Subglottal Coupling and Vowel Space: An Investigation in Quantal Theory

by

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For my parents.

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Abstract

We describe the attenuation of the second vowel formant peak near the second resonance of the subglottal system, and test whether it is a quantal acoustic-articulatory relation (Stevens 1972, 1989) dividing front and back vowels. We find strong evidence for this hypothesis within English and cross-linguistically, and illustrate one way to test proposed quantal relations.

Thesis Supervisor: Professor Kenneth N. Stevens
Title: Clarence J. LeBel Professor of Electrical Engineering and Computer Science

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This thesis makes only indirect use of what I have learned in physics classes – many helped me fill in the chasms in the knowledge I needed to research and write it.

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Chapter 1

Introduction

> "Physical and physiological representations may represent unfamiliar territory for most phonologists. Nevertheless, the one who asks the question presumably is responsible for providing the answer."
>
> – John Ohala, "The Phonetics and Phonology of Place Assimilation"

Human speech is produced when the vocal tract filters the sound produced by the vibrating vocal folds, a seemingly simple system that forms the basis of the complexities of human language. There are approximately 6000 languages in the world today, each of which consists of words made from sounds drawn from a language-specific repertoire of 50-200 *phonemes*. Countless other languages have existed in the past. Yet all these languages draw their inventories from the same set of a few hundred possible sounds, a phonetic periodic table called the International Phonetic Alphabet (IPA). Each language has a distinctive sound pattern made up of a set of sounds and conditions on how they can be distributed in speech. The sound pattern of English prescribes long vowels after consonants like /b/ and /d/, short ones after consonants like /p/ and /t/, and allows words to end but not begin with /pt/, all rules which most other languages do not obey. Sounds can also be inflected in subtle ways that are utilized differently in different languages – an English speaker does not consciously notice that the /p/ in "pat" is more aspirated than that in "spat," but in many Indian languages, the same two sounds followed by a vowel would be perceived as different words.

Human speech systems are studied in two major contexts. Phonology aims to describe the sound patterns of the world's languages and construct a theory of how these sounds are represented in speakers' minds, based on generalizations over many languages. Phonetics is the study of the physical realization of sounds, which aims to understand the speech production process and how and why sounds differ. Broadly speaking, phonology is qualitative and deductive, while phonology is quantitative and inductive.

From either perspective, a successful theory of possible speech sounds must describe what categories (if any) make up their abstract representation, and what the basis is for these categories. Cross-linguistically, phonological rules are observed to always act on the same sets of sounds, called *natural classes*. A rule may act one way on (/i/,/e/,/æ/) and another (/a/,/o/,/u/), but never on any of the other nine possible pairs of three vowels. Furthermore, rules often operate on the same sets of two natural classes, such as the two above. Phonologists say that the two classes are defined by a difference in one binary-valued *feature*, such as [back]. The set (/i/,/e/,/æ/) is [-back] while (/a/, /o/, /u/) is [+back], referring to the horizontal position of the tongue when these vowels are produced. Every possible sound is then a vector of binary variables corresponding to features.

Feature theory is the basis of modern phonology, and a core set of features and their acoustic and articulatory correlates are more or less agreed on. However, a derivation of these features from phonetics is lacking – what defines the boundaries between segments differing by one feature, and why does human language make use of the features it does? Answers to these questions would provide the crucial connection between phonetics and phonology. One attractive proposal is Kenneth Stevens' quantal theory (Stevens 1972, 1989), in which features arise from nonlinear articulatory-acoustic relations in the vocal tract when an acoustic parameter of the speech signal rapidly shifts from one stable region to another for a linear articulatory movement (schematized in Fig. 1-1). For example, moving the tongue slowly from [+anterior] /s/ to [-anterior] /ʃ/ produces an abrupt transition between the two. The corre-

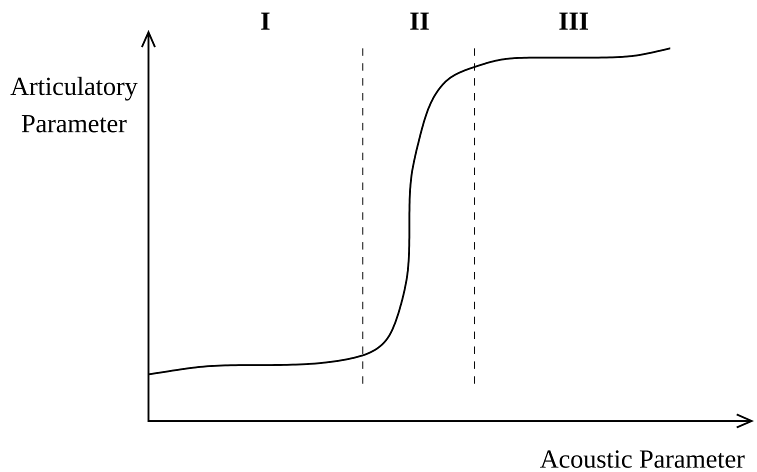


Figure 1-1: Schematic of a quantal relation. Regions I and III correspond to [+feature] and [-feature] values, region II is the abrupt transition between them.

sponding shift from a dominant higher (fifth or fourth) to lower (third) formant in the spectrum is the proposed *quantal relation* for the feature [anterior].

Quantal relations have been proposed for many features. Yet with the exception of studies on a few of those features (Stevens and Blumstein 1975, Ladefoged and Bhaskararao 1983, Perkell and Cohen 1989, Halle and Stevens 1991, Perkell et al. 2004), quantal theory is often cited and rarely tested, either directly or indirectly – most papers in the 1989 *Journal of Phonetics* special issue on quantal theory (Ohala 1989) are largely theoretical. One paper raises the "difficulty of [quantal theory's] verification" (ten Bosch and Pols, 1989: 63). This objection is valid, but symptomatic of more general facts – quantitative, testable theories are relatively new to both phonetics and phonology, and it is much easier to propose than test theories about language. Although some linguistic traditions search for laws, many important, established facts about human language are tendencies across all possible variables (language, gender, speaker, age, social class), implying a hefty burden of proof to conclusively falsify or support general hypotheses. Moreover, many more nonlinear acoustic-articulatory relations than are needed for quantal theory arise from the vocal tract – why are only some chosen as the basis for features? It is unknown whether quantal theory is a theoretical construct, a set of weak phonetic constraints, or "a principal factor shaping the inventory of... attributes that are used to signal distinctions in language" (Stevens 1989: 3). Each work on individual languages and speakers only gives modest evidence for or against even the last possibility.

However, such work must be done, not only out of good scientific practice, but as the only way to elucidate the basis of phonology (and perhaps phonetics). In this thesis, we demonstrate one way to investigate a nonlinear acoustic-articulatory relation and test whether it is used as a quantal relation. Specifically, we describe attenuation of the second formant peak (the "subglottal attenuation effect") near the second subglottal resonance due to oral-subglottal coupling, and test whether it is a quantal relation for [back]. Although this does involve data from a number of speakers and languages, we hope to show that testing quantal theory is both easier and more rewarding than one might expect, especially if the data are already at hand. At best we will have grounded a piece of phonology, and at worst understood an interesting nonlinear phenomenon of the physics of speech.

Chapter 2

Modeling Oral-Subglottal Coupling

2.1 Visualizing Speech

Speech is produced using the anatomy shown in Fig. 2-1. The diaphragm expels air from the lungs into the vocal tract, causing the vocal folds (glottis) to vibrate at high enough pressure. The glottal output is filtered by the vocal tract, whose shape can be changed by moving the *articulators*: Tongue body, tongue blade, tongue tip, tongue root, jaw, lips, uvula (not pictured), and velum. The Fourier transform of the sound pressure signal yields a spectrum whose resonant peaks vary in location and shape as the articulators move. The changing spectrum is most commonly viewed over time in a *spectrogram*, a frequency vs. time plot, as shown in Fig. 2-2. The changing frequency bands are *formants*. Different sounds have very distinctive formant patterns, and a spectrogram of speech can be readily parsed into segments upon listening, allowing for the quantitative study of how different speakers make the same sounds.

2.2 Modeling Speech

Fant's pioneering work (1960) demonstrated that the vocal tract can to a very good approximation be modeled as a linear system. Any linear system which can be written in terms of the same equations as force/distance or voltage/current can be represented as a mechanical or electrical circuit by making the appropriate changes of variables

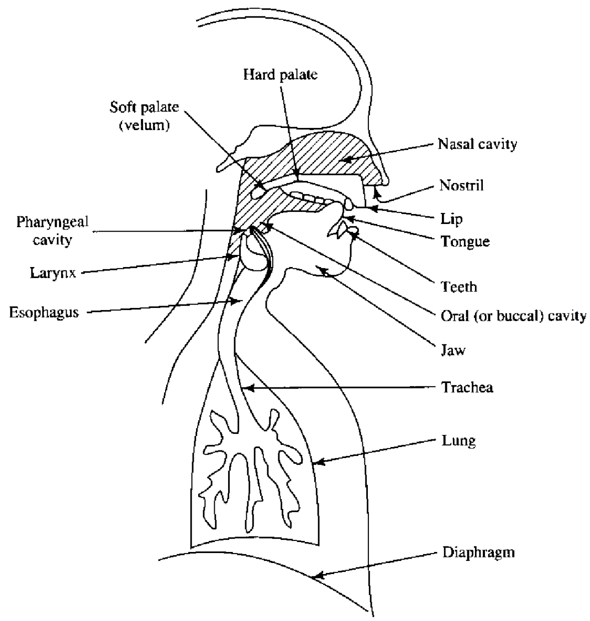


Figure 2-1: Schematized speech production anatomy, adapted from Kulkarni and Jain.

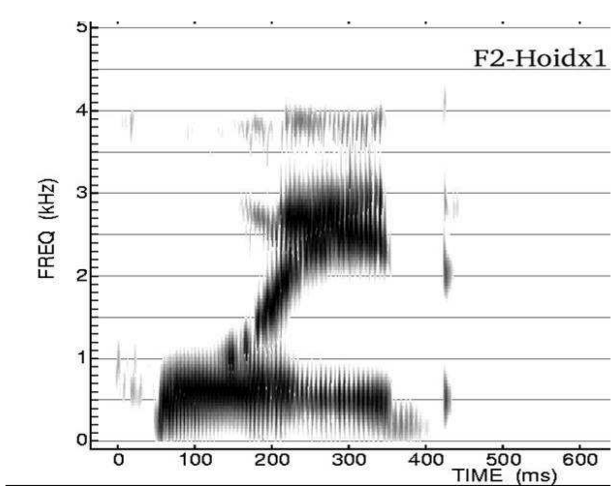


Figure 2-2: Sample spectrogram of "hoid."

Electric variable	Symbol	Acoustic variable	Symbol
Voltage	V	Sound Pressure [dynes/cm^2]	P
Current	I	Volume Velocity [cm^3/sec]	U
Impedance	Z	Acoustic Impedance [dyne-sec/cm^5] (Acoustic Ohms)]	Z
Resistance	R	Acoustic Resistance [Acoustic Ohms]	R
Inductance	L	Acoustic Mass [gm/cm^4]	M
Capacitance	C	Acoustic Compliance [cm^4/dyne]	C

Table 2.1: Acoustic-electric circuit equivalences, cgs acoustic units.

(Beranek 1986: Ch. 3). As sound pressure and air volume velocity are related by these equations, acoustic systems can conveniently be understood via electrical circuits. The vocal tract is directly analogous to a transmission line, where the tract walls have a position-dependent characteristic impedance based on the mechanical wall properties and tube area function. A full set of acoustic equivalences for electric variables is given in Table 2.1.

The volume velocity output of the glottis, $U_0(\omega)$, is filtered by the vocal tract, with transfer function $T(\omega)$. The volume velocity outside the mouth is then given by

$$U_m = U_0(\omega) \cdot T(\omega). \tag{2.1}$$

To model U_m, we first develop an expression for $T(\omega)$.

2.3 Transfer Function

The interaction between the oral and subglottal cavities can be represented by the circuit shown in Fig. 2-3.

Z_l is the impedance of the subglottal system, which can be approximated by a tube of length l_l terminated in a lossy capacitor of impedance Z_c (Ishizaka et al. 1976). Z_g is the glottal impedance, given by

$$Z_g = R_g + i\omega M_g, \tag{2.2}$$

where $R_g = \frac{12\mu h}{l_g d^3} + \frac{K\rho U_g}{(l_g d)^2}$, $M_g = \frac{\rho h}{l_g d}$, μ is the coefficient of viscosity, l_g, d, h are the

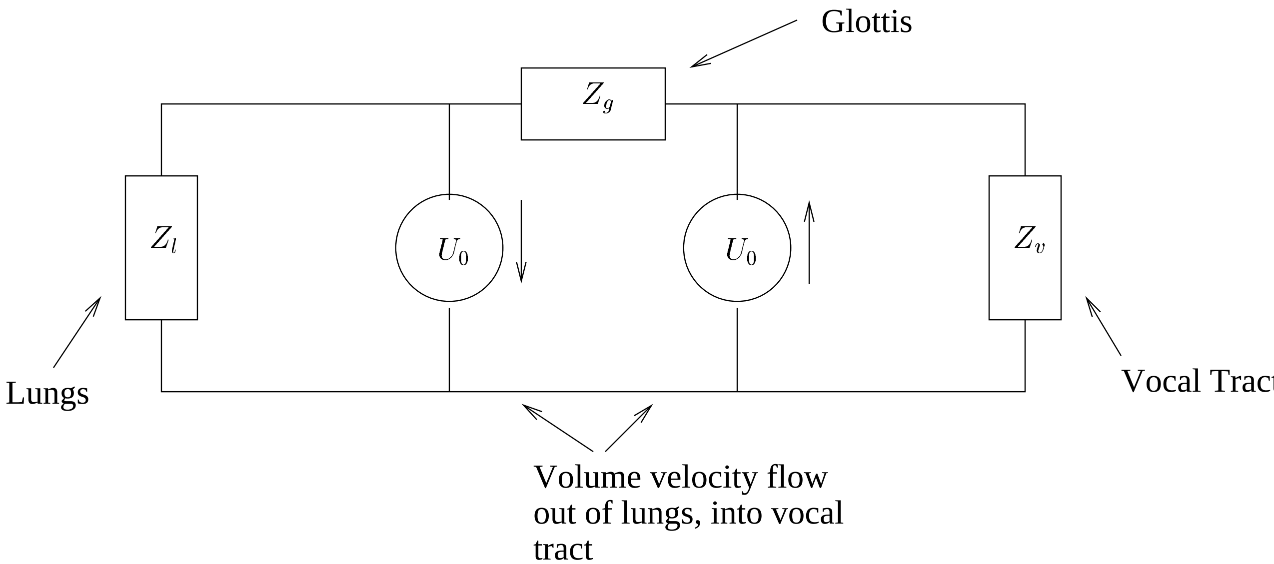


Figure 2-3: Circuit analogy of the vocal tract and subglottal system.

