical analyses on the psycholinguistic data

1	Number of pairs tested: 99
2a	Number of significant pairs at $\alpha = .0005$: 51
2b	Number of pairs not attaining significance: 48
3a	Among 51 significant pairs, number which confirm the sonority law: 37 ($p = .0001$)
3b	Number of pairs which reverse the law: 11
4	Correlation between post hoc scale in (6.6) and universal scale in table 5.28: .54 ($p = .0091$)
5a	Number of total responses from all 332 subjects (for 83 conflicting pairs) which confirm the sonority law: 15,599 (57.0%) ($p = 0$)
5b	Number of total responses which reverse the law: 11,758 (43.0%)
6	Mean percentage of total responses for each subject which follow the sonority law: 57.0%

(cont. next page)

(Table 6.10 cont.)

7	Correlation of 332 individual percentage scores with age in years: .06 (p = .29)
8a	Overall margin of victory for 62 conflicting pairs which follow the sonority law: 62.6%
8b	Overall margin of victory for 21 pairs which reverse the law: 59.5%
9	Correlation of sonority difference and direction with percentage value of winning order (for 48 significant conflicting pairs): .34 (p = .0181)
10	Correlation of sonority difference with mean judgement rating of winning order (for 48 significant pairs): .18 (p = .22)
11a	Correlation of mean judgement rating with percentage value of conjunct orders for all 99 pairs (both winning and losing orders): .45 (p = .0000)
11b	Correlation of mean judgement rating with percentage value of conjunct orders for all 99 pairs (winning orders only): .58 (p = .0000)
11c	Correlation of mean judgement rating with percentage value of conjunct orders for 51 significant pairs (both winning and losing orders): .63 (p = .0000)
11d	Correlation of mean judgement rating with percentage value of conjunct orders for 51 significant pairs (winning orders only): .49 (p = .0003)
12	Correlation of mean judgement rating with outcome result for 48 significant pairs (winning orders only): .21 (p = .14)
13a	Among 227 hypothetical pairs created by respondents, number which confirm the sonority law: 138 (60.8%) (p = .0007)
13b	Number of these spontaneous pairs which reverse the law: 89 (39.2%)

6.6 Alternative interpretations

In this section I briefly consider two alternative hypotheses which could potentially confound my results by explaining the observed patterns better than sonority does. Each one, however, turns out to be weaker than the sonority law. First, at the end of the questionnaire I asked the subjects whether they noticed any general trends in their own responses indicating what may have guided their choices (cf. §6.4). Many of them answered that alphabetic order played a role, i.e., conjunct A prefers to begin with a letter occurring earlier in the alphabet than that of conjunct B. Consequently, it is worth following up this hypothesis. Among the 51 significant pairwise results, 30 follow alphabetic order and 21 do not. This does not differ significantly from chance (*p* = .131). Also, among the total responses from all 332 subjects for all 99 test items, 16,974 individual scores confirm the alphabetic order pattern while 15,658 reverse it. This overall proportion (52.0% vs. 48.0%) is less robust than that of sonority.

Second, another obvious possibility which might affect the results is lexical frequency. One hypothesis along these lines is that conjunct A begins with a segment which is more common word-initially in English than the onset of conjunct B. To test this I used the CELEX database of approximately 17.9 million words (Burnage 1990). Of these around 1.3 million come from spoken materials and the rest (16.6 million) from written texts, resulting in about 54,000 distinct words. In comparing the overall token frequencies of the initial segments of the conjuncts, CELEX correctly predicts 31 results out of the 51 significant test pairs, and gets the remaining 20 wrong (*p* = .080). (Comparing the initial consonant plus vowel sequence in each conjunct leads to an even lower score.) Furthermore, in the tally of all responses from all subjects for all 99 pairs, CELEX has a winning result of 17,049 scores vs. 15,583 wrong ones. This proportion (52.2% vs. 47.8%) is also less significant than that obtained with the sonority law. Below I summarize the overall results of the three competing hypotheses:

