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Examining perceptual distance in phonological vowel reduction

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1. Introduction

Recent work on phonological vowel reduction has tightened the link between phonetics and phonology (see Barnes 2002; Crosswhite 1999, to appear; Flemming to appear; Herrick 2004b; Padgett and Tabain to appear). These analyses make more detailed phonetic predictions and as a result require more detailed phonetic data in order to test the accuracy of their predictions. This paper makes use of quantitative acoustic data from six dialects of Catalan to test aspects of a Dispersion Theory (DT; Flemming 1995; Padgett 1997; Sanders 2003) analysis of phonological vowel reduction. In particular, it examines the phonetic basis for DT's perceptual distance constraints.

Phonological vowel reduction refers to the neutralization of vowels under stress-dependent conditions (see Crosswhite 1999 and references therein). Reduction, then, refers to a reduction in the *number of vowels* appearing in unstressed contexts. Consider the data from Standard Catalan in (1) below.

(1) Standard Catalan vowel reduction data

	Stressed		Unstressed (diminutive)		GLOSS
a.	i	ˈbiɣə	i	biˈɣɛtə	'beam'/(dim.)
b.	e	ˈpesə	ə	pəˈsɛtə	'piece'/(dim.)
c.	ɛ	ˈbɛkə	ə	bəˈkɛtə	'grant'/(dim.)
d.	a	ˈbakə	ə	bəˈkɛtə	'cow'/(dim.)
e.	ɔ	ˈpɔkə	u	puˈkɛtə	'few/(dim.)
f.	o	ˈbokə	u	buˈkɛtə	'mouth'/(dim.)
g.	u	ˈbuk	u	buˈkɛt	'boat'/(dim.)

In stressed position, Standard Catalan allows seven vowels ([i, e, ɛ, a, ɔ, o, u]), but in unstressed position, only three vowels ([i, ə, u]) appear.[1] Appealing to phonological features, we can say that in unstressed position [+round] vowel phonemes map to [u], [−round, −high] vowels map to [ə], and the [−round, +high] vowel maps to [i]. Figure 1 illustrates this neutralization pattern.

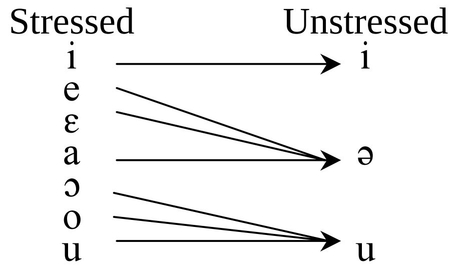

Figure 1: Neutralization pattern for Standard Catalan.

The most interesting question, however, is not *what* happens but *why* it happens. For DT, the explanation for all phonological phenomena is due to the interaction of three potentially conflicting principles of human language. First, for functional reasons, languages try to build large lexicons and sound inventories (maximize the number of contrasts). Second, for perceptual reasons, languages try to ensure the 'easy' perception of words and sounds (maximize the distinctiveness of contrasts). Third, for a variety of reasons often simplified as 'laziness', languages try to make words/sounds as easy to pronounce as possible (minimize articulatory effort). These three principles are summarized in (2).

(2) Overarching principles of DT (Flemming 1995)
a. maximize the number of contrasts (build large lexicons/sound inventories)
b. maximize the distinctiveness of contrasts (ensure 'easy' perception of words)
c. minimize articulatory effort ('laziness')

The way these three principles can account for phonological vowel reduction has been explained as follows in recent work in DT (Flemming to appear; Padgett 2004; Herrick 2003, 2004b). In order to ensure that vowels are easy to perceive (see principle (2b) above), each language enforces a particular distance (Δ) which must be maintained between contrasting vowel phonemes (see part a of Figure 2). In this case, the relevant perceptual dimensions are those of vowel height (which corresponds roughly to the first formant) and vowel color (a combination of frontness, backness, and rounding corresponding roughly to a weighted average of the second and third formants), and following the DT literature on phonological vowel reduction, we will focus only on the dimension of vowel height.