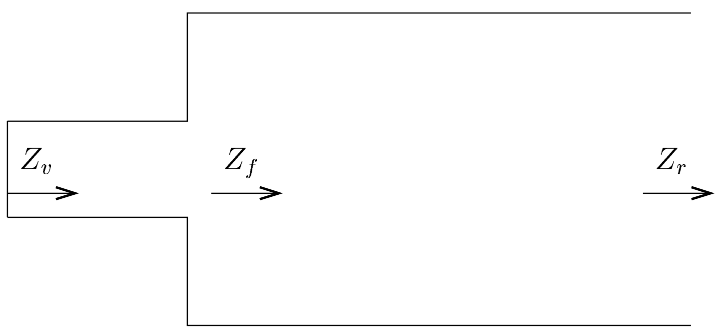
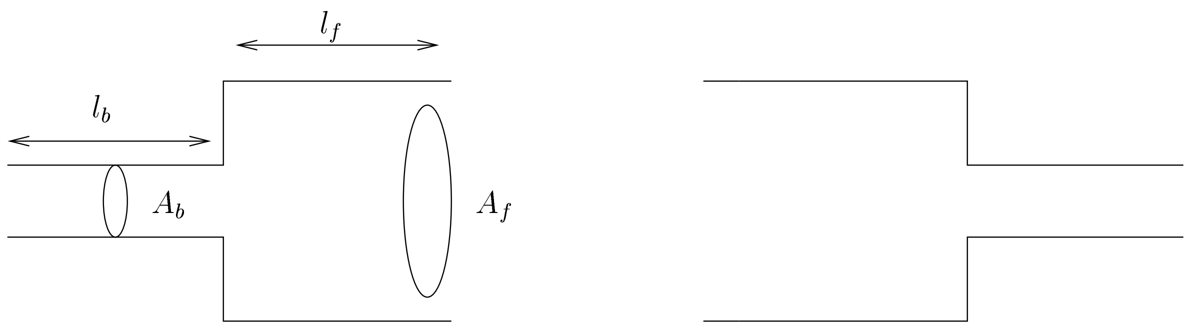


Figure 2-4: Two-tube model of the vocal tract, with impedances looking forward.

length, width, and thickness of the glottis, U_g is the volume flow through the glottis, ρ is the density of air in the vocal tract, and K is a constant taken to be ≈ 1 (Stevens 1998: 165). U_g changes with time, so we approximate it here by its average value in order to use a linear system analysis. This is a resonable approximation, as the period of U_g is small compared to speech phenomena.

The two volume velocity sources represent flow to and from the lungs, and Z_v is the impedance looking into the vocal tract from the glottis. To find Z_v, we use the two-tube model of the vocal tract shown in Fig. 2-4. This model is sufficiently accurate to predict the first two formant frequencies, which characterize different vowels (at least along the backness and height dimensions). We neglect the wall impedances,



/a/: A_b/A_f=1/8, l_b/l_f=1.2

/i/: A_b/A_f=8, l_b/l_f=1.5

Figure 2-5: Two-tube models of /a/ and /i/, adapted from (Fant, 1960: 66).

sacrificing accurate formant bandwidths for simplicity. Z_r is the radiation impedance at the lips, and Z_f is the impedance looking into the front cavity. For the frequency range simulated here, Z_r can be approximated as

$$Z_r = \frac{\rho\omega^2}{4c} K_s(\omega) + i\frac{\omega\rho(.8a)}{A_m}, \tag{2.3}$$

where A_m is the area of the mouth opening, taken here to be A_f, and $\pi a^2 = A_m$. $K_s(\omega)$ is a numerical factor accounting for the baffling effect of the head which can be approximated as 1 at low frequencies, rising to 1.7 by 2000 Hz., and 1.5 for frequencies above 2000 Hz (Stevens 1998: 153).

Below, we will model an /ai/ diphthong. The two-tube shapes and corresponding parameters for /a/ and /i/ are shown in Fig. 2-5. The impedance looking down a tube of length l and area A terminated in an impedance Z is (Kinsler and Frey 1962: 201)

$$Z_0(l, A, Z) = \frac{\rho c}{A} \cdot \frac{Z + i\frac{\rho c}{A}\tan kl}{\frac{\rho c}{A} + iZ\tan kl}, \tag{2.4}$$

where c is the speed of sound in the tube. We thus have $Z_f = Z_0(l_f, A_f, Z_r)$, and $Z_v = Z_0(l_b, A_b, Z_f)$.

To find $T(\omega) = \frac{U_m}{U_0}$, we must first find U_v, the flow into the vocal tract, given by the volume velocity (current) across Z_v. The spectrum of U_v can be computed by the principle of superposition – since the circuit in Fig. 2-3 is a linear system (taking U_g to be a constant), superimposing the responses for each ω gives the entire spectrum of U_v. Accordingly, for an input $U_0(\omega)$, solving the circuit gives

$$\frac{U_v}{U_0} = \frac{i\omega L_g + R_g}{i\omega L_g + Z_v + Z_l + R_g}, \tag{2.5}$$

We now find $\frac{U_m}{U_v}$. $P(x)$ and $U(x)$ in the front cavity are given by general solutions to the wave equation of the form

$$P_f = (\alpha_f e^{ikx} + \beta_f e^{-ikx}), \;\; U_f = (\alpha_f e^{ikx} - \beta_f e^{-ikx})/K_f, \tag{2.6}$$

where $K_f = \frac{\rho c}{A_f}$ is the characteristic impedance of the front cavity. The pressure and volume velocity for the back cavity are given by analogous expressions using α_b, β_b, and K_b. Solving for the α and β coefficients by impedance matching at the entrances to the front and back cavities gives

$$\frac{U_m}{U_v} = \frac{[K_b \cos(\omega l_b/c) - i\sin(\omega l_b/c) Z_f][K_f \cos(\omega l_f/c) - i\sin(\omega l_f/c) Z_v]}{K_b K_f}. \tag{2.7}$$

We then have

$$T(\omega) = \frac{U_m}{U_v}\frac{U_v}{U_0}, \tag{2.8}$$

using the expressions from (2.5) and (2.7). Lastly, at a distance r from the mouth (normal to the head), we approximate the radiation characteristic of sound at the lips as that of a simple source on a sphere (far field),

$$R(\omega) = \frac{K_f \omega \rho}{4\pi r} e^{-ikr}, \tag{2.9}$$

where $K(f)$ is a numerically computed function rising from 0 dB at low frequencies to $\approx$ 5 dB at 2 kHz and higher (Stevens 1998: 199). Microphones record the sound pressure of speech. The sound pressure p_r at distance r from the above source is

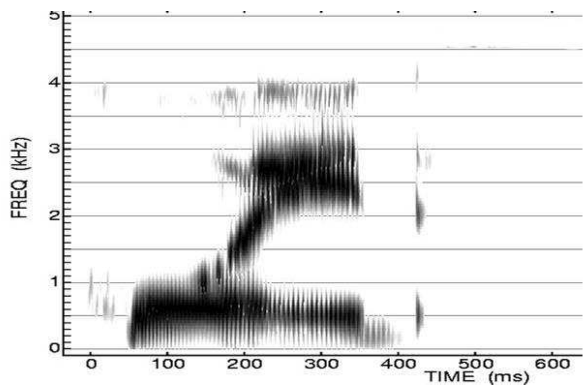


Figure 2-6: Spectrogram for an /oi/ diphthong showing F2 attenuation near AccF2.

$p_r = U_m(\omega)R_(\omega)$, giving

$$p_r = U_0(\omega)T(\omega)R(\omega). \tag{2.10}$$

The glottal source U_0 can be computed analytically, but the process is sufficiently involved that an empirically measured male U_0 is used here. Using this and the expressions in (2.8) and (2.9), we can now simulate spoken vowel spectra.

2.4 The Subglottal Attenuation Effect

The subglottal attenuation effect results from coupling between the oral and subglottal cavities. This coupling is usually negligible, but becomes important when an oral cavity formant approaches a subglottal resonance. Based on general considerations of coupled resonators, the formant peak is then predicted to be attenuated, and its frequency will appear to "jump," skipping the subglottal resonance. The second subglottal resonance (AccF2) is 1300-1500 Hz. depending on the speaker, which is also approximately the dividing line between the second formant (F2) of front ([-back]) and back ([+back]) vowels. An individual speaker's front and back vowels are usually fairly well-divided, but what determines the boundary is unknown. We hypothesize that attenuation of the F2 peak near AccF2 is the quantal relation for [back]. This effect can be anecdotally observed in some front-back diphthongs, as in Fig. 2-6.

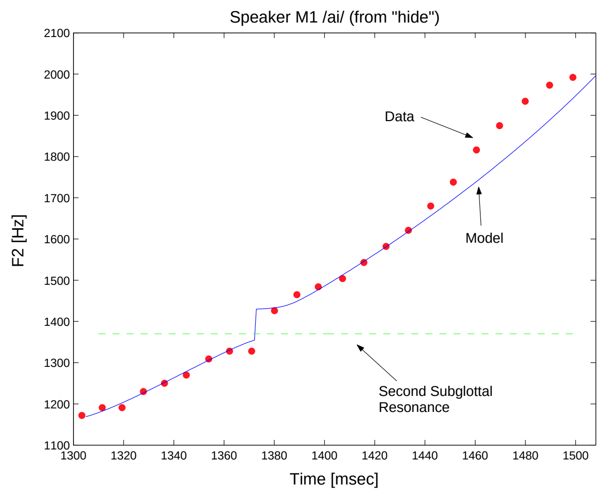


Figure 2-7: Observed and modeled F2 track for an /ai/ diphthong, speaker M1, showing an F2 jump near AccF2.

We first test whether our model predicts this effect. The sound pressure at the microphone was simulated using a model written in MATLAB, based on the above analysis. Substituting in typical values of all parameters for a male speaker (Stevens 1998) and simulating an /ai/ diphthong by transitioning linearly between the tube shapes in Fig. 2-5 does in fact give an attenuation effect. After some tweaking of parameters, the simulated track of the second formant prominence frequency matches one recorded by hand for one of speaker M1's /ai/ diphthongs, as shown in Fig. 2-7. Thus the model has some preliminary success in simulating this effect. However, as there are significant differences between speakers' vocal tracts, their nonlinear articulatory-acoustic relations presumably vary greatly. We must now check to what extent the subglottal attenuation effect is robust across speakers, and whether it can be correlated with the front-back distinction. The model predicts that the effect itself will be relatively robust, given that its parameters are ones that do not vary tremendously from speaker to speaker, and that speakers with more coupling between the oral and subglottal cavities will exhibit a stronger effect.

Chapter 3

Data Collection and Preliminary Analysis

3.1 Data Collection

To study the interaction between subglottal resonance frequencies and vowel production, speech from approximately 18 speakers from the MIT student, faculty, and staff population was recorded.[1] Of these, 7 male and 7 female speakers whose data were clean enough to analyze are presented here as M1-M7 and F1-F7. The remaining speakers' data were harder to analyze due to random experimental errors, not a systematic error in their speech.

All speakers were native speakers of American English except M7, a native speaker of British English, and M1, a native speaker of Canadian English. Subjects were recorded saying the phrase "hVd, say hVd again" for each of the American English monophthongs and diphthongs, shown in Table A.1 (except for M7, who used the very similar British set of vowels). Many phoneticians transcribe the diphthongs as /eɪ/, /aɪ/, /ɔɪ/, /aʊ/, /jʊ/. Our notation is adopted for simplicity's sake, and does not change the backness of any vowels. We considered the first vowel of /ei/ to be English /e/, and treated it as a monophthong to get as many vowels as possible. Eight

[1] Many thanks to Xuemin Chi, who did much of this recording and collaborated with me on the analysis.

Symbol	Backness	Word
/æ/	Front	"had"
/ɔ/	Back	"hawed"
/ɛ/	Front	"head"
/ɝ/	Central	"heard"
/i/	Front	"heed"
/ɪ/	Front	"hid"
/ɑ/	Back	"hodd"
/ow/	Back	"hoed"
/ʊ/	Back	"hood"
/ʌ/	Back	"hud"
/uw/	Back	"who'd"
/ei/	Front/Front	"hade"
/ai/	Back/Front	"hide"
/oi/	Back/Front	"hoid"
/au/	Back/Back	"how'd"
/iu/	Front/Back	"hued"

Table 3.1: American English vowel IPA symbols, backness, and carrier words used.

speakers showed a distinction between /ɑ/ and /ɔ/ and 6 did not, replicating a well-attested difference between English dialects. M4's dialect appeared to also include /a/, which was elicited using "hahd." Speakers were recorded in a sound room using a microphone hung approximately 8 inches from the head. In addition, speaker's subglottal pressure signals were taken using an accelerometer attached externally to the neck approximately 1 inch above the sternal notch, on the skin of the tracheal opening. Accelerometers transform skin vibrations into voltage signals, and were demonstrated by Cheyne (2002) to be a surprisingly accurate and convenient way to determine subglottal resonances. The first and second subglottal resonances are clearly visible in the sample accelerometer spectrum and spectrogram shown in Fig. 3-1.

3.2 Preliminary Analyses

To study the relationship between F2 and AccF2, their values were found for all vowels for all speakers. For each speaker, for all 10 repetitions of each monophthong,

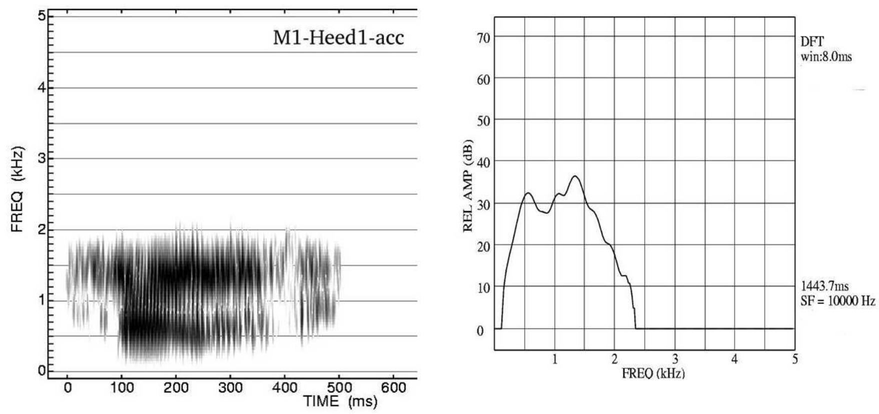


Figure 3-1: Sample accelerometer spectrogram and spectrum.

F2 was taken by hand using the xkl waveform analysis software. It is possible to do this automatically, but none of the available algorithms work with the accuracy desired here. Since AccF2 stays relatively constant during phonation, its values for all monopthongs were instead determined using a formant tracker. Means of this data over a vowel were found to agree with hand-taken data for several test vowels. The AccF2 values for each speaker conform reasonably well to normal distributions, and agree with previously reported AccF2 values found using invasive techniques (Ishizaka et al. 1976, Cranen and Boves 1987). Since subglottal resonance data are sparse in the literature, basic statistics on each speaker's AccF2 distribution are shown in Table 3.2 and all data on AccF2 and F2 are given in Appendix A.

3.3 Analysis of /oi/ diphthongs

To check the robustness of the hypothesized second formant peak attenuation across speakers, we analyzed 3-4 /oi/ diphthongs for all speakers. /oi/ was chosen because the F2 track always crosses speakers' AccF2. All speakers showed an attenuation effect for all diphthongs analyzed, though the strength of the effect varied. To check whether a stronger effect was correlated with more oral-subglottal coupling, we measured H1-H2, the difference between the first and second harmonics, at 5 points each in 10 productions of /ɑ/ (chosen because its high F1 peak interferes minimally with low

Speaker	$\bar{x}$ (Hz.)	σ (Hz.)	χ^2_ν
M1	1374	12	1.3
M2	1280	18	1.0
M3	1310	20	0.86
M4	1405	17	0.84
M5	1384	22	0.79
M6	1303	18	0.98
M7	1454	20	0.89
F1	1620	28	0.70
F2	1469	23	0.80
F3	1447	30	1.1
F4	1568	28	0.82
F5	1496	28	0.99
F6	1383	27	1.0
F7	1508	19	0.89

Table 3.2: Mean, σ, and χ^2_ν (normal distribution) for speakers' AccF2 distributions, across monophthongs and diphthongs.

harmonics) for all speakers. H1-H2 is an indicator the *breathiness* of a voice, which is related to the proportion of a glottal cycle that the glottis is open. Breathier voices have a stronger low frequency component, giving a higher H1-H2. Speakers with breathier voices should have greater oral-subglottal coupling, averaged over time.