Table 6.11: Statistical comparison of the three alternative explanations for the psycholinguistic data

hypothesis	no. of pairs matching predictions	no. of pairs reversing predictions	p	% of all responses matching predictions	% of all responses reversing predictions
sonority law	37	11	.000	57.0	43.0
alphabetic order	30	21	.131	52.0	48.0
lexical frequency	31	20	.080	52.2	47.8

As table 6.11 confirms, for the two (arguably) best indicators of goodness of fit with respect to the psycholinguistic experiment, the sonority law consistently leads to better overall results than its most obvious competitors. Its binomial p value for the number of pairs confirming the predictions is the most statistically reliable of the three. Furthermore, its margin of victory in terms of total individual responses (57.0% vs. 43.0%) translates into hundreds of scores in its favor. I therefore conclude that these facts statistically support the psychological reality of the initial segment sonority law from table 6.1.

6.7 OT analysis

In this section I sketch a very brief formal analysis of the phenomenon examined in this chapter. Rather than introducing a new, ad hoc, and language-specific constraint to account for the attested patterns, I propose to derive them from a generalized version of the Syllable Contact Law (cf. §1.2.3 and §6.2). All we need to do is slightly reformulate the SCL so that it governs not just a cluster of two heterosyllabic ***consonants***, but any sequence of two adjacent segments across a syllable boundary (be they consonants or vowels). That is, the domain of the SCL is usually considered to be ...C]$_{\sigma\cdot\sigma}$[C.... Suppose now that we generalize this to any syllabic hiatus: ...X]$_{\sigma\cdot\sigma}$[X..., where X can be either a vowel or a consonant. For example, in a hypothetical pair such as *roshy-toshy*, one of the points of syllable contact is the /i/ of *roshy* immediately followed by the /t/ of *toshy*: *rosh*/i/]$_{\sigma\cdot\sigma}$[/t/*oshy*. If we allow the SCL (or a constraint similar to it) to evaluate this type of syllable juncture as well, we can now account for why the order *toshy-roshy* is dispreferred: its syllable contact (between the two morphemes) is worse than the alternative, because /r/ is higher in sonority than /t/ and therefore makes for a less harmonic (word-internal) onset. That is, [...i]$_{\sigma\cdot\sigma}$[t...] is preferred over [...i]$_{\sigma\cdot\sigma}$[r...] on grounds of general (universal) unmarkedness, all else being equal. On the other hand, the consonant at the very beginning of the entire prosodic word is by definition immune to the SCL since it is not immediately preceded by any other segment. (Actually, as I noted in §1.2.3, 1.2.4, and 6.2, facts such as these can ultimately be derived from the Sonority Dispersion Principle itself.) I therefore posit the following constraint, modeled after Murray and Vennemann's (1983:520) "Extended Syllable Contact Law":

(6.7) Generalized Syllable Contact Law (GSCL)

> A heterosyllabic sequence of two segments *A.B* is more harmonic the higher the sonority of *A* and the lower the sonority of *B*.

I assume, following McCarthy and Prince (1993a-b), that in a situation of this type, word-internal morphemes can be linearly unordered in the input. In this case the correct output form is straightforwardly chosen by the GSCL, regardless of where this constraint is ranked in the language-specific hierarchy of English:

(6.8)

	GSCL
a. ☞ roshy-toshy	
b. toshy-roshy	*!