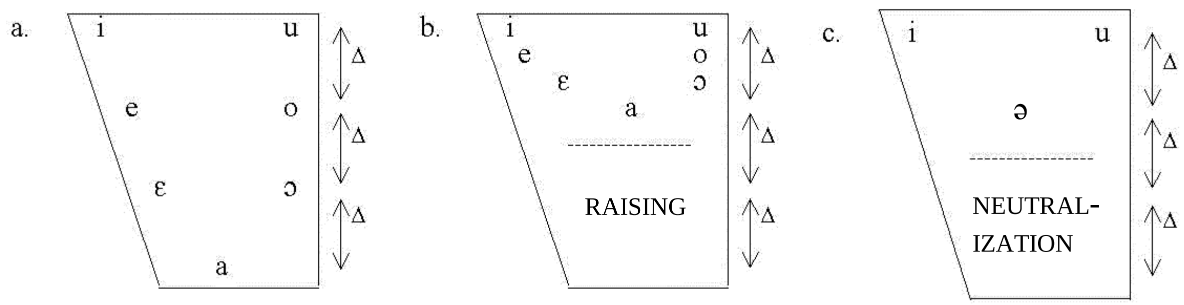

Figure 2: Vowel spacing diagrams illustrating the enforcement of minimal distance constraints (part a), the crowding of the space after raising (part b), and the return to obeying the minimal distance constraint after neutralization (part c). (Based on similar diagrams in Padgett 2004 and Padgett and Tabain to appear.)

When vowels are not stressed, articulatory constraints against low vowels in unstressed syllables cause the vowel 'floor' to raise, and the perceptual distance between vowels shrinks (as shown in part b of Figure 2). The reason for this is related to questions of articulatory effort (see principle (2c) above). Low vowels require greater jaw lowering than high vowels, and it requires extra time to complete the gesture. However, in unstressed syllables, vowels are shorter in duration than stressed vowels, so in unstressed position the jaw must be lowered more quickly (extra effort) in order to achieve the same jaw lowering as in stressed position. If this extra effort is not made, the necessary jaw lowering will not be achieved, and the ‘floor’ of the vowel space will raise (reducing the overall size of the vowel space – phonetic vowel reduction). In this compressed space, the distance between vowel phonemes shrinks, and if the raising of the low vowels increases too much, the language specific distance (Δ) cannot be met (see part b of Figure 2).

The crucial assumption to DT here is that if the perceptual distance between vowels is less than Δ, then hearers will be unable to distinguish the phonemes, and the result will be neutralization. Once vowels neutralize, there will be more space available along the perceptual dimension (in this case – vowel height), and the distance between the remaining vowels should satisfy the language specific perceptual distance constraint Δ (shown in part c of Figure 2).

A more complete explanation can be found in Flemming (1995, to appear); Padgett (2004); Padgett and Tabain (to appear); or Herrick (2003). Related but non-DT explanations are available in the work of Barnes (2002) and Crosswhite (1999, to appear). However, without going into more detail, we can identify three testable aspects of this account of phonological vowel reduction. First, DT assumes that vowel reduction will result in the complete neutralization of contrasting segments. Is this the case with Catalan? Is the neutralization complete? (If not, one could argue that the vowels are distinct but simply more crowded and easier to confuse – as shown in part b of Figure 2.) Second, the DT explanation depends, in large part, upon constraints against duration and jaw lowering to drive the neutralization of contrasts, and this predicts that vowel reduction is due primarily to raising – and not necessarily centralization (the general movement of vowels towards a central point in the vowel space). Is this the case with the Catalan data? To what extent do we find raising? Third, DT makes extensive use of perceptual distance constraints – is there empirical evidence to support this? To what extent do vowels obey a language specific minimal distance (Δ) in both stressed and unstressed position? While this paper will address all three of these question, a special emphasis will be paid to the third question – that of perceptual distance constraints.

2. The experimental methodology

The Catalan language provides an ideal testing ground for this research because its numerous dialects are distinguished primarily by differences in the vowel system. The dialects examined in this paper – those of Bages, Girona, Ciutadella, Palma, Lloseta, and Lleida – each exhibit a slightly different vowel inventory or neutralization pattern (summarized in Table 1 below). Of the six dialects, one represents Western Catalan (typically characterized by the lack of schwa in both stressed and unstressed position), two represent Central Catalan (characterized by the presence of schwa in unstressed – but not stressed – position), and three represent Balearic Catalan (characterized by the presence of schwa in both stressed and unstressed position – though Lloseta is exceptional in not allowing stressed schwa). Table 1 differentiates each of the six dialects in terms of the number of stressed or unstressed vowels as well as the appearance of stressed or unstressed schwa. For more details on the background of each dialect see Herrick (2003). (For those able to read Catalan, see Recasens 1991.)

For each dialect, I recorded three female speakers (college students aged 18-25) giving a total of 18 speakers. Each speaker uttered a series of nonsense words (embedded in a carrier phrase) which highlighted all the stressed and corresponding unstressed vowels of their dialect. In the case of Bages Catalan (representative of Standard Catalan), I collected data on all seven stressed vowel phonemes as well as data on the corresponding unstressed version of each vowel phoneme (thus, I have data for the schwa corresponding to unstressed /a/, /e/, and /ɛ/). Doing this allows for the statistical analysis of neutralization, and provides data for the stressed as well as the unstressed vowel systems (allowing us to test raising and the minimal distance between vowels).