Statistics on average jump size and attenuation in /oi/, difference between jump center frequency and AccF2 (Δ_{freq}), and H1-H2 are shown in Table 3.3. Δ_{freq} for a word was calculated by approximating the frequency of the middle of the F2 track jump, then subtracting the average AccF2 value for the word's vowel. The speakers are arranged in order from the smallest H1-H2 to the largest H1-H2, separately for each gender. The data show a good correlation between H1-H2 and jump size and H1-H2 and attenuation, and a weaker correlation between H1-H2 and Δ_{freq}, at least when separated by sex. This separation is well-motivated by the significant differences between male and female speech. The attenuation effect is thus observed to be both robust and dependent on the degree of oral-subglottal coupling, as predicted by the model. The source of the weak dependence of Δ_{freq} on H1-H2 is unknown, but is minor and will be ignored here. Since the frequency of maximum attenuation is significantly different from AccF2 for some speakers, it is certainly valid to wonder how

Speaker	H1-H2	Jump Size (Hz.)	Attenuation (dB)	Δ_{freq}
M7	-8.5	99	1.9	-25
M2	-4.5	280	3.8	-135
M4	-4.3	143	2.6	16
M6	-3.6	183	2.1	68
M5	-3.1	211	2.9	-53
M3	-1.3	248	4.0	36
M1	-1.1	225	4.2	-59
Speaker	H1-H2	Jump Size (Hz.)	Attenuation (dB)	Δ_{freq}
F1	-3.1	108	1.3	-25
F6	-2.1	145	1.7	-44
F4	-1.6	164	1.3	-102
F5	0.4	195	1.7	-65
F3	1.7	156	1.2	13
F7	3.8	196	3.3	-85
F2	5.1	311	4.0	-202

Table 3.3: Breathiness, jump, attenuation, and Δ_{freq} averages for male and female speakers, arranged by ascending breathiness. Correlation coefficients between H1-H2 and the jump variables are .69, .74, .10 for males, .84, .83, -.56 for females.

these speakers could be dividing their front and back vowels based on the attenuation effect, as hypothesized. However, we found that even when AccF2 is not near the jump center frequency, it is always within the period of attenuation. Thus, speakers could just as well be using the attenuation effect associated with AccF2, even when the exact frequencies are off.

The subglottal attenuation effect is therefore robust and fairly strong across speakers, suggesting that it could be used as a quantal relation – we now test whether it is.

Chapter 4

Evidence for a Quantal Relation

4.1 Evidence from English Data

To test whether speakers' front-back distinctions might be structured around the subglottal attenuation effect, AccF2-F2 values for all monophthongs for all speakers were examined. We call each group of 10 repetitions of the same vowel produced by the same speaker a *vowel group*. We tested whether AccF2-F2 was significantly ($p < .05$) positive or negative for all vowel groups, taking σ for all AccF2 values for each speaker to be the σ for their entire AccF2 distribution (across all vowels), and taking σ for a vowel group's F2 to be the standard deviation of F2 values for vowels in the group.

Positive AccF2-F2 for back vowels or negative AccF2-F2 for front vowels were "expected" under our hypothesis. All front vowel groups were significantly positive, but at least one group was not significantly negative for each back vowel. In Table 4.1, statistics for only back vowel groups across all speakers are given. The /d/ in "hud" has a tendency to pull the F2 of /ʌ/ upwards. Using data from "hub" instead and taking F2 less conservatively for /u/[1] gives the statistics for back vowel groups in Table 4.2. Finally, statistics including front and back vowel groups are given for the

[1]There is some debate about how to take F2 for this vowel, since F2 often falls across the entire vowel due to the rounding gesture, but must be taken at a point where some rounding has occurred because /u/ is [+round]. In Table 4.1 /u/ was taken with minimal rounding, in Table 4.2 halfway between minimum and maximum rounding.

Significant, Expected	Non-Significant, Expected	Non-Significant, Non-Expected	Significant, Non-Expected
65 (**83%**)	6 (**8%**)	3 (**4%**)	4 (**5%**)

Table 4.1: Back vowel group statistics, conservative F2's. 14 speakers, 78 groups.

Significant, Expected	Non-Significant, Expected	Non-Significant, Non-Expected	Significant, Non-Expected
71 (**91%**)	2 (**3%**)	2 (**3%**)	3 (**4%**)

Table 4.2: Back vowel group statistics for problem groups, less conservative F2's. 14 speakers, 78 groups.

conservative and less conservative F2 values in Tables 4.3 and 4.4. The number of vowel groups in these tables are not perfect multiples of 12 (the number of American English monophthongs) because different speakers' dialects have different numbers of low vowels.

The data in these tables support our hypothesis across English speakers, at least as a highly significant asymmetry in how vowels are produced. One possibility is that this is merely a scaling effect – all the resonant frequencies of speech, including AccF2, could scale together, so that it would not surprising that we see the same pattern across speakers. But the statistics for the /ɝ/ vowel groups in Table 4.5 show that this vowel patterns above and below AccF2, depending on the speaker. Assuming /ɝ/ scales similarly to other vowels, this rules out a general scaling effect. Interestingly, the /ɝ/ data supports specifying central vowels as neither [+back] or [-back], one proposed solution to the long-standing phonological dilemma of how to treat central vowels.

Another possibility is that this pattern is just a property of English vowels, as the vowel spaces of different languages have different characteristic shapes, to some degree. We thus turn to cross-linguistic data.

Significant, Expected	Non-Significant, Expected	Non-Significant, Non-Expected	Significant, Non-Expected
135 (**91%**)	6 (**4%**)	3 (**2%**)	4 (**3%**)

Table 4.3: Front and back vowel group statistics, conservative F2's. 14 speakers, 148 groups.

Significant, Expected	Non-Significant, Expected	Non-Significant, Non-Expected	Significant, Non-Expected
141 (**95%**)	2 (**1%**)	2 (**1%**)	3 (**2%**)

Table 4.4: Front and back vowel group statistics, less conservative F2's. 14 speakers, 148 groups.

Significant, Expected	Non-Significant, Expected	Non-Significant, Non-Expected	Significant, Non-Expected
5 (**42%**)	1 (**8%**)	1 (**8%**)	5 (**42%**)

Table 4.5: /ɝ/ vowel group statistics, 14 speakers, 12 groups (F2 and F3 could not be distinguished for speakers M5 and M6).

4.2 Evidence from Cross-Linguistic Data

Ideally, to test our hypothesis cross-linguistically, analyses of many individual speakers of a genetically diverse set of languages would be carried out to rule out the possibility that the effect observed for English is a property of English dialects or Germanic languages. This unfortunately was not possible. Analyses of speaker M7 (British English) and a male native Polish speaker (not included in the rest of the study) support our hypothesis. This is encouraging, but only anecdotal.

Instead, we assembled a corpus of published vowel formant data for 53 languages, described in Appendix B. Only data averaged over three or more speakers were used, giving male data from 46 languages and female data from 19 languages, encompassing 26 vowel qualities and long, short, oral, nasal, breathy, and pharyngealized variants. To the best of our knowledge, this is the largest cross-linguistic corpus of formant data to date. Graphing this data on an F1-F2 plot gives an idea of how front, back, and central vowels pattern cross-linguistically, shown in Figs. 4-1 and 4-2. Figs. 4-3 and 4-4 show that even cross-linguistically, there is a fairly sharp boundary between front and back vowels. To determine this boundary's location, we chose an arbitrary error metric,

$$\text{error}(f) = (3 \cdot \text{front vowels below} f + \text{back vowels above} f). \quad (4.1)$$

We weigh the front vowels relative to the back vowels, since fronting processes

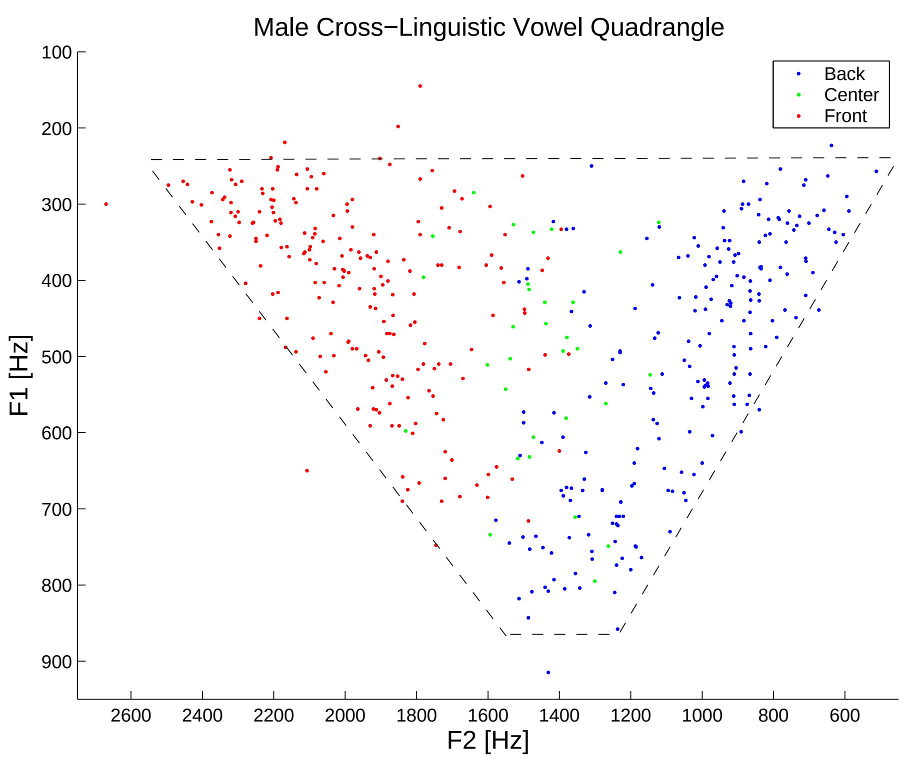


Figure 4-1: Male cross-linguistic formant values. Dotted lines are the implied boundary of vowel space.

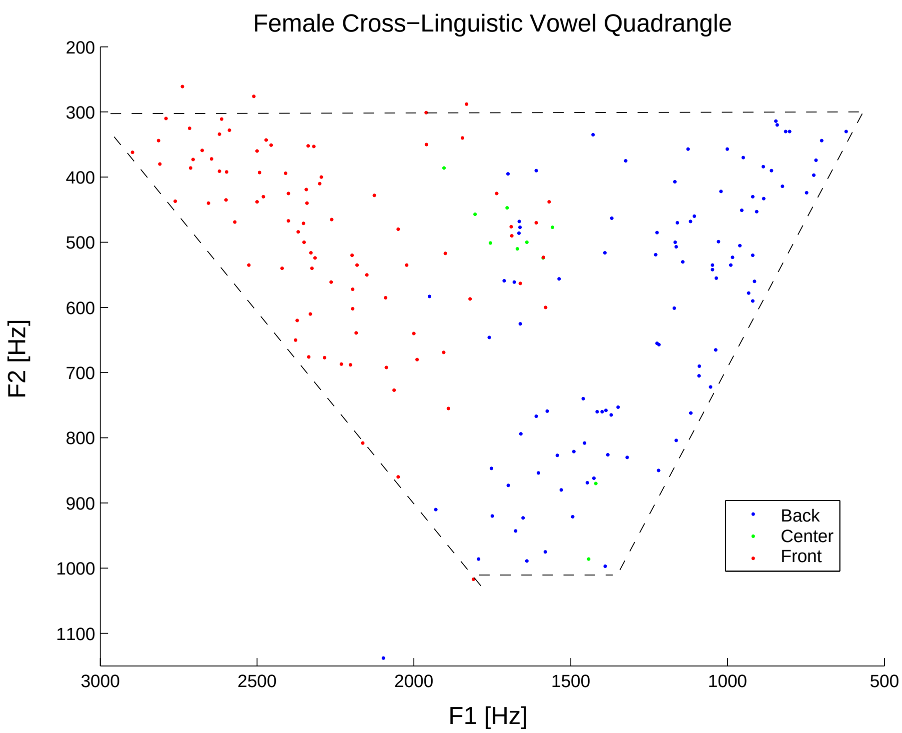


Figure 4-2: Female cross-linguistic formant values. Dotted lines are the implied boundary of vowel space.

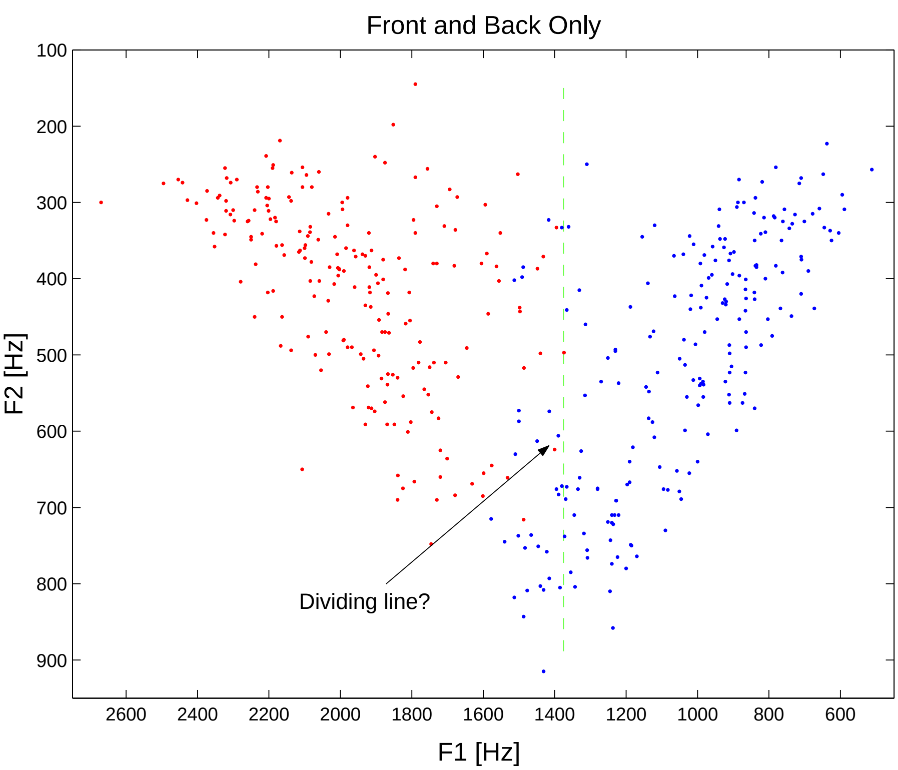


Figure 4-3: Male cross-linguistic front and back formant values. Dotted line indicates a possible front-back boundary.