In (6.8), candidate *b* (*toshy-roshy*) violates GSCL, so it is a clear loser even without other constraints. It violates GSCL (fatally) because the initial /r/ at the beginning of conjunct B is a less than perfect onset. Candidate *a* (*roshy-toshy*) is inherently more harmonic than *toshy-roshy* since the /t/ at the beginning of conjunct B in *roshy-toshy* perfectly fulfills GSCL by virtue of having the lowest possible sonority index. However, a complicating issue is that the preceding /i/ (at the end of conjunct A in both candidates) is a suboptimal nucleus since we could potentially improve on it (and therefore on the satisfaction of GSCL) by lowering it to an /a/ (*ceteris paribus*). Nevertheless, I assume that this particular "repair" is blocked by a series of high-ranking faithfulness constraints of the IDENT(FEATURE) family which dominate GSCL. For the sake of simplicity I have left these out of the tableau above. However, this detail highlights the fact that GSCL is in reality a gradient constraint rather than a categorical one (cf. SYLLABLE CONTACT SLOPE (Bat-El 1996, Shin 1997, Davis 1998) and SONORITY CONTOUR SLOPE (Rose 2000), mentioned in §1.2.3). Again I eschew this complication by limiting our consideration here to just the two competing candidates which reverse the order of the two morphemes. While *roshy-toshy* may violate GSCL to a minor degree because of the nucleus /i/ (at the end of conjunct A), it is clear that *toshy-roshy* does even worse on this constraint, and that is all that matters here. I also ignore the fact that in an exhaustive tableau we would need to evaluate two other loci of contact in each candidate as well: the syllable gap between the *o* and the *sh* in the middle of each conjunct. All of these minutiae would take us too far afield of our main concern, which is simply to explain why *roshy-toshy* is preferred over **toshy-roshy*.

In conclusion, in this little exercise I have purposely glossed over a number of crucial issues which are orthogonal to the main focus of this chapter. These include, among other things, how violations of the sonority law (and/or GSCL) should be quantified (to simplify they are treated here as categorical), and how to deal with the numerous exceptions to the general *roly-poly* type of pattern (both in attested live freezes as well as in my experimental corpus). I refer the reader to Anttila and Cho (1998) for an OT model capable of dealing with free variation, and to Boersma and Hayes (2001) for a conceptualization of OT constraints as statistical tendencies or probabilities rather than outright (all-or-nothing) grammatical prohibitions. Nevertheless, I hope to have given a small glimpse of how the OT analysis needs to work, as well as the centrality of sonority in the principal constraint. Furthermore, by invoking a generalized version of the Syllable Contact Law, I have shown that we can deal with the formal aspects of this phenomenon by relying on mechanisms which are independently motivated cross-linguistically, such as the Sonority Dispersion Principle (cf. chapter 1). Consequently, there is no need to posit a novel, ad hoc constraint which would probably be active in only one language (English).

CONCLUSION

To summarize this dissertation, let us return to the questions raised in the Introduction and review the answers that have been provided. (1) *What is sonority?* Sonority is a scalar phonological feature which classifies all speech sounds into an autonomous hierarchy accessible to the constraint component CON. It is thus a theoretical primitive of Universal Grammar. (2) *What is the articulatory and/or acoustic basis of sonority?* The best way to characterize the physical basis of sonority is in terms of intensity. We have seen that phonetic measurements consistently yield a near perfect correlation between sonority indices and mean intensity values for the entire range of phonemic segments from English and Spanish. Peak intraoral air pressure measurements provide additional confirmation of the articulatory reality of sonority in that the two scales are very strongly correlated in a negative direction. (3) *How should the sonority hierarchy be quantified?* I have shown that it is both feasible and appropriate to define sonority by means of a linear regression equation such as $sonority = 5.16 + .37 \times dB$. However, in terms of actual phonological analyses it is sufficient to express sonority indices as whole integers with identical distances between successive pairs. More precise and/or language-specific indices are too variable to be of much practical use. (4) *Is the sonority scale universal or language-specific?* We have seen that it is possible and beneficial to establish a single, exhaustive sonority hierarchy which is valid for all languages. Furthermore, phonetic measurements of sonority display remarkable similarity across speakers, genders, and prosodic positions. However, minor variations within the phonological sonority scale are possible, but these are limited to a restrictive and highly-constrained set of adjustments, most of which are quite local in nature.