Region	Minor variety	No. of stressed vowels	No. of unstressed vowels	stressed ə ?	unstressed ə ?
Bages	Central	7: i e ɛ a ɔ o u	3: i ə u	N	Y
Girona	Central	6: i e ɛ a O u	3: i ə u	N	Y
Ciutadella	Balearic	8: i e ɛ a ə ɔ o u	3: i ə u	Y	Y
Palma	Balearic	8: i e ɛ a ə ɔ o u	4(5): i (e) ə o u	Y	Y
Lloseta	Balearic	7: i e ɛ a ɔ o u	4(5): i (e) ə o u	N	Y
Lleida	Western	7: i e ɛ a ɔ o u	5: i e a o u	N	N

Table 1: A summary of the differences in vowel inventories between the six Catalan dialects which are examined in this paper.

All recordings were made on a DAT recorder using a headset microphone. The recordings were digitized at 44.1kHz, and analyzed using the PRAAT phonetics software package (version 4.0.16; Boersma and Weenink 2002). A more detailed discussion of the methodology can be found in Herrick (2003).

3. Translating between theory and acoustic data

The investigation of neutralization and raising/centralization in Catalan vowel inventories is fairly straightforward. Neutralization can be tested perceptually, statistically, and impressionistically (though I will present only statistical results here), and raising can be tested by comparing F1 x F2 vowel plots for the stressed and unstressed data. The question of how we can or should represent perceptual distance, however, is still open and remains largely unexplored.[2] With this in mind, the purpose of this section is to lay out the assumptions for a preliminary translation between the quantitative acoustic data for Catalan vowels and the constraints on perceptual distance found in DT.

The first choice we must make regards the appropriate scale for measuring vowels, and since we are investigating a perceptual property, it makes sense to use a perceptual/auditory scale such as Mel, Bark or ERB (Equivalent

Rectangular Bandwidth) rather than Hertz. The phonetic literature suggests that ERB provides the most accurate model for human perception (Moore and Glasberg 1996), so the data in this paper have been measured in ERB.

The second choice regards whether we represent the distance between vowels as a raw measure in ERB, or as a percentage (of the total distance available in the vowel space). Clearly, the simplest solution is to provide the distance in ERB; however, this runs into problems when comparing the data between different speakers. As an example, consider the distance in vowel height between /i/ and /e/ for two speakers of Palma Catalan. For speaker A, the distance is 1.9 ERB, but for speaker B it is 2.8 ERB – a difference of nearly one ERB. However, when we look at the distance in height between these vowels as a percent of the total available vowel space, speaker A shows a distance of 38% and speaker B shows a distance of 39% of the total vowel space – there is almost no difference between the speakers. In order to facilitate comparison between speakers and evaluation against the theoretical predictions, the distances between vowels have been calculated as percentages of the total available vowel space (determined by the maximal and minimal attested F1 values among the tokens for a given speaker).

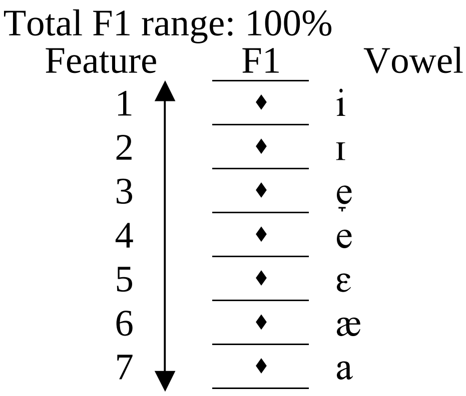

Figure 3: Vowel height features in Flemming (to appear).

Since we will express the distance between vowels as a percent of the total vowel space, the next step is to translate DT’s distances constraints into percentages so that we know how to evaluate them against the acoustic data. Flemming (to appear) appeals to multivalued features (ranging from 1 to 7) to describe vowel height. As shown in Figure 3, the high vowel /i/ is assigned the value 1, and the low vowel /a/ is assigned the value 7 (with the other vowels being given intermediate values). Minimal distance, then, is determined by simple subtraction of vowel height features – the distance between /i/ and /ɪ/ is one (2-1=1) and /i/ and /a/ is six (7-1=6). Flemming presents these constraints as MINDISTF1:1 and MINDISTF1:6 respectively, and for the purpose of this paper, I will only consider this version of minimal distance (Padgett 1997, 2004; and Sanders 2003 offer alternative definitions).