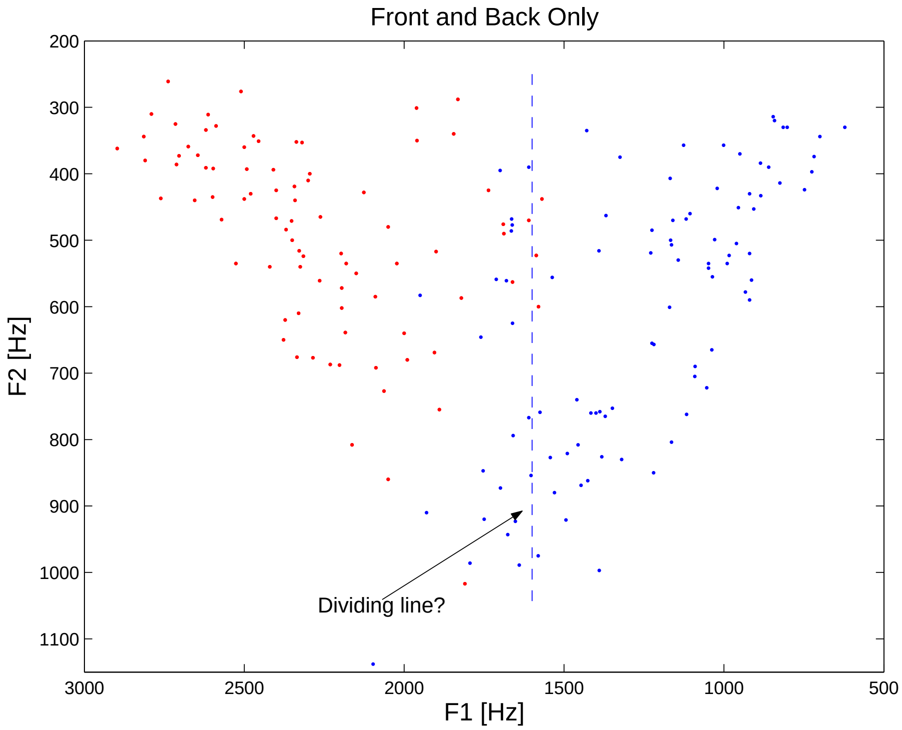


Figure 4-4: Female cross-linguistic front and back formant values. Dotted line indicates a possible front-back boundary.

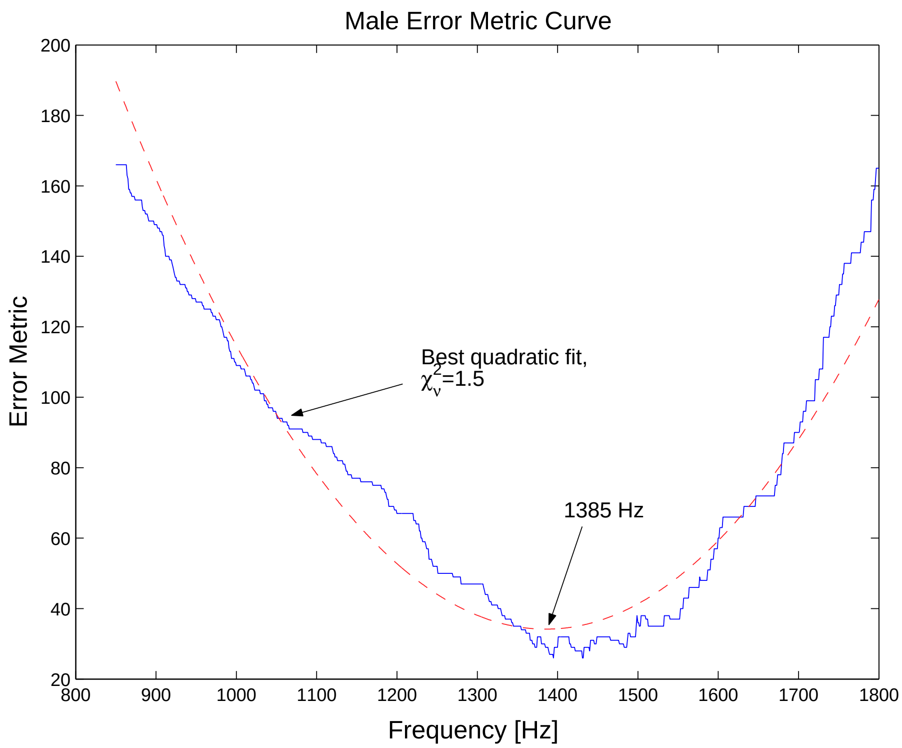


Figure 4-5: Male error metric plot, with quadratic fit.

are far more common than backing processes diachronically. However, the numerical factor (3) is arbitrary – it could perhaps be determined more carefully by choosing a number which maximizes the goodness of fit of some standard distribution to the resulting error metric curve.

Plots of the metric in (4.1) versus frequency and quadratic fits are shown in Figs. 4-5 and 4-6. By this method, the boundary lines are found to be at 1385 Hz (male) and 1592 Hz (female), in good agreement with the average AccF2 values of 1355 ± 56 and 1528 ± 104 found by averaging our AccF2 data with that reported in previous studies (Ishizaka et al. 1976, Cranen and Boves 1987) for Japanese and Dutch.

Also, male central vowels are split 20/42 (20 above) by 1385 Hz. and female central vowels are split 6/14 (6 above) by 1592 Hz. While these ratios are far from the 1:1 predicted by the hypothesis that central vowels are unspecified for [back], they are encouraging, given that the identity of vowels transcribed as central is often uncertain or contested.

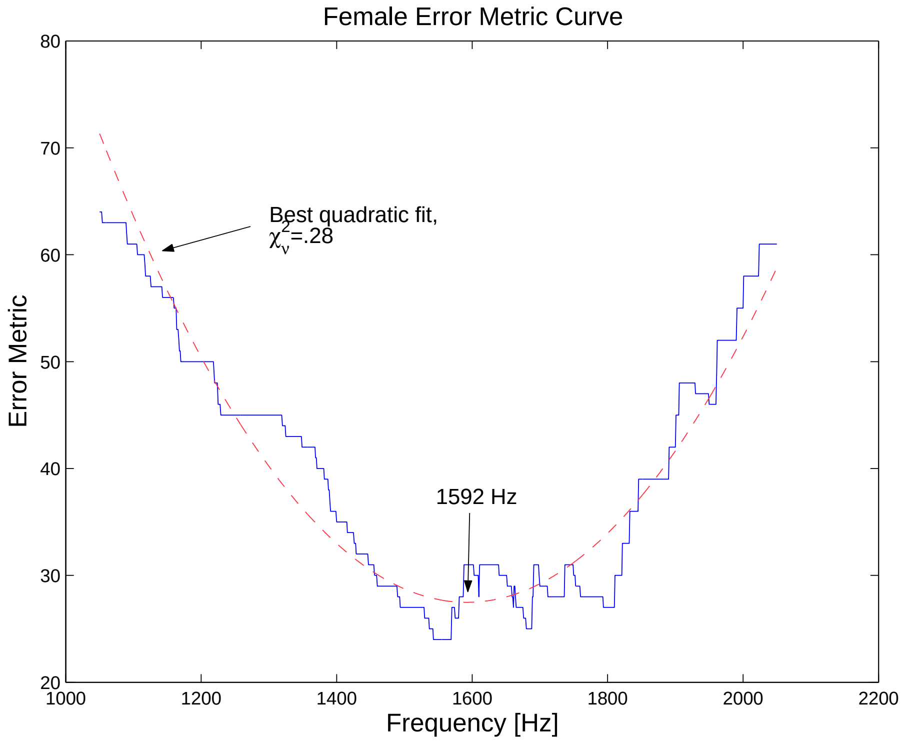


Figure 4-6: Female error metric plot, with quadratic fit.

These results should be taken with a grain of salt – not only is the weighting factor in (4.1) arbitrary, but the formant data survey is weighted towards Indo-European languages, especially Germanic ones. As Germanic languages have possibly the largest average number of vowels of any language subfamily, a *Sprachbund* effect could potentially skew our result. Nonetheless, given 2000 Hz. of possible values to take on, it is remarkable that the boundary line between front and back vowels cross-linguistically should be so close to AccF2.

4.3 Theoretical Implications

Interpreting the graphs above in light of our hypothesis, vowel spaces are constrained by an unstable region near AccF2, and may structure their front-back distinction based on it. These facts are not fully captured in current theories of vowel inventories.

In Adaptive Dispersion Theory (Lijencrants and Lindblom 1972, Lindblom *pas-*

sim), vowel spaces tend towards minimal articulatory effort, maximum contrast, and maximum number of vowels, measured by phonetic metrics. Flemming (1995) captures the same principles in an Optimality Theory framework as more detailed phonetically-based constraints whose mutual ranking determines the vowel inventory.

Later versions of Adaptive Dispersion Theory are able to incorporate any warping of possible vowel space, in principle including attenuation near AccF2. Flemming's model does not include disfavored frequency ranges, but could incorporate them as constraints. However, neither of these adjustments makes the connection demonstrated here between a disfavored frequency region and the identity of the sounds that avoid it. More generally, neither of these theories incorporate features, or explain the mapping between vowels' phonological identities and phonetic realization. Although the evidence is scarce so far, it seems plausible that features should play some role in dividing up and structuring vowel space phonetically, since they do so phonologically. By the same token, perhaps all theories dealing with sounds in any way as abstract, phonological units contrasting with each other should somehow incorporate features. This is especially true for theories of vowel inventory structure, since patterns in vowel inventories, viewed phonologically, arguably form the primary evidence for features.

Chapter 5

Conclusion

We have sketched out one way of understanding a nonlinear acoustic-articulatory relation and testing whether it is a quantal phenomenon. We first modeled the relation, fit the model parameters to sample data, and predicted that its effect should be robust across speakers and dependent on a speaker-dependent parameter (oral-subglottal coupling). These predictions were borne out by quantifying the effect for a number of English speakers. We then examined whether the way speakers produced [+feature] and [-feature] sounds could be correlated with the effect, and found that it could. Finally, we tested for the same correlation cross-linguistically as best we could. Ideally, we would also have tested the proposed correlation perceptually, as in Stevens and Blumstein's study of retroflex consonants (1975), especially since quantal relations are both articulatory and *acoustic* effects.

All of these tests are somewhat anecdotal, and certainly involve enough averaging and subjective human judgment to give one pause. The cross-linguistic evidence rests on many averages and an arbitrary scale factor, while the evidence from individual speakers rests on formant values consciously taken by hand. Encouragingly, none of these tests falsified the hypothesis, but is our hypothesis that the effect is used as a quantal relation falsifiable? A similar attenuation effect exists for AccF1 and does not appear related to the features [low] or [high] on preliminary analysis (not presented here), but one could argue that the relation is very weak, reflecting the debated interpretation of how to represent vowel height phonologically.

More generally, what does it mean for a nonlinear acoustic-articulatory relation to be "used" as a quantal phenomenon? It is impossible to test directly whether a speaker is consciously or unconsciously "using" his knowledge of the phenomenon to structure vowel space. Yet even if it were possible, failure to find the speaker doing so would not rule out the possibility. Current phonological work assumes that mechanisms for structuring sound patterns and phonological processes are present in the mind at some level, operating from a primarily rationalist viewpoint. This is certainly a reasonable assumption to make for older phonological analyses, in which features and rules are abstract enough that it is difficult to see what general principles they would result from if not stored explicitly in the mind. But as phonology has incorporated increasingly more phonetics over the past fifteen years, what such general principles would be is increasingly clear. Many constraints proposed in Optimality Theory are indirect statements of phonetic properties of the vocal tract, as are all proposed quantal relations. Though we cannot tell whether such statements of phonetic knowledge are truly somehow stored in the brain or not, it seems equally possible that *these* principles are stored nowhere except in the laws of physics as that they are stored in speakers' minds. Perhaps speakers know that nonlinear acoustic-articulatory relations exist and utilize them, or perhaps these relations warp naive speakers' phonetic output, synchronically and diachronically.

Whether a nonlinear relation is stored in physical laws or the mind, we can only test whether it is used as a quantal relation by observing how speakers produce and perceive different sounds. Given the most careful experimental work in this area, little enough is currently known about how speech and language work in the brain that the result can almost always be interpreted to fuel theoretical arguments from any perspective. Thus, perhaps quicker progress in understanding the basis of features, and maybe phonetics and phonology more generally, rests on pursuing research based on data, quantitative or not, that remains as open to theoretical interpretation as possible. A focus on data, rather than its interpretation, would exploit the powerful technologies now available to study sounds and sound patterns, and advance our knowledge of phonetics and phonology independent of the ultimately correct theory.

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Appendix A

Acoustic and Accelerometer Data

Carrier words for each English vowel are listed in Table A.1. Speaker M4 had an additional low vowel, elicited using "hahd." The vowels in each speaker's dialect can be read off from the data, which also includes F2 and AccF2 measurements for all utterances. If a speaker only has data for one of "hawed" or "hodd," the vowel produced is /ɑ/, regardless of the notation.

For each word X, a speaker repeated the sentence "X, say X again" 5 times. "Repetition" is the repetition number, and "1st" and "2nd" refer to the first and second X in the utterance. "n/a" appears for diphthong F2's, since they are by definition dynamic.

Speaker	Repetition	Word	1st F2	2nd F2	1st AccF2	2nd AccF2
M1	1	had	1710	1850	1344	1379
M1	2	had	1800	1840	1372	1365
M1	3	had	1850	1750	1359	1341
M1	4	had	1758	1806	1360	1366
M1	5	had	1830	1710	1375	1369
M1	1	hade	2050	2220	1373	1391
M1	2	hade	2040	2180	1362	1371
M1	3	hade	2130	2130	1384	1379
M1	4	hade	2050	2075	1376	1383
M1	5	hade	2030	2075	1368	1372
M1	1	hawed	780	880	1379	1376
M1	2	hawed	780	780	1373	1352
M1	3	hawed	859	840	1372	1382
M1	4	hawed	830	850	1367	1355
M1	5	hawed	852	830	1374	1374
M1	1	head	1953	2024	1372	1355
M1	2	head	1910	1930	1376	1349
M1	3	head	1890	1990	1388	1383
M1	4	head	1960	1825	1379	1367
M1	5	head	1880	1910	1385	1379
M1	1	heard	1172	1211	1363	1366
M1	2	heard	1061	1104	1377	1373
M1	3	heard	1133	1172	1388	1393

Symbol	Backness	Word
/æ/	Front	"had"
/ɔ/	Back	"hawed"
/ɛ/	Front	"head"
/ɝ/	Central	"heard"
/i/	Front	"heed"
/ɪ/	Front	"hid"
/ɑ/	Back	"hodd"
/ow/	Back	"hoed"
/ʊ/	Back	"hood"
/ʌ/	Back	"hud"
/uw/	Back	"who'd"
/ei/	Front/Front	"hade"
/ai/	Back/Front	"hide"
/oi/	Back/Front	"hoid"
/au/	Back/Back	"how'd"
/iu/	Front/Back	"hued"

Table A.1: American English vowel IPA symbols, backness, and carrier words used.