APPENDIX A

COMPLETE LIST OF ENGLISH WORDS USED TO ELICIT PHONETIC DATA

As discussed in §4.2.3, the following list exhaustively displays all of the English words used in obtaining instrumental data for four of the five phonetic parameters (intensity, air pressure, air flow, and duration). The items used for F_1 measurements are discussed separately in §4.3.3.1. Following each word I indicate which of its segments were actually analyzed and included in the statistical results presented in chapter 4. The order of presentation here follows that of one of the three randomized lists which the subjects had in front of them when reading the target sentences.

match	m æ č
lay	l e
comb	k o m
badge	b æ ǰ
amount	ə m
can	k æ n
thaw	θ ɔ
laugh	l æ f
mass	m æ s
bet	b ɛ t
tin	t ɪ n
car	k a r
zen	z ɛ n
address	ə
hay	h e
nab	n æ b
mat	m æ t
gain	g e n
bit	b ɪ t
alarm	ə l
din	d ɪ n
coal	k o l
bait	b e t
he	h i
gin	ǰ ɪ n
map	m æ p
rouge	r u ž
new	n u
abode	ə b o d
math	m æ θ
beet	b i t
who	h u
saw	s ɔ
bought	b ɔ t
mack	m æ k
nag	n æ g
call	k a l
jaw	ǰ ɔ
attack	ə t æ k
hoe	h o
way	w e
lathe	l e ð
chin	č ɪ n
jazz	ǰ æ z
core	k o r
boot	b u t
vane	v e n
accord	ə k
know	n o
coy	k
sin	s ɪ n
put	p ʊ t
have	h æ v
mash	m æ š
yea	y e
cone	k o n
gong	g ɔ ŋ
kin	k ɪ n
assist	ə s
shin	š ɪ n
knee	n i
mad	m æ d
Latin	l æ ʔ
bot	b a t
raw	r ɔ
cam	k æ m
arrest	ə r
pin	p ɪ n
butt	b ʌ t
then	ð ɛ n
nay	n e
vision	v ɪ ž
bat	b æ t
law	l ɔ
ray	r e
bin	b ɪ n
may	m e
fin	f ɪ n
uh-oh	(ʔ) ʌ ʔ
gnaw	n ɔ
boat	b o t
thin	θ ɪ n
paw	p ɔ

APPENDIX B

COMPLETE LIST OF SPANISH WORDS USED TO ELICIT PHONETIC DATA

cosa	[una kó.sa]	‘thing’
a***bis***mo	[un a.βís.mo]	‘abyss, chasm’
péndulo	[um pén.du.lo]	‘pendulum’
rosa	[una řó.sa]	‘rose’
ñata	[una ñá.ta]	‘pug-nosed female’
alto	[un ál.to]	‘tall person (m.)’
jota	[una hó.ta]	‘jot, bit’
pinza	[una pín.sa]	‘tweezers; clamp’
carne	[una kář.ne]	‘meat; flesh’
gota	[una γó.ta]	‘drop (of liquid)’
tos	[una tós]	‘cough, coughing’
piso	[um pí.so]	‘floor; ground’
re***loj***	[un ře.lóh]	‘clock, watch’
alma	[un ál.ma]	‘soul, spirit’
sopa	[una só.pa]	‘soup’
choza	[una čó.sa]	‘hut; cabin’
peso	[um pé.so]	‘weight; heaviness’
oftalmólogo	[un òf.tal.mó.lo.γo]	‘ophthalmologist’
moza	[una mó.sa]	‘girl, lass, maid’
punto	[um pún.to]	‘point, dot’
bosque	[um bós.ke]	‘woods, forest’
campo	[uŋ kám.po]	‘field; countryside’
gozo	[uŋ gó.so]	‘joy, delight, pleasure’
panza	[una pán.sa]	‘belly’
yuca	[una ǰú.ka]	‘piece of manioc’
dosis	[una ðó.sis]	‘dose; amount, portion’
puso	[um pú.so]	‘(he/she) put’
taxi	[un ták.si]	‘taxi’
ponche	[um póñ.če]	‘punch (beverage)’
voz	[una βós]	‘voice’
nota	[una nó.ta]	‘note’
pozo	[um pó.so]	‘well; pit, hole’
inyección	[una ìñ.ǰek.syón]	‘injection’
huelga	[una wél.γa]	‘(labor) strike’
paso	[um pá.so]	‘step’
fosa	[una fó.sa]	‘grave, pit, tomb’
ho***rós***copo	[un o.řós.ko.po]	‘horoscope’
admisión	[una àð.mi.syón]	‘admission, acceptance’

dos	[un dós]	‘two, deuce’
***ét**nico*	[un ét.ni.ko]	‘ethnic person’
***car**ta*	[una kář.ta]	‘letter’
***ag**nóstico*	[un aγ.nós.ti.ko]	‘agnostic person’
***lo**sa*	[una ló.sa]	‘slab, stone, tile’
***hip**nosis*	[una ip.nó.sis]	‘hypnosis’
***yun**que*	[uñ ǰúŋ.ke]	‘anvil’
***ab**negación*	[una àβ.ne.γa.syón]	‘self-denial, selflessness’