Given this feature system, the maximal range for vowel height is the distance between /i/ and /a/. However, when translating to actual data, the points in space for /i/ and /a/ represent data averages – not the extremes of the height continuum. (A few tokens for /i/ will be above and a few tokens for /a/ will be below the average values.) This means that the total range for vowel height is (slightly) greater than the distance between /i/ and /a/, and since it is impossible to determine the exact (and appropriate) maximal range of F1 for each speaker, I have used the maximal range found among the tokens for /i/ and /a/. When averaged across all 18 speakers, this results in a 14% increase to the overall vowel height range,[3] and this has been indicated in Figure 4 below.

Once we have the maximal range for vowel height (the distance between /i/ and /a/ + 14%), we can complete the translation of Flemming's MINDISTF1 constraints to percentage terms. Since we are assuming that vowels are evenly spaced, a diagram of all the possible vowel height distinctions allowed by MINDISTF1:1 shows six equal spaces between all the vowel pairs (Figure 4). Given 86% of the overall vowel space to work (100% – 14% = 86%) with and six equidistant intervals separating neighboring vowel pairs, then each of the vowels are located roughly 14% of the total F1 distance apart from their immediate neighbors (86% / 6 = 14.3%).

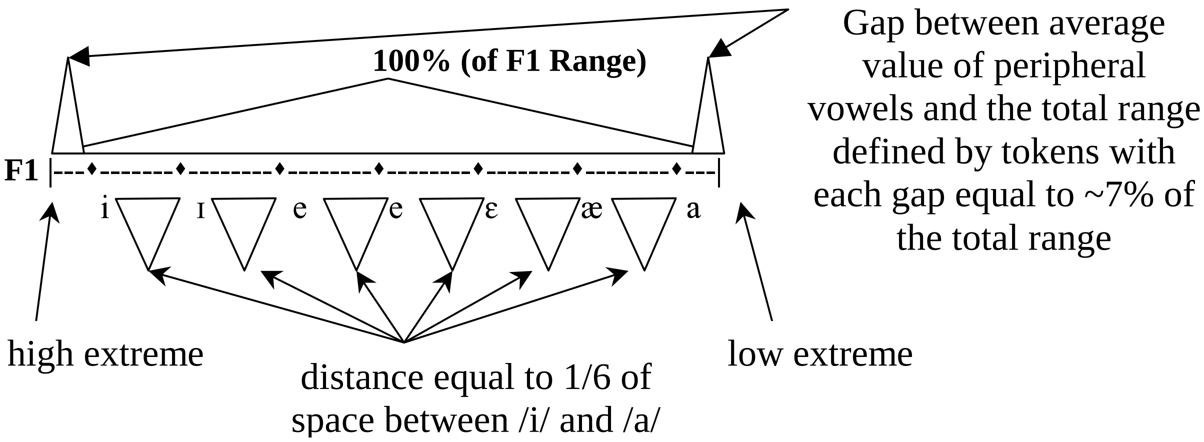

Figure 4: Linking Flemming's features to the F1 dimension

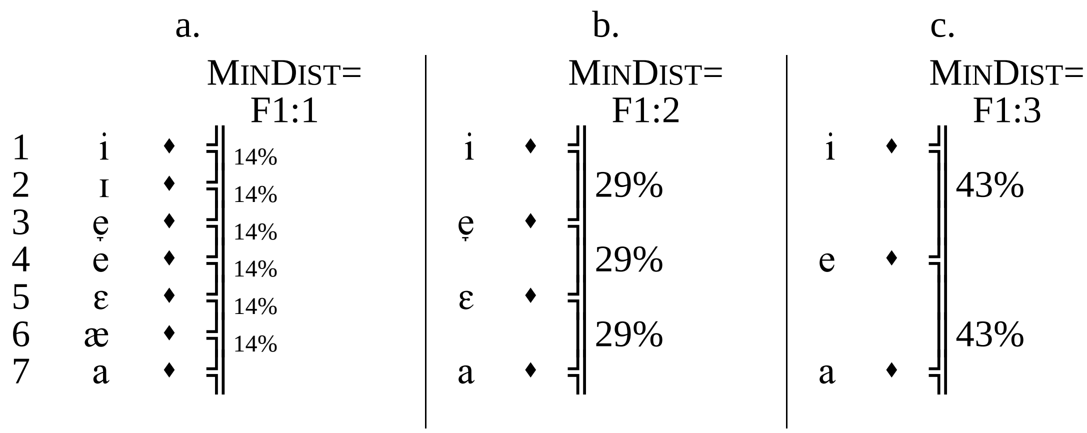

Figure 5: MINDISTF1 constraints translated to percentage terms.