M1	4	heard	1225	1220	1387	1385
M1	5	heard	1140	1172	1385	1384
M1	1	heed	2290	2320	1356	1386
M1	2	heed	2266	2295	1367	1396
M1	3	heed	2200	2324	1373	1383
M1	4	heed	2350	2340	1382	1396
M1	5	heed	2290	2315	1368	1369
M1	1	hid	2050	2050	1363	1372
M1	2	hid	2070	2000	1377	1377
M1	3	hid	2020	2070	1376	1369
M1	4	hid	2010	2070	1386	1372
M1	5	hid	1930	2060	1367	1380
M1	2	hide	n/a	n/a	1364	1371
M1	3	hide	n/a	n/a	1345	1345
M1	4	hide	n/a	n/a	1357	1353
M1	5	hide	n/a	n/a	1360	1357
M1	1	hodd	1025	1025	1361	1351
M1	2	hodd	980	1020	1374	1382
M1	3	hodd	1030	1025	1391	1391
M1	4	hodd	1030	1030	1366	1362
M1	5	hodd	1050	1040	1371	1380
M1	1	hoed	859	830	1388	1361
M1	2	hoed	880	810	1380	1369
M1	3	hoed	850	800	1387	1375
M1	4	hoed	850	780	1385	1377
M1	5	hoed	811	898	1373	1379
M1	1	hoid	n/a	n/a	1376	1369
M1	2	hoid	n/a	n/a	1379	1390
M1	3	hoid	n/a	n/a	1378	1386

M1	4	hoid	n/a	n/a	1371	1386
M1	5	hoid	n/a	n/a	1380	1375
M1	1	hood	977	1025	1366	1367
M1	2	hood	977	1000	1374	1366
M1	3	hood	1016	950	1395	1379
M1	4	hood	1005	1055	1389	1368
M1	5	hood	1000	1025	1407	1376
M1	1	howd	n/a	n/a	1374	1348
M1	2	howd	n/a	n/a	1362	1361
M1	3	howd	n/a	n/a	1363	1374
M1	4	howd	n/a	n/a	1347	1379
M1	5	howd	n/a	n/a	1372	1372
M1	1	hub	1016	1094	1367	1362
M1	2	hub	1016	1090	1373	1362
M1	3	hub	1094	1215	1374	1371
M1	4	hub	1075	1016	1377	1371
M1	5	hub	1016	1080	1353	1365
M1	1	hud	1133	1133	1341	1368
M1	2	hud	1120	1140	1375	1378
M1	3	hud	1075	1150	1388	1380
M1	4	hud	1150	1190	1376	1373
M1	5	hud	1150	1190	1390	1376
M1	1	hued	n/a	n/a	1368	1368
M1	2	hued	n/a	n/a	1380	1370
M1	3	hued	n/a	n/a	1373	1378
M1	4	hued	n/a	n/a	1365	1383
M1	5	hued	n/a	n/a	1377	1393
M1	1	whod	898	938	1387	1365
M1	2	whod	918	938	1391	1365
M1	3	whod	898	935	1395	1380
M1	4	whod	1016	1070	1386	1370
M1	5	whod	1016	977	1385	1380
M2	1	had	1563	1543	1284	1267
M2	2	had	1689	1572	1286	1307
M2	3	had	1602	1630	1268	1290
M2	4	had	1553	1573	1268	1302
M2	5	had	1593	1576	1297	1300
M2	1	hade	1972	1985	1281	1283
M2	2	hade	1992	2057	1252	1273
M2	3	hade	1944	1992	1260	1273
M2	4	hade	2001	1953	1281	1305
M2	5	hade	2010	2005	1299	1289
M2	1	hawed	898	875	1265	1256
M2	2	hawed	850	830	1271	1276
M2	3	hawed	943	924	1282	1284
M2	4	hawed	898	910	1219	1278
M2	5	hawed	820	781	1296	1298
M2	1	head	1738	1728	1224	1298
M2	2	head	1758	1788	1319	1313
M2	3	head	1738	1728	1285	1303
M2	4	head	1742	1738	1282	1271
M2	5	head	1827	1829	1292	1295
M2	1	heard	1094	1270	1272	1270
M2	2	heard	1055	977	1267	1283

M2	3	heard	1040	1000	1293	1280
M2	4	heard	898	820	1271	1274
M2	5	heard	1030	1260	1256	1319
M2	1	heed	2193	2198	1237	1277
M2	2	heed	2095	2338	1241	1291
M2	3	heed	2079	2292	1278	1272
M2	4	heed	2109	2266	1253	1282
M2	5	heed	2168	2118	1276	1268
M2	1	hid	2020	2061	1258	1264
M2	2	hid	1822	2050	1270	1272
M2	3	hid	1875	1905	1279	1276
M2	4	hid	1870	2031	1270	1297
M2	5	hid	1914	2040	1263	1290
M2	1	hide	n/a	n/a	1283	1293
M2	2	hide	n/a	n/a	1285	1307
M2	3	hide	n/a	n/a	1293	1294
M2	4	hide	n/a	n/a	1262	1294
M2	5	hide	n/a	n/a	1293	1291
M2	1	hoed	1075	1055	1247	1276
M2	2	hoed	1025	990	1277	1302
M2	3	hoed	1025	955	1269	1300
M2	4	hoed	977	977	1280	1252
M2	5	hoed	1080	1016	1267	1288
M2	1	hoid	n/a	n/a	1283	1305
M2	2	hoid	n/a	n/a	1275	1281
M2	3	hoid	n/a	n/a	1290	1298
M2	4	hoid	n/a	n/a	1280	1314
M2	5	hoid	n/a	n/a	1284	1281
M2	1	hood	1090	1269	1289	1294
M2	2	hood	1080	1030	1279	1256
M2	3	hood	1060	977	1280	1254
M2	4	hood	990	1030	1279	1301
M2	5	hood	1016	1080	1273	1282
M2	1	howd	n/a	n/a	1284	1304
M2	2	howd	n/a	n/a	1259	1256
M2	3	howd	n/a	n/a	1276	1278
M2	4	howd	n/a	n/a	1263	1299
M2	5	howd	n/a	n/a	1259	1285
M2	1	hub	1055	1230	1272	1272
M2	2	hub	1080	1270	1301	1263
M2	3	hub	1060	1328	1259	1288
M2	4	hub	1055	1280	1262	1308
M2	5	hub	1080	1094	1301	1256
M2	1	hud	1280	1280	1261	1284
M2	3	hud	1280	1260	1272	1283
M2	4	hud	1270	1308	1268	1339
M2	5	hud	1289	1260	1279	1296
M2	1	hued	n/a	n/a	1259	1256
M2	2	hued	n/a	n/a	1290	1278
M2	3	hued	n/a	n/a	1295	1310
M2	4	hued	n/a	n/a	1246	1274
M2	5	hued	n/a	n/a	1266	1279
M2	1	whod	760	830	1277	1255
M2	2	whod	800	781	1281	1309

M2	3	whod	830	820	1276	1283
M2	4	whod	898	900	1274	1293
M2	5	whod	770	825	1268	1298
M3	1	had	1620	1602	1307	1325
M3	2	had	1660	1771	1268	1277
M3	3	had	1620	1573	1322	1335
M3	4	had	1556	1602	1297	1323
M3	5	had	1611	1630	1294	1313
M3	1	hade	1959	2148	1314	1331
M3	2	hade	2178	2230	1311	1309
M3	3	hade	2188	2298	1314	1317
M3	4	hade	2109	2115	1325	1327
M3	5	hade	2175	2227	1304	1287
M3	1	head	1630	1627	1273	1300
M3	2	head	1981	1939	1319	1343
M3	3	head	1771	1758	1310	1292
M3	4	head	1777	1747	1323	1306
M3	5	head	1710	1869	1307	1327
M3	1	heard	1200	1172	1336	1321
M3	2	heard	1172	1211	1320	1336
M3	3	heard	1150	1190	1327	1335
M3	4	heard	1094	1211	1309	1347
M3	5	heard	1172	1172	1333	1320
M3	1	heed	2300	2320	1308	1297
M3	2	heed	2402	2461	1305	1327
M3	3	heed	2461	2416	1312	1327
M3	4	heed	2320	2344	1287	1268
M3	5	heed	2330	2363	1312	1329
M3	1	hid	1914	2001	1314	1278
M3	2	hid	2210	2198	1312	1328
M3	3	hid	1990	2148	1305	1324
M3	4	hid	2039	2059	1319	1307
M3	5	hid	2020	2031	1336	1338
M3	1	hide	n/a	n/a	1322	1254
M3	2	hide	n/a	n/a	1265	1301
M3	3	hide	n/a	n/a	1298	1316
M3	4	hide	n/a	n/a	1274	1292
M3	5	hide	n/a	n/a	1324	1328
M3	1	hodd	1094	1073	1308	1281
M3	2	hodd	1133	1055	1305	1311
M3	3	hodd	1148	1205	1310	1290
M3	4	hodd	1133	1160	1335	1324
M3	5	hodd	950	977	1277	1297
M3	1	hoed	1055	1133	1302	1316
M3	2	hoed	1055	1035	1319	1297
M3	3	hoed	1094	1172	1293	1295
M3	4	hoed	1060	1065	1313	1317
M3	5	hoed	1040	1075	1292	1326
M3	1	hoid	n/a	n/a	1320	1321
M3	2	hoid	n/a	n/a	1310	1339
M3	3	hoid	n/a	n/a	1278	1333
M3	4	hoid	n/a	n/a	1290	1294
M3	5	hoid	n/a	n/a	1323	1314
M3	1	hood	1055	1211	1328	1342

M3	2	hood	1120	1250	1316	1297
M3	3	hood	1172	1211	1286	1284
M3	4	hood	1172	1211	1300	1302
M3	5	hood	1172	1230	1331	1330
M3	1	howd	n/a	n/a	1307	1259
M3	2	howd	n/a	n/a	1277	1335
M3	3	howd	n/a	n/a	1293	1301
M3	4	howd	n/a	n/a	1287	1309
M3	5	howd	n/a	n/a	1300	1272
M3	1	hub	1094	1090	1290	1306
M3	2	hub	1020	1120	1259	1301
M3	3	hub	1090	1085	1280	1300
M3	4	hub	1145	1060	1304	1280
M3	5	hub	1133	1058	1262	1266
M3	1	hud	1090	1110	1343	1320
M3	2	hud	1030	1063	1305	1334
M3	3	hud	1094	1114	1307	1306
M3	4	hud	1075	1030	1275	1296
M3	5	hud	1110	1123	1284	1266
M3	1	hued	n/a	n/a	1332	1338
M3	2	hued	n/a	n/a	1315	1334
M3	3	hued	n/a	n/a	1329	1325
M3	4	hued	n/a	n/a	1319	1315
M3	5	hued	n/a	n/a	1316	1293
M3	1	whod	1010	1048	1317	1315
M3	2	whod	977	996	1325	1290
M3	3	whod	938	898	1293	1303
M3	4	whod	977	1445	1303	1297
M3	5	whod	1020	1016	1290	1304
M4	1	had	1690	1608	1387	1360
M4	2	had	1580	1563	1377	1396
M4	3	had	1593	1503	1370	1415
M4	4	had	1523	1520	1380	1389
M4	5	had	1573	1530	1387	1412
M4	1	hade	2852	2656	1391	1403
M4	2	hade	2109	2120	1406	1409
M4	3	hade	2344	2461	1424	1393
M4	4	hade	2109	2305	1398	1436
M4	5	hade	2207	2070	1405	1439
M4	1	hahd	1094	1166	1403	1416
M4	2	hahd	1172	1211	1411	1411
M4	3	hahd	1072	1140	1404	1401
M4	4	hahd	1094	1211	1419	1397
M4	5	hahd	1172	1194	1429	1402
M4	1	hawed	970	950	1402	1404
M4	2	hawed	953	1011	1382	1399
M4	3	hawed	1027	977	1404	1384
M4	4	hawed	1049	985	1431	1404
M4	5	hawed	962	1005	1442	1413
M4	1	head	1771	1750	1416	1356
M4	2	head	1680	1689	1381	1427
M4	3	head	1689	1667	1387	1410
M4	4	head	1738	1641	1409	1414
M4	5	head	1708	1611	1428	1420

M4	1	heard	1180	1230	1394	1404
M4	2	heard	1250	1300	1380	1403
M4	3	heard	1289	1240	1422	1423
M4	4	heard	1240	1367	1405	1408
M4	5	heard	1260	1320	1421	1437
M4	1	heed	3055	3125	1409	1392
M4	2	heed	3086	3018	1379	1403
M4	3	heed	3208	3125	1361	1384
M4	4	heed	3020	3125	1417	1426
M4	5	heed	3130	3220	1415	1442
M4	1	hid	2607	2591	1384	1413
M4	2	hid	2569	2491	1385	1383
M4	3	hid	2519	2491	1423	1426
M4	4	hid	2578	2510	1448	1386
M4	5	hid	2485	2480	1417	1415
M4	1	hide	n/a	n/a	1405	1398
M4	2	hide	n/a	n/a	1402	1408
M4	3	hide	n/a	n/a	1406	1410
M4	4	hide	n/a	n/a	1389	1419
M4	5	hide	n/a	n/a	1411	1402
M4	1	hodd	1016	945	1419	1385
M4	2	hodd	951	975	1399	1383
M4	3	hodd	996	957	1399	1403
M4	4	hodd	1016	979	1408	1417
M4	5	hodd	996	972	1401	1409
M4	1	hoed	938	1105	1382	1390
M4	2	hoed	940	950	1413	1397
M4	3	hoed	1016	955	1381	1404
M4	4	hoed	970	980	1413	1431
M4	5	hoed	930	907	1363	1424
M4	1	hoid	n/a	n/a	1388	1421
M4	2	hoid	n/a	n/a	1410	1383
M4	3	hoid	n/a	n/a	1403	1389
M4	4	hoid	n/a	n/a	1399	1399
M4	5	hoid	n/a	n/a	1390	1409
M4	1	hood	1130	1205	1402	1402
M4	2	hood	1094	1230	1412	1412
M4	3	hood	1055	1080	1401	1435
M4	4	hood	1190	1150	1401	1420
M4	5	hood	1070	1160	1416	1407
M4	1	howd	n/a	n/a	1379	1406
M4	2	howd	n/a	n/a	1394	1404
M4	3	howd	n/a	n/a	1422	1433
M4	4	howd	n/a	n/a	1423	1405
M4	5	howd	n/a	n/a	1423	1385
M4	1	hub	1140	1176	1362	1394
M4	2	hub	1133	1094	1379	1380
M4	3	hub	1060	1211	1404	1411
M4	4	hub	1147	1172	1434	1429
M4	5	hub	1250	1328	1419	1400
M4	1	hud	1215	1328	1394	1402
M4	2	hud	1290	1300	1419	1423
M4	3	hud	1289	1328	1383	1401
M4	4	hud	1328	1350	1396	1424