APPENDIX C

ORAL AIR FLOW MEASUREMENTS

As discussed in §4.3.4.1, in this appendix and the next one I give air flow data broken down separately for the oral and nasal channels, respectively. For most consonants these oral air flow measurements are the peak values which occur at any point during their articulation. For the nasals, however, the values given usually correspond to oral air flow measurements at the point when nasal air flow is at its peak. Consequently, these values should not be assumed to be peak oral air flow measurements for nasal consonants.

Table C.1: Oral air flow of onset consonants for English males (in ml/sec)

segment	mean	*n*	sd
p	1427.8	36	363.9
t	1409.7	23	377.8
k	1227.8	131	386.1
č	1063.9	12	361.1
h	1055.6	60	338.9
š	941.7	12	180.6
f	701.4	12	169.4
b	670.9	152	194.4
s	663.9	35	258.3
θ	627.8	24	125.0
d	625.0	13	161.1
ž	544.4	12	113.9
ǰ	526.4	36	141.7
ð	488.9	12	108.3
v	472.2	24	163.9
z	415.3	12	138.9
g	388.9	23	105.6

(cont. next page)

Table C.2: Oral air flow of onset consonants for English females (in ml/sec)

segment	mean	*n*	sd
p	1275.0	36	508.3
t	1227.8	24	375.0
k	880.6	132	441.7
h	880.6	60	483.3
č	836.1	12	241.7
f	627.8	11	213.9
š	625.0	12	191.7
s	566.7	35	183.3
θ	511.1	24	222.2
b	481.9	149	213.9
d	383.3	12	163.9
ǰ	372.2	36	163.9
z	309.7	12	127.8
v	297.2	23	133.3
ž	252.8	12	138.9
g	250.0	24	122.2
ð	247.2	12	158.3

(cont. next page)

(Table C.1 cont.)

r	200.0	45	58.3
l	186.1	69	61.1
y	186.1	12	63.9
w	138.9	12	52.8
ʔ	81.9	30	83.3
n	38.9	84	16.7
m	37.5	120	25.0

(Table C.2 cont.)

r	152.8	42	66.7
w	144.4	12	55.6
y	134.7	10	33.3
l	122.2	69	44.4
ʔ	69.4	31	47.2
m	30.6	120	22.2
n	29.1	84	13.9

Table C.3: Oral air flow of coda consonants for English males (in ml/sec)

segment	mean	*n*	sd
š	888.9	12	150.0
f	826.4	12	277.8
s	786.1	13	266.7
p	748.6	12	213.9
θ	733.3	12	180.6
k	691.7	23	266.7
č	627.8	12	155.6
ž	608.3	12	180.6
b	602.8	12	250.0
ð	572.2	12	116.7
d	513.9	23	116.7
ǰ	477.8	12	105.6
v	419.4	10	91.7
z	411.1	12	136.1
r	375.0	15	105.6
t	359.7	138	147.2
l	322.2	17	77.8
g	316.7	12	122.2
ŋ	87.5	12	41.7
m	52.8	24	47.2
n	33.3	214	33.3

Table C.4: Oral air flow of coda consonants for English females (in ml/sec)

segment	mean	*n*	sd
š	747.2	12	222.2
f	677.8	10	319.4
θ	661.1	12	158.3
s	644.4	12	263.9
k	586.1	24	222.2
č	480.6	12	127.8
p	413.9	12	138.9
b	327.8	11	150.0
ð	313.9	12	63.9
d	288.9	22	83.3
t	270.8	140	169.4
v	263.9	11	86.1
ǰ	251.4	12	102.8
z	241.7	12	91.7
ž	236.1	12	136.1
r	219.4	13	41.7
l	200.0	16	75.0
g	180.6	12	63.9
ŋ	98.6	12	55.6
n	27.8	203	22.2
m	16.7	23	22.2