This means that Flemming's MINDISTF1:1 constraint (which allows the seven way height contrast shown in Figures 3 and 4) can be thought of as the demand for all vowels to be at least 14% of the total distance away from their immediate neighbors (see Figure 5a). Extending this, MINDISTF1:2 is a demand for all vowels to be at least 29% of the total F1 distance away (14.3% x 2 = 28.6%) from their nearest neighbors (Figure 5b), and MINDISTF1:3 requires neighboring vowels to be at least 43% of the total F1 distance apart from one another (Figure 5c).

Since Catalan contrasts four vowels along the height dimension (/i, e, ε, a/), our first prediction is that Catalan vowels will obey MINDISTF1:2 and be at least 29% of the F1 range apart from one another, and this prediction leads, in turn, to a second prediction about raising. If the minimal distance threshold for the F1 dimension in Catalan is equal to 29%, then in stressed position, the vowels will look as they do in Figure 6; each of the neighboring vowels along the height dimension will be separated by at least 29% of the overall F1 range. If, however, the vowel floor raises by, for example, 16%, then the vowels must space themselves out along the remaining 84% of the F1 dimension (100% - 16% raising = 84%). If we maintain the 7% gaps at each periphery (the 14% due to variation mentioned above), then the vowels only have 70% of the total vowel space available to them. And if the vowels are evenly spaced along this remaining 70%, then each pair will be separated by only 23% (70% / 3 pairs = 23.3%) of the total F1 range. Since 23% is less than the minimal distance threshold of 29%, the theory predicts neutralization will occur. This neutralization pattern, in which we move from a four vowel height contrast to a three vowel height contrast, is illustrated in Figure 7.

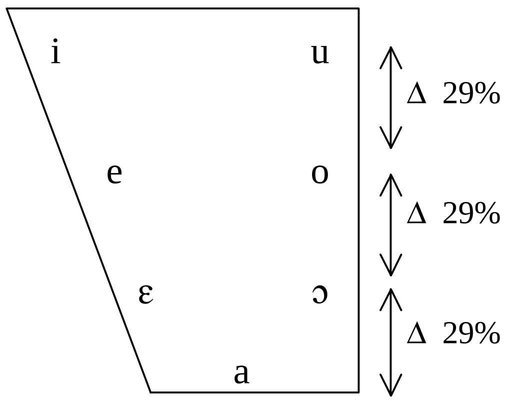

Figure 6: Vowel spacing diagram illustrating a minimal distance requirement of 29% (of MINDISTF1=2).

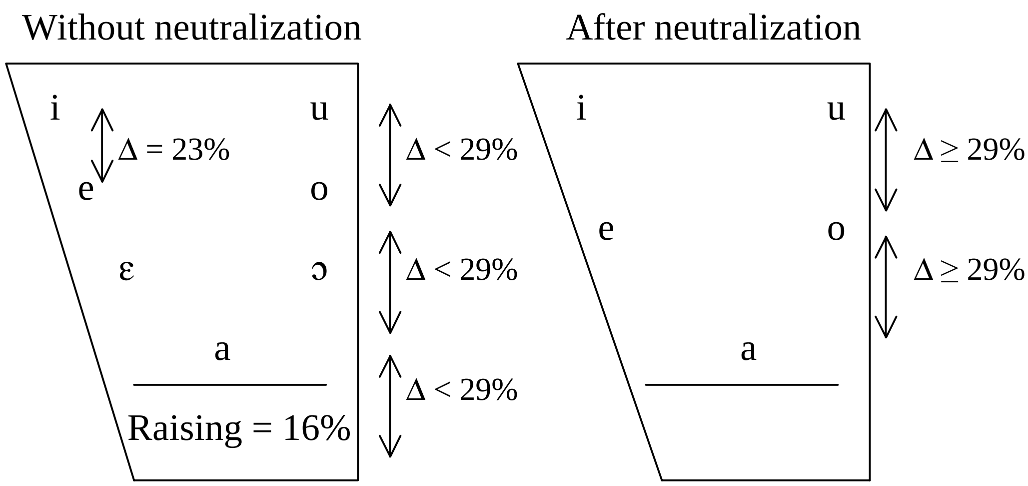

Figure 7: Vowel spacing diagram illustrating 16% raising.

With the current assumptions, reduction from 1-28% results in the neutralization to a three vowel (two pair) height system. However, given the variation in production of low vowels, we can find certain stressed tokens for /a/ which are ‘raised’ (albeit minimally) compared to the average value. As a result, it seems clear that the system must tolerate at least some degree of variation. As an initial approximation, I assume here that the grammar will tolerate variation (in this case ‘raising’) equal to at least one standard deviation for the low vowel. When expressed as a percent of the total vowel height, the standard deviation for F1 for /a/ (for all 18 speakers) comes to roughly 6%, so I assume that in order to force neutralization to a three vowel height system, we need between 7-28% raising.[4] The pattern shown in Figure 7 is exactly what we find in Western Catalan (represented in this study by three speakers from Lleida), so the prediction is that we will find raising of between 7-28% in the vowel systems of the speakers of this dialect.