M4	5	hud	1255	1280	1414	1413
M4	1	hued	n/a	n/a	1366	1408
M4	2	hued	n/a	n/a	1392	1410
M4	3	hued	n/a	n/a	1402	1404
M4	4	hued	n/a	n/a	1373	1399
M4	5	hued	n/a	n/a	1412	1399
M4	1	whod	898	960	1395	1421
M4	2	whod	850	912	1374	1394
M4	3	whod	905	820	1415	1430
M4	4	whod	900	930	1437	1416
M4	5	whod	810	860	1399	1406
M5	1	had	1514	1576	1373	1343
M5	2	had	1596	1533	1355	1343
M5	3	had	1563	1582	1358	1390
M5	4	had	1630	1530	1368	1395
M5	5	had	1680	1650	1352	1363
M5	1	hade	2422	2330	1329	1352
M5	2	hade	2430	2525	1369	1400
M5	3	hade	2422	2435	1383	1387
M5	4	hade	2320	2305	1386	1382
M5	5	hade	2328	2617	1379	1413
M5	1	head	1621	1612	1333	1353
M5	2	head	1738	1680	1350	1384
M5	3	head	1660	1630	1386	1406
M5	4	head	1758	1602	1384	1385
M5	5	head	1680	1728	1348	1376
M5	1	heard	n/a	n/a	1395	1387
M5	2	heard	n/a	n/a	1415	1407
M5	3	heard	n/a	n/a	1425	1422
M5	4	heard	n/a	n/a	1422	1426
M5	5	heard	n/a	n/a	1409	1403
M5	1	heed	2487	2422	1334	1364
M5	2	heed	2440	2383	1338	1315
M5	3	heed	2500	2452	1375	1394
M5	4	heed	2452	2396	1386	1380
M5	5	heed	2474	2383	1386	1379
M5	1	hid	2422	2344	1340	1419
M5	2	hid	2383	2393	1373	1364
M5	3	hid	2539	2500	1397	1403
M5	4	hid	2450	2344	1349	1414
M5	5	hid	2578	2422	1406	1407
M5	1	hide	n/a	n/a	1367	1361
M5	2	hide	n/a	n/a	1381	1410
M5	3	hide	n/a	n/a	1389	1408
M5	4	hide	n/a	n/a	1381	1375
M5	5	hide	n/a	n/a	1350	1388
M5	1	hodd	1055	1087	1384	1374
M5	2	hodd	1080	1139	1386	1386
M5	3	hodd	1053	1140	1386	1380
M5	4	hodd	1102	1074	1354	1388
M5	5	hodd	1064	1065	1379	1433
M5	1	hoed	1110	1055	1350	1355
M5	2	hoed	1190	1060	1365	1377
M5	3	hoed	1113	1029	1382	1392

M5	4	hoed	1126	1172	1401	1393
M5	5	hoed	1170	1224	1396	1415
M5	1	hoid	n/a	n/a	1373	1385
M5	2	hoid	n/a	n/a	1387	1384
M5	3	hoid	n/a	n/a	1397	1405
M5	4	hoid	n/a	n/a	1424	1411
M5	5	hoid	n/a	n/a	1384	1410
M5	1	hood	1133	1310	1396	1395
M5	2	hood	1211	1220	1391	1397
M5	3	hood	1177	1295	1404	1401
M5	4	hood	1165	1225	1414	1398
M5	5	hood	1220	1215	1401	1393
M5	1	howd	n/a	n/a	1358	1389
M5	2	howd	n/a	n/a	1372	1423
M5	3	howd	n/a	n/a	1370	1389
M5	4	howd	n/a	n/a	1358	1376
M5	5	howd	n/a	n/a	1367	1385
M5	1	hub	1172	1220	1355	1385
M5	2	hub	1185	1250	1385	1450
M5	3	hub	1197	1380	1369	1380
M5	4	hub	1220	1218	1374	1399
M5	5	hub	1152	1211	1376	1419
M5	1	hud	1250	1429	1370	1404
M5	2	hud	1160	1320	1387	1393
M5	3	hud	1230	1445	1383	1427
M5	4	hud	1217	1250	1370	1380
M5	5	hud	1180	1250	1401	1412
M5	1	hued	n/a	n/a	1367	1371
M5	2	hued	n/a	n/a	1378	1362
M5	3	hued	n/a	n/a	1385	1393
M5	4	hued	n/a	n/a	1375	1397
M5	5	hued	n/a	n/a	1379	1383
M5	1	whod	1289	1310	1364	1388
M5	2	whod	1328	1390	1376	1378
M5	3	whod	1484	1530	1382	1420
M5	4	whod	1454	1406	1399	1389
M5	5	whod	1380	1328	1390	1406
M6	1	had	1646	1484	1292	1299
M6	2	had	1602	1641	1291	1294
M6	3	had	1686	1591	1308	1307
M6	4	had	1553	1602	1306	1300
M6	5	had	1560	1530	1328	1291
M6	1	hade	1875	1992	1315	1290
M6	2	hade	1939	1933	1275	1292
M6	4	hade	1914	2109	1310	1306
M6	5	hade	1914	2270	1312	1310
M6	1	hawed	1016	1067	1296	1310
M6	2	hawed	1014	1053	1272	1274
M6	3	hawed	986	1079	1325	1311
M6	4	hawed	1035	1007	1298	1316
M6	5	hawed	1020	1172	1306	1323
M6	1	head	1532	1593	1298	1304
M6	2	head	1610	1641	1292	1268
M6	3	head	1680	1563	1305	1309

M6	4	head	1475	1563	1282	1301
M6	5	head	1533	1570	1280	1266
M6	1	heard	n/a	n/a	1279	1266
M6	2	heard	n/a	n/a	1333	1302
M6	3	heard	n/a	n/a	1290	1282
M6	4	heard	n/a	n/a	1346	1298
M6	5	heard	n/a	n/a	1282	1331
M6	1	heed	2070	2148	1306	1306
M6	2	heed	2220	2227	1280	1277
M6	3	heed	2201	2179	1326	1302
M6	4	heed	2296	2357	1323	1300
M6	5	heed	2266	2220	1285	1305
M6	1	hid	1680	1719	1331	1336
M6	2	hid	1725	1777	1302	1282
M6	3	hid	1728	1719	1318	1329
M6	4	hid	1749	1768	1302	1287
M6	5	hid	1738	1777	1322	1337
M6	1	hide	n/a	n/a	1314	1306
M6	2	hide	n/a	n/a	1304	1328
M6	3	hide	n/a	n/a	1316	1302
M6	4	hide	n/a	n/a	1314	1293
M6	5	hide	n/a	n/a	1292	1216
M6	1	hodd	1195	1211	1299	1285
M6	2	hodd	1098	1077	1320	1302
M6	3	hodd	1094	1111	1305	1312
M6	4	hodd	1116	1119	1321	1305
M6	5	hodd	1115	1138	1300	1320
M6	1	hoed	1055	938	1300	1302
M6	2	hoed	1045	1055	1290	1299
M6	3	hoed	1040	1020	1322	1311
M6	4	hoed	1094	1150	1340	1323
M6	5	hoed	985	1005	1296	1293
M6	1	hoid	n/a	n/a	1317	1292
M6	2	hoid	n/a	n/a	1312	1307
M6	3	hoid	n/a	n/a	1289	1293
M6	4	hoid	n/a	n/a	1318	1302
M6	5	hoid	n/a	n/a	1296	1313
M6	1	hood	1172	1260	1301	1298
M6	2	hood	1110	1250	1266	1278
M6	3	hood	1055	1140	1301	1297
M6	4	hood	1240	1289	1289	1300
M6	5	hood	1250	1395	1330	1271
M6	1	howd	n/a	n/a	1308	1317
M6	2	howd	n/a	n/a	1273	1279
M6	3	howd	n/a	n/a	1302	1290
M6	4	howd	n/a	n/a	1315	1317
M6	5	howd	n/a	n/a	1294	1307
M6	1	hub	1220	1100	1305	1314
M6	2	hub	1130	1150	1273	1253
M6	3	hub	1211	1142	1312	1318
M6	4	hub	1070	1150	1291	1279
M6	5	hub	1140	1055	1299	1300
M6	1	hud	1211	1225	1299	1316
M6	2	hud	1150	1220	1278	1295

M6	3	hud	1211	1240	1311	1303
M6	4	hud	1191	1250	1340	1336
M6	5	hud	1245	1270	1324	1322
M6	1	hued	n/a	n/a	1321	1314
M6	2	hued	n/a	n/a	1296	1266
M6	3	hued	n/a	n/a	1302	1292
M6	4	hued	n/a	n/a	1308	1305
M6	5	hued	n/a	n/a	1303	1298
M6	1	whod	1016	1150	1308	1298
M6	2	whod	1055	1094	1276	1254
M6	3	whod	1290	1211	1301	1293
M6	4	whod	1000	1205	1314	1321
M6	5	whod	1367	1220	1301	1311
M7	1	had	1458	1537	1445	1524
M7	2	had	1533	1536	1463	1422
M7	3	had	1464	1569	1467	1459
M7	4	had	1563	1516	1508	1489
M7	5	had	1509	1553	1464	1463
M7	1	haird	n/a	n/a	1440	1439
M7	2	haird	n/a	n/a	1420	1418
M7	3	haird	n/a	n/a	1482	1442
M7	4	haird	n/a	n/a	1488	1448
M7	5	haird	n/a	n/a	1479	1458
M7	1	hard	1078	1094	1444	1420
M7	2	hard	1098	1094	1436	1458
M7	3	hard	1055	1090	1448	1427
M7	4	hard	1069	1090	1456	1465
M7	5	hard	1005	1133	1443	1453
M7	1	hawed	610	664	1435	1452
M7	2	hawed	781	625	1465	1455
M7	3	hawed	820	742	1469	1478
M7	4	hawed	664	703	1461	1458
M7	5	hawed	664	664	1473	1469
M7	1	hayed	1710	1797	1459	1444
M7	2	hayed	1758	1641	1460	1446
M7	3	hayed	1628	1651	1462	1463
M7	4	hayed	1660	6141	1473	1469
M7	5	hayed	1719	1641	1453	1447
M7	1	head	1602	1602	1423	1424
M7	2	head	1602	1680	1428	1451
M7	3	head	1608	1630	1414	1417
M7	4	head	1654	1602	1450	1434
M7	5	head	1608	1615	1469	1474
M7	1	heed	2260	2270	1467	1441
M7	2	heed	2838	2675	1437	1432
M7	3	heed	2841	2723	1469	1458
M7	4	heed	2782	2708	1437	1439
M7	5	heed	2109	2148	1468	1477
M7	1	herd	1543	1602	1418	1430
M7	2	herd	1630	1602	1429	1432
M7	3	herd	1493	1602	1463	1442
M7	4	herd	1484	1602	1490	1471
M7	5	herd	1503	1589	1446	1456
M7	1	hered	n/a	n/a	1451	1445

M7	2	hered	n/a	n/a	1446	1438
M7	3	hered	n/a	n/a	1467	1465
M7	4	hered	n/a	n/a	1442	1446
M7	5	hered	n/a	n/a	1439	1456
M7	1	hid	1836	1810	1464	1417
M7	2	hid	1875	1758	1454	1431
M7	3	hid	1749	1760	1474	1471
M7	4	hid	1710	1875	1483	1463
M7	5	hid	1836	1850	1451	1476
M7	1	hide	n/a	n/a	1430	1417
M7	2	hide	n/a	n/a	1431	1445
M7	3	hide	n/a	n/a	1447	1453
M7	4	hide	n/a	n/a	1456	1445
M7	5	hide	n/a	n/a	1437	1443
M7	1	hired	n/a	n/a	1463	1485
M7	2	hired	n/a	n/a	1465	1443
M7	3	hired	n/a	n/a	1468	1418
M7	4	hired	n/a	n/a	1461	1450
M7	5	hired	n/a	n/a	1485	1457
M7	1	hod	898	977	1455	1469
M7	2	hod	938	938	1431	1486
M7	3	hod	910	977	1453	1446
M7	4	hod	914	900	1476	1455
M7	5	hod	920	970	1467	1498
M7	1	hoed	n/a	n/a	1479	1457
M7	2	hoed	n/a	n/a	1460	1439
M7	3	hoed	n/a	n/a	1449	1422
M7	4	hoed	n/a	n/a	1441	1451
M7	5	hoed	n/a	n/a	1494	1434
M7	1	hoid	n/a	n/a	1438	1438
M7	2	hoid	n/a	n/a	1440	1427
M7	3	hoid	n/a	n/a	1449	1430
M7	4	hoid	n/a	n/a	1464	1464
M7	5	hoid	n/a	n/a	1457	1474
M7	1	hood	1430	1523	1452	1439
M7	2	hood	1484	1563	1465	1426
M7	3	hood	1172	1484	1441	1441
M7	4	hood	1380	1509	1507	1468
M7	5	hood	1289	1425	1497	1473
M7	1	howd	n/a	n/a	1451	1414
M7	2	howd	n/a	n/a	1454	1461
M7	3	howd	n/a	n/a	1469	1466
M7	4	howd	n/a	n/a	1456	1438
M7	5	howd	n/a	n/a	1470	1453
M7	1	hub	1211	1270	1436	1449
M7	2	hub	1094	1172	1451	1439
M7	3	hub	1172	1220	1442	1463
M7	4	hub	1107	1172	1418	1447
M7	5	hub	1100	1211	1454	1450
M7	1	hud	1172	1320	1421	1447
M7	2	hud	1211	1250	1477	1490
M7	3	hud	1250	1294	1445	1452
M7	4	hud	1211	1172	1457	1454
M7	5	hud	1172	1202	1442	1449

M7	1	hued	n/a	n/a	1454	1440
M7	2	hued	n/a	n/a	1437	1450
M7	3	hued	n/a	n/a	1447	1442
M7	4	hued	n/a	n/a	1454	1457
M7	5	hued	n/a	n/a	1458	1491
M7	1	whod	1602	1680	1432	1424
M7	2	whod	1445	1367	1465	1434
M7	3	whod	1553	1666	1440	1442
M7	4	whod	1553	1680	1457	1475
M7	5	whod	1497	1611	1446	1462
F1	1	had	1875	1800	1604	1627
F1	2	had	1729	1770	1619	1588
F1	3	had	1764	1775	1596	1563
F1	4	had	1884	1758	1614	1569
F1	5	had	1822	1767	1610	1551
F1	1	hade	2540	2405	1605	1601
F1	2	hade	2441	2550	1635	1631
F1	3	hade	2500	2461	1619	1644
F1	4	hade	2405	2410	1617	1579
F1	5	hade	2422	2470	1618	1644
F1	1	head	1983	2080	1605	1655
F1	2	head	2044	2050	1624	1680
F1	3	head	2109	2089	1626	1656
F1	4	head	1966	2070	1623	1581
F1	5	head	2022	2100	1603	1662
F1	1	heard	1640	1738	1609	1582
F1	2	heard	1641	1738	1627	1579
F1	3	heard	1680	1816	1609	1614
F1	4	heard	1705	1895	1628	1635
F1	5	heard	1660	1836	1638	1663
F1	1	heed	2891	2826	1611	1614
F1	2	heed	2910	2875	1611	1645
F1	3	heed	2882	2841	1643	1639
F1	4	heed	2800	2780	1605	1671
F1	5	heed	2843	2877	1619	1569
F1	1	hid	2100	2163	1604	1618
F1	2	hid	2168	2260	1603	1615
F1	3	hid	2253	2246	1635	1610
F1	4	hid	2175	2181	1644	1711
F1	5	hid	2198	2255	1635	1642
F1	1	hide	n/a	n/a	1609	1638
F1	2	hide	n/a	n/a	1655	1607
F1	3	hide	n/a	n/a	1618	1567
F1	4	hide	n/a	n/a	1608	1595
F1	5	hide	n/a	n/a	1607	1594
F1	1	hodd	1421	1615	1620	1591
F1	2	hodd	1520	1563	1595	1589
F1	3	hodd	1445	1563	1603	1558
F1	4	hodd	1445	1641	1594	1667
F1	5	hodd	1490	1549	1616	1565
F1	1	hoed	1367	1426	1600	1609
F1	2	hoed	1289	1504	1631	1574
F1	3	hoed	1289	1465	1598	1676
F1	4	hoed	1445	1445	1612	1626