Table C.5: Oral air flow of vowels for English males (in ml/sec)

segment	mean	*n*	sd
ʊ	394.4	12	116.7
ʌ	341.7	24	130.6
u	308.3	48	72.2
ɪ	287.5	157	169.4
ɛ	281.9	36	91.7
e	279.2	128	80.6
æ	262.5	226	83.3
o	261.1	98	77.8
a	258.3	65	77.8
i	256.9	36	75.0
ɔ	255.6	76	94.4
ə	216.7	87	75.0

Table C.6: Oral air flow of vowels for English females (in ml/sec)

segment	mean	*n*	sd
ʊ	282.0	12	108.3
ʌ	216.7	24	91.7
ɛ	181.9	36	91.7
o	180.6	94	75.0
u	169.4	48	86.1
e	163.9	125	55.6
ɪ	152.8	147	77.8
a	150.0	61	63.9
æ	150.0	219	50.0
ɔ	145.9	77	66.7
i	127.8	36	58.3
ə	125.0	85	55.6

Table C.7: Oral air flow of onset consonants for Spanish males (in ml/sec)

segment	mean	*n*	sd
č	1254.3	12	442.7
s	999.0	12	466.2
t	786.6	24	355.5
h	746.1	12	228.1
p	599.2	120	238.5
d	578.8	13	279.8
r̃	540.8	12	205.0
f	535.5	12	253.9
k	523.7	48	184.6
g	444.6	13	192.5
b	409.4	13	169.1
ř	376.7	11	110.9
ð	369.5	11	201.7
ǰ	347.3	24	162.2
β	218.7	21	106.1
w	200.4	12	77.9
l	196.8	24	47.8

(cont. next page)

Table C.8: Oral air flow of onset consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
č	901.6	12	273.2
h	586.3	12	339.9
f	453.4	11	185.7
p	375.6	117	164.9
k	362.0	43	169.1
t	338.2	23	111.1
s	331.4	11	210.8
d	304.9	12	182.2
r̃	258.9	12	106.7
b	238.6	13	143.4
ǰ	221.3	24	107.2
ð	218.0	12	117.0
ř	199.2	12	90.9
g	194.5	12	112.9
β	138.9	23	87.7
w	129.4	12	47.1
l	125.2	24	53.8

(cont. next page)

(Table C.7 cont.)

γ	171.4	11	105.7
m	31.9	12	11.4
n	30.5	12	16.5
ñ	12.9	12	28.4

(Table C.8 cont.)

γ	108.8	12	72.7
m	20.4	12	18.2
n	4.5	12	9.6
ñ	1.2	12	2.9

Table C.9: Oral air flow of coda consonants for Spanish males (in ml/sec)

segment	mean	*n*	sd
s	694.2	72	392.1
f	564.6	11	413.9
ř	457.8	24	166.9
h	448.6	9	262.6
k	391.9	12	252.1
l	203.6	36	77.1
γ	198.2	12	182.1
t	159.9	12	189.8
β	143.0	11	120.1
ð	103.6	10	133.9
ŋ	76.5	12	87.8
n	39.6	47	26.9
p	34.8	10	40.6
ñ	24.0	24	15.2
m	17.6	12	13.0

Table C.10: Oral air flow of coda consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
f	388.6	12	312.4
s	367.7	72	202.4
h	345.4	12	270.3
k	330.2	11	102.9
ř	265.1	23	100.8
l	166.7	36	77.6
γ	128.4	11	91.1
t	118.3	12	96.9
ð	78.0	12	98.7
ŋ	28.6	12	21.1
n	21.7	48	22.5
β	16.0	11	26.0
ñ	9.6	24	9.8
p	8.9	12	11.4
m	1.5	12	2.0

Table C.11: Oral air flow of vowels for Spanish males (in ml/sec)

segment	mean	*n*	sd
u	315.7	48	112.2
o	306.8	250	128.6
e	276.2	48	120.9
a	239.2	144	122.3
i	200.3	55	90.2