If raising exceeds 28% we would require additional neutralization in order to meet the minimal distance constraint. Raising of between 29-57% will result in a two vowel height contrast in unstressed position.[5] Imagine that the vowel floor has raised 45% as in the situation depicted in Figure 8. Here, the four vowels contrasting along the height dimension must spread out along the remaining 41% of the F1 dimension (100% - 45% raising – 14% peripheral gap = 41%). This means the neighboring vowels will only be 14% (41% / 3 = 13.7%) apart from one another, clearly violating the minimal distance constraint of 29%. Neutralization to a three vowel height contrast (as in Figure 7) is not enough (41% / 2 pairs = 20.5%; and 21% is still less than the required 29% minimal distance), so further neutralization to a two vowel height contrast (41% / 1 pair = 41%) is necessary. The pattern shown in Figure 8 is what we find in Central and Balearic Catalan (represented by speakers from Bages, Girona, Ciutadella, Palma, and Lloseta), so the prediction is that these speakers will exhibit raising of over 29%.

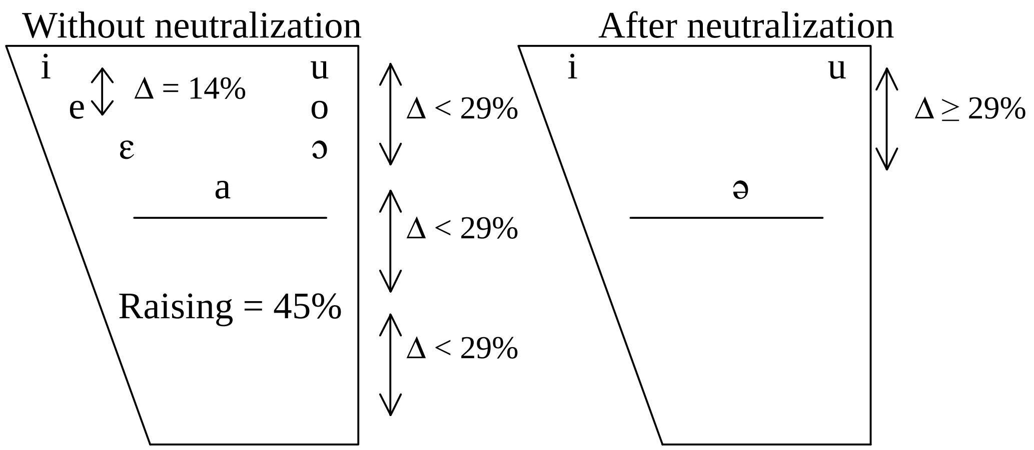

Figure 8: Vowel spacing diagram indicating 45% raising.

To summarize, the main predictions are that unstressed vowels in Catalan will show complete neutralization, that we will find raising of 7-28% for Western Catalan and 29-57% with Eastern Catalan, and that the minimal distance (for vowel height) between Catalan vowels will be 29%.

4. Results

4.1 Neutralization

Incomplete neutralization arises when small systematic phonetic differences can be found between phonemes which, impressionistically, appear to have neutralized. In Catalan, the impressionistic data indicate that there is neutralization; however, prior to this research, there have been no acoustic studies which demonstrate (or which *could* demonstrate) that neutralization is complete.

Figure 9 shows a vowel plot for a speaker of Bages Catalan which contains the average values for stressed vowels (solid squares) and the corresponding unstressed vowels. As can be seen, there are small differences between the unstressed vowels which reportedly surface as schwa. The key question now is, are these differences statistically significant or not?

As reported in Herrick (2003, 2004a), statistical tests (ANOVA with p set to < 0.01) show that there are no significant differences between any of the Catalan vowels which are reported to neutralize in unstressed position. That is, all unstressed vowels which are reported to neutralize (e.g. unstressed versions of /e, ɛ, a/ which neutralize as schwa) do, in fact, neutralize. This finding is important because it supports one of the primary assumptions of the DT analysis of phonological vowel reduction – namely, that the neutralization of unstressed vowels is complete.