F1	5	hoed	1230	1367	1613	1640
F1	1	hoid	n/a	n/a	1609	1633
F1	2	hoid	n/a	n/a	1621	1638
F1	3	hoid	n/a	n/a	1616	1648
F1	4	hoid	n/a	n/a	1594	1602
F1	5	hoid	n/a	n/a	1624	1647
F1	1	hood	1570	1671	1596	1610
F1	2	hood	1512	1621	1636	1627
F1	3	hood	1386	1537	1632	1704
F1	4	hood	1473	1615	1624	1581
F1	5	hood	1450	1475	1621	1683
F1	1	howd	n/a	n/a	1628	1619
F1	2	howd	n/a	n/a	1627	1615
F1	3	howd	n/a	n/a	1599	1651
F1	4	howd	n/a	n/a	1633	1670
F1	5	howd	n/a	n/a	1629	1644
F1	1	hub	1484	1632	1650	1582
F1	2	hub	1484	1553	1644	1624
F1	3	hub	1497	1600	1636	1651
F1	4	hub	1475	1656	1600	1640
F1	5	hub	1500	1558	1636	1625
F1	1	hud	1543	1738	1621	1571
F1	2	hud	1484	1713	1654	1633
F1	3	hud	1550	1686	1610	1573
F1	4	hud	1445	1590	1623	1591
F1	5	hud	1550	1693	1602	1642
F1	1	hued	n/a	n/a	1613	1612
F1	2	hued	n/a	n/a	1622	1655
F1	3	hued	n/a	n/a	1613	1595
F1	4	hued	n/a	n/a	1638	1650
F1	5	hued	n/a	n/a	1612	1644
F1	1	whod	1406	1641	1643	1641
F1	2	whod	1504	1550	1607	1588
F1	3	whod	1230	1550	1628	1627
F1	4	whod	1460	1484	1624	1705
F1	5	whod	1560	1465	1617	1610
F2	1	had	1849	1836	1445	1426
F2	2	had	1841	1849	1486	1448
F2	3	had	2005	1855	1458	1479
F2	4	had	1992	1997	1456	1439
F2	5	had	1990	1973	1459	1468
F2	1	hade	2461	2539	1465	1481
F2	2	hade	2539	2539	1473	1441
F2	3	hade	2422	2510	1472	1451
F2	4	hade	2500	2569	1470	1462
F2	5	hade	2530	2525	1468	1446
F2	1	hawed	1133	1094	1468	1424
F2	2	hawed	1113	1113	1486	1435
F2	3	hawed	1094	1113	1480	1476
F2	4	hawed	1074	1016	1472	1425
F2	5	hawed	996	1133	1510	1490
F2	1	head	2020	2031	1494	1418
F2	2	head	2017	2109	1487	1408
F2	3	head	2040	2022	1472	1426

F2	4	head	2011	1953	1502	1448
F2	5	head	2122	1914	1506	1519
F2	1	heard	1445	1503	1487	1409
F2	2	heard	1490	1475	1510	1445
F2	3	heard	1458	1475	1456	1437
F2	4	heard	1289	1529	1448	1457
F2	5	heard	1425	1432	1485	1440
F2	1	heed	2799	2813	1455	1483
F2	2	heed	2803	2930	1480	1462
F2	3	heed	2743	2803	1467	1447
F2	4	heed	2793	2800	1466	1417
F2	5	heed	2743	2787	1491	1466
F2	1	hid	2415	2338	1479	1472
F2	2	hid	2285	2266	1470	1460
F2	3	hid	2330	2275	1455	1487
F2	4	hid	2266	2236	1472	1463
F2	5	hid	2448	2275	1474	1437
F2	1	hide	n/a	n/a	1437	1465
F2	2	hide	n/a	n/a	1488	1455
F2	3	hide	n/a	n/a	1468	1472
F2	4	hide	n/a	n/a	1461	1471
F2	5	hide	n/a	n/a	1468	1514
F2	1	hodd	1390	1397	1469	1518
F2	2	hodd	1393	1406	1489	1500
F2	3	hodd	1400	1400	1457	1463
F2	4	hodd	1415	1367	1472	1483
F2	5	hodd	1390	1470	1463	1492
F2	1	hoed	1040	1005	1498	1421
F2	2	hoed	1110	1065	1495	1487
F2	3	hoed	1020	1055	1419	1455
F2	4	hoed	1015	1020	1475	1499
F2	5	hoed	977	972	1484	1512
F2	1	hoid	n/a	n/a	1479	1484
F2	2	hoid	n/a	n/a	1479	1489
F2	3	hoid	n/a	n/a	1433	1449
F2	4	hoid	n/a	n/a	1469	1449
F2	5	hoid	n/a	n/a	1474	1489
F2	1	hood	1367	1445	1490	1440
F2	2	hood	1392	1523	1469	1488
F2	3	hood	1328	1425	1474	1494
F2	4	hood	1438	1419	1472	1480
F2	5	hood	1390	1477	1461	1468
F2	1	howd	n/a	n/a	1467	1469
F2	2	howd	n/a	n/a	1458	1486
F2	3	howd	n/a	n/a	1459	1465
F2	4	howd	n/a	n/a	1464	1442
F2	5	howd	n/a	n/a	1459	1487
F2	1	hub	1367	1415	1432	1497
F2	2	hub	1367	1406	1445	1492
F2	3	hub	1440	1460	1422	1463
F2	4	hub	1390	1450	1466	1453
F2	5	hub	1380	1406	1482	1503
F2	1	hud	1395	1450	1470	1444
F2	2	hud	1440	1455	1471	1444

F2	3	hud	1380	1464	1483	1453
F2	4	hud	1497	1440	1471	1429
F2	5	hud	1373	1503	1494	1467
F2	1	hued	n/a	n/a	1477	1507
F2	2	hued	n/a	n/a	1463	1492
F2	3	hued	n/a	n/a	1465	1443
F2	4	hued	n/a	n/a	1489	1483
F2	5	hued	n/a	n/a	1472	1437
F2	1	whod	977	1040	1483	1470
F2	2	whod	1016	1000	1463	1491
F2	3	whod	898	1090	1502	1509
F2	4	whod	938	1030	1476	1488
F2	5	whod	1010	1035	1483	1458
F3	1	had	1845	1719	1436	1484
F3	2	had	1719	1845	1437	1466
F3	3	had	1836	1750	1415	1499
F3	4	had	1797	1758	1419	1467
F3	5	had	1836	1820	1434	1380
F3	1	hade	2305	2280	1458	1378
F3	2	hade	2310	2280	1445	1468
F3	3	hade	2422	2357	1455	1399
F3	4	hade	2275	2250	1445	1491
F3	5	hade	2257	2375	1480	1421
F3	1	hawed	1250	1328	1447	1481
F3	2	hawed	1450	1320	1429	1450
F3	3	hawed	1480	1350	1460	1431
F3	4	hawed	1406	1340	1453	1471
F3	5	hawed	1510	1520	1447	1456
F3	1	head	1910	1770	1428	1441
F3	2	head	1930	1816	1467	1393
F3	3	head	1875	1866	1446	1419
F3	4	head	1888	1836	1405	1467
F3	5	head	1923	1914	1484	1447
F3	1	heard	1493	1570	1404	1418
F3	2	heard	1670	1602	1412	1384
F3	3	heard	1563	1602	1409	1382
F3	4	heard	1596	1615	1413	1415
F3	5	heard	1612	1625	1442	1404
F3	1	heed	2552	2597	1455	1410
F3	2	heed	2589	2682	1457	1458
F3	3	heed	2675	2725	1461	1500
F3	4	heed	2656	2656	1460	1428
F3	5	heed	2734	2679	1473	1467
F3	1	hid	2031	2227	1440	1434
F3	2	hid	2001	2183	1479	1452
F3	3	hid	1992	2220	1474	1454
F3	4	hid	2011	2109	1466	1421
F3	5	hid	2017	2118	1462	1430
F3	1	hide	n/a	n/a	1458	1512
F3	2	hide	n/a	n/a	1433	1490
F3	3	hide	n/a	n/a	1435	1455
F3	4	hide	n/a	n/a	1431	1493
F3	5	hide	n/a	n/a	1474	1376
F3	1	hodd	1406	1367	1459	1463

F3	2	hodd	1440	1500	1453	1493
F3	3	hodd	1420	1340	1471	1490
F3	4	hodd	1450	1484	1462	1485
F3	5	hodd	1445	1400	1453	1416
F3	1	hoed	1410	1399	1458	1395
F3	2	hoed	1406	1397	1476	1395
F3	3	hoed	1440	1358	1463	1387
F3	4	hoed	1406	1370	1466	1476
F3	5	hoed	1450	1410	1481	1420
F3	1	hoid	n/a	n/a	1443	1384
F3	2	hoid	n/a	n/a	1469	1453
F3	3	hoid	n/a	n/a	1462	1402
F3	4	hoid	n/a	n/a	1459	1443
F3	5	hoid	n/a	n/a	1452	1412
F3	1	hood	1415	1650	1457	1411
F3	2	hood	1450	1670	1479	1424
F3	3	hood	1440	1484	1439	1450
F3	4	hood	1450	1438	1466	1420
F3	5	hood	1445	1430	1472	1435
F3	1	howd	n/a	n/a	1442	1474
F3	2	howd	n/a	n/a	1451	1468
F3	3	howd	n/a	n/a	1460	1437
F3	4	howd	n/a	n/a	1447	1479
F3	5	howd	n/a	n/a	1449	1376
F3	1	hub	1453	1582	1505	1514
F3	2	hub	1400	1575	1489	1471
F3	3	hub	1445	1553	1448	1510
F3	4	hub	1450	1436	1491	1437
F3	5	hub	1406	1415	1462	1422
F3	1	hud	1611	1617	1468	1370
F3	2	hud	1582	1602	1434	1529
F3	3	hud	1445	1627	1433	1450
F3	4	hud	1610	1641	1460	1410
F3	5	hud	1615	1635	1481	1386
F3	1	hued	n/a	n/a	1468	1431
F3	2	hued	n/a	n/a	1480	1427
F3	3	hued	n/a	n/a	1467	1454
F3	4	hued	n/a	n/a	1425	1457
F3	5	hued	n/a	n/a	1472	1441
F3	1	whod	1460	1430	1457	1443
F3	2	whod	1405	1465	1485	1458
F3	3	whod	1370	1530	1467	1464
F3	4	whod	1450	1440	1472	1410
F3	5	whod	1415	1475	1466	1473
F4	1	had	2148	2227	1565	1547
F4	2	had	2257	2230	1562	1545
F4	3	had	2266	2227	1536	1578
F4	4	had	2227	2227	1547	1580
F4	5	had	2266	2305	1557	1584
F4	1	hade	2669	2344	1563	1514
F4	2	hade	2270	2550	1553	1491
F4	3	hade	2260	2266	1577	1574
F4	4	hade	2260	2422	1572	1540
F4	5	hade	2402	2383	1577	1563

F4	1	hawed	1005	1230	1557	1518
F4	2	hawed	1211	1300	1563	1522
F4	3	hawed	1211	1328	1563	1554
F4	4	hawed	1230	1280	1586	1542
F4	5	hawed	1200	1260	1561	1588
F4	1	head	2178	2120	1594	1578
F4	2	head	2148	2160	1546	1530
F4	3	head	2100	2178	1551	1588
F4	4	head	2148	2119	1568	1547
F4	5	head	2100	2145	1552	1558
F4	1	heard	1689	1641	1559	1558
F4	2	heard	1693	1953	1558	1581
F4	3	heard	1593	1582	1546	1571
F4	4	heard	1596	1595	1582	1553
F4	5	heard	1732	1572	1566	1564
F4	1	heed	2773	2675	1555	1620
F4	2	heed	2695	2764	1564	1579
F4	3	heed	2773	2813	1573	1643
F4	4	heed	2793	2793	1561	1621
F4	5	heed	2813	2704	1578	1516
F4	1	hid	2367	2389	1531	1612
F4	2	hid	2281	2236	1538	1547
F4	3	hid	2281	2207	1576	1526
F4	4	hid	2246	2291	1549	1604
F4	5	hid	2314	2188	1538	1597
F4	1	hide	n/a	n/a	1565	1545
F4	2	hide	n/a	n/a	1599	1569
F4	3	hide	n/a	n/a	1599	1541
F4	4	hide	n/a	n/a	1563	1542
F4	5	hide	n/a	n/a	1592	1570
F4	1	hodd	1289	1298	1612	1528
F4	2	hodd	1211	1280	1582	1563
F4	4	hodd	1260	1240	1564	1567
F4	5	hodd	1289	1289	1580	1558
F4	1	hoed	1200	867	1588	1516
F4	2	hoed	1094	1100	1572	1596
F4	3	hoed	900	1016	1532	1541
F4	4	hoed	1080	1200	1553	1519
F4	5	hoed	1133	1191	1579	1559
F4	1	hoid	n/a	n/a	1572	1566
F4	2	hoid	n/a	n/a	1558	1569
F4	3	hoid	n/a	n/a	1585	1555
F4	4	hoid	n/a	n/a	1586	1574
F4	5	hoid	n/a	n/a	1562	1511
F4	1	hood	1250	1593	1559	1565
F4	2	hood	1250	1172	1561	1587
F4	3	hood	1386	1580	1587	1567
F4	4	hood	1280	1445	1568	1628
F4	5	hood	1406	1445	1596	1593
F4	1	howd	n/a	n/a	1581	1550
F4	2	howd	n/a	n/a	1586	1573
F4	3	howd	n/a	n/a	1591	1599
F4	4	howd	n/a	n/a	1553	1567
F4	5	howd	n/a	n/a	1598	1564

F4	1	hub	1211	1373	1580	1556
F4	2	hub	1236	1375	1542	1560
F4	3	hub	1220	1410	1530	1606
F4	4	hub	1347	1380	1543	1573
F4	5	hub	1333	1367	1561	1550
F4	1	hud	1380	1590	1566	1537
F4	2	hud	1380	1573	1570	1559
F4	3	hud	1367	1516	1571	1519
F4	4	hud	1401	1535	1548	1529
F4	5	hud	1289	1445	1576	1591
F4	1	hued	n/a	n/a	1558	1565
F4	2	hued	n/a	n/a	1548	1610
F4	3	hued	n/a	n/a	1548	1629
F4	4	hued	n/a	n/a	1575	1599
F4	5	hued	n/a	n/a	1552	1645
F4	1	whod	1255	1289	1581	1598
F4	2	whod	1181	1172	1573	1607
F4	3	whod	1289	1211	1551	1645
F4	4	whod	1133	1211	1609	1643
F4	5	whod	1269	1260	1601	1529
F5	1	had	1700	1610	1471	1499
F5	2	had	1583	1602	1503	1445
F5	3	had	1580	1523	1505	1472
F5	4	had	1490	1523	1468	1498
F5	5	had	1484	1580	1506	1491
F5	1	hade	2305	2270	1495	1446
F5	2	hade	2344	2350	1483	1515
F5	3	hade	2320	2422	1486	1508
F5	4	hade	2330	2266	1502	1484
F5	5	hade	2318	2280	1485	1497
F5	1	hawed	1010	1048	1476	1428
F5	2	hawed	1016	990	1514	1534
F5	3	hawed	1055	1060	1482	1466
F5	4	hawed	990	1010	1514	1494
F5	5	hawed	1055	1065	1520	1536
F5	1	head	2891	2813	1542	1503
F5	2	head	2383	2422	1476	1548
F5	3	head	2422	2836	1468	1456
F5	4	head	2422	2861	1510	1558
F5	5	head	1875	1880	1477	1479
F5	1	heard	1416	1440	1454	1477
F5	2	heard	1430	1434	1484	1447
F5	3	heard	1512	1523	1483	1470
F5	4	heard	1497	1055	1500	1496
F5	5	heard	1445	1094	1525	1506
F5	1	heed	2484	2431	1515	1494
F5	2	heed	2431	2422	1532	1541
F5	3	heed	2441	2409	1475	1526
F5	4	heed	2392	2413	1500	1503
F5	5	heed	2445	2422	1512	1519
F5	1	hid	2240	2188	1434	1436
F5	2	hid	2355	2266	1429	1431
F5	3	hid	2270	2195	1484	1556
F5	4	hid	2393	2194	1525	1522