Table C.12: Oral air flow of vowels for Spanish females (in ml/sec)

segment	mean	*n*	sd
e	164.0	48	69.1
o	149.6	251	63.3
u	136.6	48	81.2
a	123.7	143	58.0
i	104.4	60	62.2

APPENDIX D

NASAL AIR FLOW MEASUREMENTS

The nasal air flow values below represent the peak measurements only for nasal consonants. For all other segments they usually correspond to the point at which oral air flow is at its maximum. See §4.3.4.1 for further discussion.

Table D.1: Nasal air flow of onset consonants for English males (in ml/sec)

segment	mean	*n*	sd
n	325.0	84	63.9
m	290.3	120	61.1
h	91.7	60	63.9
y	72.2	12	33.3
l	61.1	69	27.8
r	61.1	45	27.8
g	55.6	23	27.8
ð	55.6	12	16.7
v	55.6	24	11.1
z	54.2	12	11.1
ʔ	54.2	30	30.6
ž	52.8	12	8.3
d	50.0	13	13.9
w	50.0	12	8.3
b	45.9	152	8.3
ǰ	45.8	36	8.3
p	41.7	36	8.3
s	41.7	35	16.7
θ	41.7	24	16.7
č	38.9	12	11.1
f	37.5	12	2.8
t	37.5	23	2.8
k	36.1	131	5.6
š	36.1	12	2.8

Table D.2: Nasal air flow of onset consonants for English females (in ml/sec)

segment	mean	*n*	sd
n	190.2	84	69.4
m	163.9	120	61.1
h	108.3	60	105.6
č	69.4	12	61.1
ð	61.1	12	36.1
f	55.6	11	38.9
s	55.6	35	30.6
θ	52.8	24	30.6
š	47.2	12	11.1
l	47.2	69	22.2
z	45.8	12	19.4
p	41.7	36	22.2
t	41.7	24	22.2
ž	41.7	12	22.2
y	40.3	10	5.6
v	38.9	23	16.7
r	38.9	42	5.6
w	38.9	12	8.3
b	37.4	149	5.6
k	36.1	132	22.2
d	36.1	12	11.1
ǰ	36.1	36	11.1
ʔ	36.1	31	11.1
g	33.3	24	11.1

Table D.3: Nasal air flow of coda consonants for English males (in ml/sec)

segment	mean	*n*	sd
n	388.9	214	75.0
m	358.3	24	63.9
ŋ	334.7	12	50.0
d	88.9	23	41.7
b	80.6	12	36.1
ð	77.8	12	33.3
ǰ	72.2	12	19.4
g	66.7	12	16.7
č	63.9	12	86.1
t	62.5	138	33.3
z	61.1	12	11.1
v	55.6	10	8.3
ž	50.0	12	8.3
k	47.2	23	36.1
l	47.2	17	13.9
f	45.8	12	13.9
p	45.8	12	8.3
r	44.4	15	5.6
s	38.9	13	2.8
š	38.9	12	2.8
θ	38.9	12	2.8

Table D.4: Nasal air flow of coda consonants for English females (in ml/sec)

segment	mean	*n*	sd
n	183.3	203	72.2
m	180.6	23	66.7
ŋ	151.4	12	44.4
š	105.6	12	61.1
s	77.8	12	41.7
θ	66.7	12	25.0
k	52.8	24	30.6
č	50.0	12	33.3
f	41.7	10	13.9
d	38.9	22	11.1
t	37.5	140	13.9
p	36.1	12	5.6
g	36.1	12	5.6
b	36.1	11	5.6
ž	36.1	12	2.8
z	36.1	12	2.8
v	36.1	11	2.8
l	33.3	16	2.8
r	33.3	13	5.6
ǰ	31.9	12	2.8
ð	30.6	12	2.8

Table D.5: Nasal air flow of vowels for English males (in ml/sec)

segment	mean	*n*	sd
ə	150.0	87	44.4
ɪ	131.9	157	55.6
æ	115.3	226	55.6
i	101.3	36	69.4
e	90.3	128	55.6
ɛ	90.2	36	41.7
o	86.1	98	63.9
u	72.2	48	50.0

(cont. next page)

Table D.6: Nasal air flow of vowels for English females (in ml/sec)

segment	mean	*n*	sd
ə	86.1	85	27.8
ɪ	72.2	147	33.3
æ	63.9	219	30.6
i	61.1	36	38.9
ɛ	56.9	36	30.6
e	55.6	125	36.1
o	52.8	94	33.3
u	44.4	48	19.4

(cont. next page)

(Table D.5 cont.)