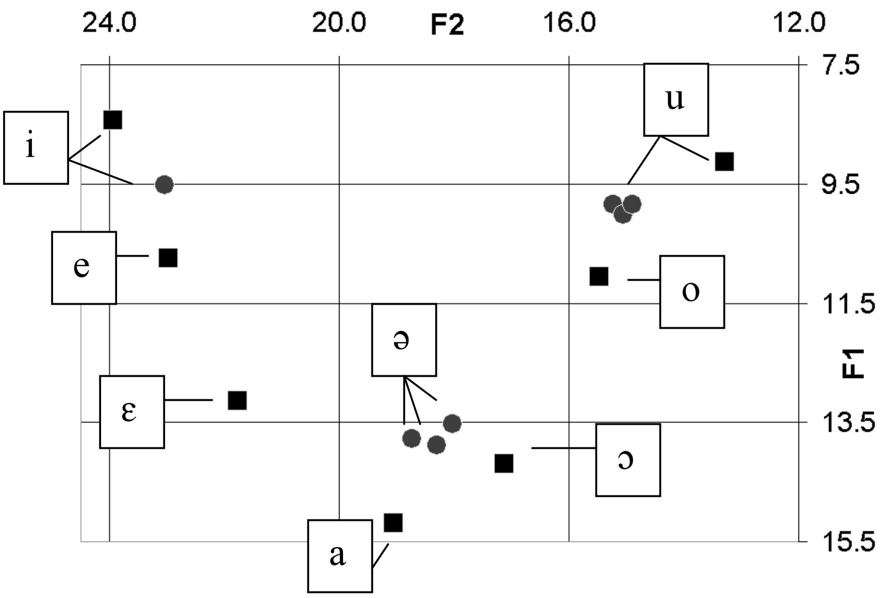

Figure 9: F1 x F2 vowel plot for a speaker of Bages Catalan.

4.2 Raising

Section 3 of this paper lays out predictions about the degree to which we will find raising in Western Catalan (7-28%; exemplified here by Lleida Catalan) and Central and Balearic Catalan (29-57%; exemplified by the other five dialects). The data in Table 2 give the range of F1 and F2 for stressed and unstressed vowels for each of the dialects. By comparing the stressed and unstressed ranges with one another, we can determine the degree to which F1 and F2 reduce in unstressed position.[6] Furthermore, as reported in Herrick (2003, 2004c), the primary acoustic characteristic of Catalan vowel reduction is raising (reduction along F1) and not centralization (raising and lowering combined with a reduction along F2). The data in Table 2 show that reduction along F2 is neither consistent nor considerable (while it is both for F1), and this supports theories of vowel reduction like DT which are linked to 'raising' or 'jaw-lowering'.

	Stressed		Unstressed			
Region	F1Range	F2Range	F1Range	F2Range	**ReduxF1**	**ReduxF2**
Bages AVE	6.5	10.9	4.6	10.2	**29%**	**6%**
Girona AVE	6.2	10.3	3.9	9.9	**38%**	**4%**
Palma AVE	6.5	10.1	3.8	8.9	**42%**	**13%**
Lloseta AVE	7.1	10.9	3.5	10.3	**50%**	**5%**
Ciutadella AVE	5.9	9.5	3.8	10.1	**35%**	**-6%**
Lleida AVE	5.6	9.4	4.7	9.4	**16%**	**-1%**

Table 2: Reduction data for six Catalan dialects; data given in ERB.

DT predicts that we will find a certain degree of raising in all cases of phonological vowel reduction, and these predictions are met by all six Catalan dialects (though only just met in the case of Bages Catalan) examined here. Lleida Catalan is particularly interesting since this dialect does not allow schwa (stressed /a/ surfaces as /a/ – not schwa – in unstressed position), and we might have expected to find no or very little raising in this case. The fact that the predictions are met here (and in the five other dialects) adds support to the DT analysis of phonological vowel reduction.

4.3 Perceptual distance

All six of the Catalan dialects possess a four vowel height contrast (at least among the front vowels – Girona Catalan has only one mid back vowel). Given the translation of Flemming's MINDISTF1 constraints set out in the previous section, the prediction is that Catalan vowels will be spaced out evenly at 29% intervals along the F1 dimension. The data in Table 3, however, show that this prediction is not met. Instead, we find that the distance between neighboring vowel pairs ranges from 11% to 40% of the maximal range for vowel space.

Under the most straight-forward interpretation, then, the predictions for minimal distance constraints in DT have not been met. Is this a fair conclusion though? To a certain extent, we must predict that the spacing of vowels will not be perfectly even. It has long been known that languages, dialects, and individual speakers vary in their production of phonemes. Balearic dialects are known to have a relatively low quality for the open-mid vowels (/ɛ/ and /ɔ/), and if these vowels are relatively low, then they should be closer in height to the low vowel /a/ (see the data for Ciutadella and Palma Catalan).