F5	5	hid	2141	2134	1496	1509
F5	1	hide	n/a	n/a	1513	1479
F5	2	hide	n/a	n/a	1504	1468
F5	3	hide	n/a	n/a	1498	1497
F5	4	hide	n/a	n/a	1528	1490
F5	5	hide	n/a	n/a	1481	1483
F5	1	hodd	1209	1061	1480	1450
F5	2	hodd	1250	1407	1458	1467
F5	3	hodd	1005	1416	1456	1491
F5	4	hodd	1260	1367	1493	1502
F5	5	hodd	1372	1392	1511	1509
F5	1	hoed	1206	1211	1516	1441
F5	2	hoed	1240	1211	1502	1431
F5	3	hoed	1289	1250	1500	1456
F5	4	hoed	1259	1250	1491	1480
F5	5	hoed	1289	1289	1515	1497
F5	1	hoid	n/a	n/a	1479	1480
F5	2	hoid	n/a	n/a	1458	1472
F5	3	hoid	n/a	n/a	1481	1474
F5	4	hoid	n/a	n/a	1487	1493
F5	5	hoid	n/a	n/a	1522	1504
F5	1	hood	1280	1289	1487	1498
F5	2	hood	1220	1289	1470	1485
F5	3	hood	1211	1350	1506	1511
F5	4	hood	1289	1250	1478	1543
F5	5	hood	1328	1289	1524	1520
F5	1	howd	n/a	n/a	1476	1476
F5	2	howd	n/a	n/a	1512	1465
F5	3	howd	n/a	n/a	1487	1533
F5	4	howd	n/a	n/a	1523	1501
F5	5	howd	n/a	n/a	1481	1465
F5	1	hub	1289	1296	1520	1540
F5	2	hub	1240	1328	1439	1453
F5	3	hub	1219	1202	1467	1446
F5	4	hub	1225	1209	1472	1465
F5	5	hub	1300	1248	1549	1472
F5	1	hud	1320	1250	1487	1472
F5	2	hud	1250	1400	1512	1484
F5	3	hud	1275	1510	1515	1529
F5	4	hud	1220	1470	1474	1485
F5	5	hud	1250	1250	1472	1473
F5	1	hued	n/a	n/a	1519	1500
F5	2	hued	n/a	n/a	1508	1532
F5	3	hued	n/a	n/a	1521	1536
F5	4	hued	n/a	n/a	1541	1534
F5	5	hued	n/a	n/a	1513	1532
F5	1	whod	1133	1300	1512	1538
F5	2	whod	1133	1110	1540	1539
F5	3	whod	1140	1133	1510	1538
F5	4	whod	1180	1030	1499	1526
F5	5	whod	1133	1133	1488	1508
F6	1	had	1738	1840	1381	1351
F6	2	had	1758	1810	1388	1356
F6	3	had	1806	1846	1393	1370

F6	4	had	1797	1953	1395	1377
F6	5	had	1836	1815	1382	1347
F6	1	hade	2519	2552	1418	1420
F6	2	hade	2486	2480	1393	1353
F6	3	hade	2539	2422	1377	1403
F6	4	hade	2530	2567	1412	1350
F6	5	hade	2476	2539	1407	1342
F6	1	hawed	1289	1280	1381	1438
F6	2	hawed	1309	1250	1380	1411
F6	3	hawed	1320	1260	1384	1424
F6	4	hawed	1330	1306	1378	1449
F6	5	hawed	1230	1339	1414	1366
F6	1	head	2374	2188	1333	1390
F6	2	head	2285	2337	1398	1356
F6	3	head	2291	2298	1380	1386
F6	4	head	2390	2305	1355	1341
F6	5	head	2376	2392	1384	1328
F6	1	heard	1744	1690	1395	1311
F6	2	heard	1719	1712	1372	1335
F6	3	heard	1803	1708	1386	1381
F6	4	heard	1797	1719	1386	1366
F6	5	heard	1788	1771	1373	1383
F6	1	heed	2682	2714	1381	1374
F6	2	heed	2695	2690	1416	1374
F6	3	heed	2705	2695	1405	1344
F6	4	heed	2617	2640	1391	1385
F6	5	heed	2723	2704	1424	1376
F6	1	hid	2408	2539	1368	1364
F6	2	hid	2486	2374	1377	1387
F6	3	hid	2363	2402	1397	1392
F6	4	hid	2491	2369	1401	1372
F6	5	hid	2413	2402	1367	1416
F6	1	hide	n/a	n/a	1336	1359
F6	2	hide	n/a	n/a	1358	1439
F6	3	hide	n/a	n/a	1376	1364
F6	4	hide	n/a	n/a	1393	1417
F6	5	hide	n/a	n/a	1378	1342
F6	1	hoed	1573	1406	1407	1388
F6	2	hoed	1395	1367	1379	1352
F6	3	hoed	1320	1289	1402	1448
F6	4	hoed	1358	1484	1392	1409
F6	5	hoed	1406	1380	1383	1371
F6	1	hoid	n/a	n/a	1398	1391
F6	2	hoid	n/a	n/a	1379	1345
F6	3	hoid	n/a	n/a	1373	1338
F6	4	hoid	n/a	n/a	1362	1346
F6	5	hoid	n/a	n/a	1395	1358
F6	1	hood	1454	1591	1375	1396
F6	2	hood	1470	1560	1351	1379
F6	3	hood	1445	1550	1429	1365
F6	4	hood	1493	1523	1396	1368
F6	5	hood	1523	1503	1384	1398
F6	1	howd	n/a	n/a	1444	1371
F6	2	howd	n/a	n/a	1410	1329

F6	3	howd	n/a	n/a	1391	1322
F6	4	howd	n/a	n/a	1399	1342
F6	5	howd	n/a	n/a	1413	1345
F6	1	hub	1410	1530	1393	1416
F6	2	hub	1530	1460	1439	1385
F6	3	hub	1436	1550	1456	1378
F6	4	hub	1484	1540	1391	1391
F6	5	hub	1406	1523	1431	1431
F6	1	hud	1576	1783	1350	1387
F6	2	hud	1445	1563	1394	1339
F6	3	hud	1484	1634	1361	1383
F6	4	hud	1563	1725	1391	1389
F6	5	hud	1543	1680	1384	1351
F6	1	hued	n/a	n/a	1413	1421
F6	2	hued	n/a	n/a	1413	1408
F6	3	hued	n/a	n/a	1418	1369
F6	4	hued	n/a	n/a	1382	1390
F6	5	hued	n/a	n/a	1396	1382
F6	1	whod	1040	1020	1412	1416
F6	2	whod	1406	1360	1396	1391
F6	3	whod	1300	1380	1381	1369
F6	4	whod	1350	1365	1420	1397
F6	5	whod	1445	1410	1385	1415
F7	1	had	1630	1719	1539	1519
F7	2	had	1749	1641	1535	1522
F7	3	had	1611	1680	1516	1511
F7	4	had	1728	1719	1527	1506
F7	5	had	1630	1758	1545	1510
F7	1	hade	2500	2530	1537	1509
F7	2	hade	2383	2431	1510	1500
F7	3	hade	2510	2408	1519	1489
F7	4	hade	2593	2402	1495	1476
F7	5	hade	2578	2410	1502	1541
F7	1	head	1981	1712	1506	1491
F7	2	head	1939	1738	1498	1503
F7	3	head	1940	1719	1533	1484
F7	4	head	1776	1782	1510	1502
F7	5	head	1944	1783	1534	1508
F7	1	heard	1454	1419	1500	1486
F7	2	heard	1471	1523	1489	1502
F7	3	heard	1471	1523	1490	1499
F7	4	heard	1494	1563	1503	1512
F7	5	heard	1523	1586	1512	1505
F7	1	heed	2843	2891	1507	1539
F7	2	heed	2871	2960	1520	1509
F7	3	heed	2978	2949	1502	1509
F7	4	heed	2988	2930	1514	1475
F7	5	heed	2862	2891	1497	1485
F7	1	hid	2530	2095	1502	1525
F7	2	hid	2402	2363	1511	1501
F7	3	hid	2227	2402	1513	1517
F7	4	hid	2383	2367	1484	1521
F7	5	hid	2353	2383	1526	1498
F7	1	hide	n/a	n/a	1526	1510

F7	2	hide	n/a	n/a	1526	1515
F7	3	hide	n/a	n/a	1505	1516
F7	4	hide	n/a	n/a	1499	1516
F7	5	hide	n/a	n/a	1504	1489
F7	1	hodd	1068	1085	1534	1523
F7	2	hodd	1115	1094	1515	1530
F7	3	hodd	1090	1074	1520	1490
F7	4	hodd	1094	1119	1519	1520
F7	5	hodd	1085	1065	1503	1507
F7	1	hoed	1020	854	1507	1496
F7	2	hoed	1090	898	1510	1506
F7	3	hoed	977	890	1513	1501
F7	4	hoed	910	861	1497	1502
F7	5	hoed	885	901	1511	1500
F7	1	hoid	n/a	n/a	1520	1500
F7	2	hoid	n/a	n/a	1501	1500
F7	3	hoid	n/a	n/a	1502	1493
F7	4	hoid	n/a	n/a	1510	1511
F7	5	hoid	n/a	n/a	1496	1498
F7	1	hood	1199	1211	1517	1506
F7	2	hood	1228	1289	1547	1499
F7	3	hood	1250	1419	1533	1481
F7	4	hood	1211	1189	1502	1530
F7	5	hood	1250	1484	1520	1501
F7	1	howd	n/a	n/a	1505	1531
F7	2	howd	n/a	n/a	1503	1479
F7	3	howd	n/a	n/a	1515	1535
F7	4	howd	n/a	n/a	1530	1489
F7	5	howd	n/a	n/a	1502	1423
F7	1	hub	1493	1454	1530	1468
F7	2	hub	1425	1436	1489	1506
F7	3	hub	1432	1386	1495	1522
F7	4	hub	1436	1376	1492	1636
F7	5	hub	1386	1386	1533	1533
F7	1	hud	1588	1406	1509	1529
F7	2	hud	1416	1563	1483	1531
F7	3	hud	1425	1484	1495	1480
F7	4	hud	1593	1416	1531	1521
F7	5	hud	1514	1464	1499	1491
F7	1	hued	n/a	n/a	1497	1491
F7	2	hued	n/a	n/a	1511	1492
F7	4	hued	n/a	n/a	1509	1513
F7	5	hued	n/a	n/a	1514	1533
F7	1	whod	845	859	1515	1420
F7	2	whod	889	848	1519	1444
F7	3	whod	928	911	1528	1509
F7	4	whod	928	895	1537	1498
F7	5	whod	898	907	1526	1519

Appendix B

Formant Studies

Bibliography of sources for vowel formant data plotted in 4.2.[1] Vowel contexts are *not* listed, but the author is developing a website for data and information on the methods and vowel contexts for these and other studies.

Due to theoretical and typographic uncertainties, the status of low back vowels in a given language is often debatable. We took the low back unrounded vowel for every language to be [ɑ], unless there were two such vowels, one of which was explicitly described as central [a].

An asterisk (*) next to the number of male/female speakers indicates the male/female data were not used due to small sample size. A double asterisk indicates the data was not used because data for the same language with more speakers was available in another study. A question mark alone indicates that the number of male versus female speakers is not given, while a question mark next to a number indicates that this is probably the number of male/female speakers, though not explicitly stated in the text.

[1] Thanks to Ocke-Schwen Bohn for allowing the use of his Frisian data prior to its publication.

Language	**Reference**	**Males**	**Females**
Western Apache	Potter et. al. 2000	5	3
Avatime	Maddieson 1995	8	4
Baarin Mongolian	Svantesson 1985	1*	0
Banawá	Ladefoged et. al. 1996	5	0
Bengali	Chakrabarti	20	0
Bora	Parker 2001	8	6
Chickasaw (short, lengthened, long vowels)	Gordon et. al. 2000	8	5
Shanghai Chinese	Svantesson 1989	3	0
Danish	Fisher-Jørgensen 1972	8	0
Defaka (oral, nasal vowels)	Shryock et. al. 1996/1997	12	0
DhoLuo	Jacobsen 1978	8?	0?
Dinka (non-breathy, breathy vowels)	Malou 1988	3	0
Dutch	van Nierop et. al.	0	25
Dutch	Pols et. al. 1973	50	0
British English	Wells 1962	25?	0?
California English	Hagiwara 1997	?	?
General American English	Peterson and Barney 1952	33	28
Midwestern English	Hillenbrand et. al. 1995	45	48
Fering (North Frisian)	Bohn 2004	10	0
Finnish (short, long vowels)	Wiik 1965	?	0?
French	Dowd et. al 1998	0	7
Bavarian German	Disner 1983	8	0
Standard German (short, long vowels)	Iivonen 1987b	5?	0?
Viennese German (short, long vowels)	Iivonen 1987a	0	3
Greek	Sfakianaki 2002	10	10
Hadza	Sands et. al. 1996	3	4
Hebrew	Aronson et. al. 1996	6	6
Hindi	Khan and Rizvi 1994	15	6
Italian	Disner 1983	25	0
Kabardian	Choi 1990	3	0
Khalkha Mongolian	Svantesson 1985	1*	0
Khonoma Angami	Blankenship et. al. 1993	4	2*
Korean	Yang 1996	10	10
Kwawu (Akan)	Hess 1987	1*	0
Mon (non-breathy, breathy vowels)	Thongkum 1987	8	0
Norwegian	Disner 1983	10	0
Paici (oral, nasal vowels)	Gordon and Maddieson 1996a	5	3
Brazillian Portegese	Godinez 1978	9	0
Lisbon Portuguese	Delgado-Martins 1964	8	0
Sele	Gordon and Maddieson 1996b	8	6
Šiliingol Monglolian	Svantesson 1985	1*	0
Solon	Svantesson 1985	1*	0

Language	Reference	Males	Females
Argentine Spanish	Godinez 1978	4?	0?
Castillian Spanish	Godinez 1978	6?	0?
Mexican Spanish	Godinez 1978	6?	0?
Finnish Swedish (Short, Long vowels)	Reuter 1971	4	0
Swedish	Eklund and Traunmüller 1997	6**	6
Swedish	Fant 1973	24	0
Taiwanese (H, L tones)	Zee 1978	3	0
Telugu (short, long)	Majumder et. al. 1978	3	0
Toda	Shalev et. al. 1993	6	0
Tsez (plain, pharyngealized)	Maddieson et. al.	?	?
Tsou	Wright and Ladefoged 1994	8	5
Wari'	MacEachern et. al. 1996	6	6
Yoruba	Disner 1983	10?	0?

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