ʌ	66.7	24	36.1
ɔ	63.9	76	41.7
a	52.8	65	27.8
ʊ	44.4	12	8.3

(Table D.6 cont.)

ɔ	43.1	77	25.0
ʌ	41.7	24	13.9
a	38.9	61	13.9
ʊ	34.7	12	2.8

Table D.7: Nasal air flow of onset consonants for Spanish males (in ml/sec)

segment	mean	*n*	sd
ñ	302.4	12	118.5
m	293.5	12	136.5
n	269.8	12	96.8
h	124.5	12	93.4
γ	93.0	11	100.9
l	72.0	24	39.1
b	69.4	13	57.9
w	69.0	12	52.0
β	67.5	21	27.5
ǰ	62.1	24	24.7
s	61.9	12	47.1
g	61.4	13	46.7
d	59.4	13	13.5
ř	56.1	11	18.4
r̃	55.1	12	16.1
f	51.6	12	22.9
ð	51.5	11	13.7
t	46.4	24	19.5
p	45.0	120	13.5
k	41.4	48	13.9
č	35.5	12	5.3

Table D.8: Nasal air flow of onset consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
ñ	239.9	12	54.8
n	231.7	12	58.4
m	183.3	12	70.5
s	73.3	11	42.4
h	72.1	12	56.6
f	70.5	11	37.1
w	56.4	12	22.0
β	54.6	23	42.1
ǰ	51.0	24	15.4
l	49.2	24	8.7
b	48.1	13	8.6
d	47.8	12	12.5
γ	47.8	12	19.6
ř	47.0	12	13.6
g	44.6	12	11.3
ð	44.3	12	10.2
r̃	42.0	12	13.3
k	39.8	43	24.9
p	38.6	117	10.7
č	37.1	12	2.7
t	35.7	23	11.1

Table D.9: Nasal air flow of coda consonants for Spanish males (in ml/sec)

segment	mean	*n*	sd
n	386.7	47	144.7
m	366.8	12	142.3
ŋ	364.5	12	165.3
ñ	331.8	24	126.5
p	194.9	10	59.3
ð	187.4	10	97.0
t	141.9	12	133.3
β	132.0	11	89.6
γ	124.7	12	97.7
l	106.6	36	82.8
f	87.1	11	104.2
s	57.2	72	31.7
k	52.7	12	16.9
ř	48.4	24	12.9
h	44.4	9	21.5

Table D.10: Nasal air flow of coda consonants for Spanish females (in ml/sec)

segment	mean	*n*	sd
n	249.2	48	97.7
ñ	237.5	24	87.1
m	228.3	12	88.5
ŋ	222.2	12	79.4
p	145.7	12	53.1
β	126.9	11	52.4
ð	101.3	12	51.4
f	80.8	12	46.0
γ	71.5	11	24.5
l	56.6	36	22.6
t	55.1	12	26.2
s	46.9	72	20.4
k	46.7	11	8.7
h	40.7	12	6.5
ř	40.1	23	17.1

Table D.11: Nasal air flow of vowels for Spanish males (in ml/sec)

segment	mean	*n*	sd
i	100.5	55	69.8
u	87.9	48	73.7
a	87.7	144	53.9
e	64.2	48	38.8
o	60.4	250	41.1

Table D.12: Nasal air flow of vowels for Spanish females (in ml/sec)

segment	mean	*n*	sd
i	75.7	60	35.1
a	63.5	143	31.6
u	61.6	48	43.5
o	51.0	251	29.1
e	46.8	48	23.5

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