Variety	i~e	e~ɛ	ɛ~a
Bages	19%	29%	20%
Girona	13%	38%	21%
Ciutadella	29%	35%	16%
Palma	30%	30%	11%
Lloseta	23%	40%	19%
Lleida	23%	38%	17%

Table 3: Linear distance (along F1) in vowel height for STRESSED VOWELS (expressed as a percent of the total F1 range)

Furthermore, for various reasons including loudness and (the relatively) lower frequency, research into the perception of vowels has shown that vowel height is primary (as opposed to color) in distinguishing vowels (Lindblom 1986; Schwartz et al 1997). If this is the case, perhaps the best conclusion to make is that minimal distance constraints on vowel height cannot be translated into acoustic terms by a simple division of the vowel space (as I suggested above). Or perhaps distance cannot be evaluated one dimension at a time (for example, though the F1 distance between Girona /i~e/ and Palma /ɛ~a/ is very small, both vowel pairs also show a considerable difference in F2); that is, the appropriate measure of minimal distance may combines information from multiple sources (loudness, F1 frequency, F2 frequency, and so on). Regardless, the data show that vowels are not evenly spaced along the height dimension, and that they do not obey a minimal distance constraint of 29%.

5. Conclusion

Recent theories of phonological vowel reduction make more precise phonetic predictions which cannot be tested by impressionistic data alone – acoustic data is necessary. This paper provides quantitative acoustic data from six dialects of Catalan to evaluate three aspects of a Dispersion Theoretic account of phonological vowel reduction. First, it highlights three assumptions and predictions of DT (completeness of neutralization, raising, and minimal distance) and suggests a way to translate a DT analysis of vowel reduction into numbers which can be evaluated against the acoustic data. The primary findings are: first, that neutralization is complete in all six dialects of Catalan (consistent with DT); second, that the predictions for raising are met by all six dialects (consistent with DT); and third, that the minimal perceptual distances between vowels in the stressed vowel systems of these six dialects vary between 11-40% of the total vowel height range (not necessarily consistent with DT).

The simplest conclusion is that DT's perceptual distance constraints are not supported by the Catalan data; however, I would like to argue that this conclusion is premature. First, I take the positive results (on neutralization and raising) to indicate that this is an area worth investigating further. Second, the translation from theory to acoustic terms presented here is unavoidably straightforward and most likely oversimplified – acoustic research into minimal distance is in its infancy, and at this point, several assumptions can only be guessed at. In particular, the assumption that phonemes will be equally spaced along a single perceptual dimension must be examined further. Perhaps the minimal distance between vowels must take more than one dimension at a time into consideration. Or perhaps, the mismatches found here between the acoustic data and constraints on minimal distance (with equal spacing) always exist, and this tension between a grammatical ideal (competence) and the actual production/perception of sounds (performance) could prove useful in explaining the source of (at least some) language change.

Notes

* Acknowledgment: I would like to thank all the speakers who participated in this project (along with all the people who helped put me in touch with the speakers in the first place). This research was supported in part by a Mie University COE grant.

[1] Mascaró (1978, 2002) notes that there are three types of phonological exceptions: lexical exceptions (often loanwords such as [ˈboston]), morphological exceptions (often compounds), and contextual exceptions (possibly to avoid the creation of long schwa due to hiatus).

[2] I know of my own research (Herrick 2003) and that of Padgett (2004) and Padgett and Tabain (to appear). Otherwise, research into perceptual distance constraints – and DT in particular – either uses impressionistic data (a

reasonable first approximation, but not sufficient to test the full extent of the predictions of the theory) or it has not been completed.

[3] I arrived at the number of 14% by dividing the F1 range for vowel averages (the range between /i/ and /a/) by the maximal F1 range for vowel tokens (Average F1 range / Token F1 range) and then subtracting this number from 1. This calculation gives a percentage value for the amount of 'gap' there is between the peripheral vowels /i/ and /a/ and the edge of the maximum vowel space. I calculated this for each of the eighteen speakers, and the average value was 14.2% (max = 20.9% for speaker 17; min = 7.6% for speaker 15). Clearly, this is only an arbitrary approximation, but it seems like a reasonable place to start. It is impossible to know exactly what the maximal range of F1 is (for either a given speaker or set of speakers) because we cannot control for the amount of effort a given speaker exerts to make 'the /i/-est /i/' or the '/a/-est /a/'. Presumably we could ask speakers to make the most /i/-like and /a/-like vowels they can, then ask for even more effort, and stop when the sounds exhibit signs of frication (indicating a change from vowel to approximant or fricative), but it is not clear that such data would have any strong connection to natural speech – or even innate knowledge of natural speech.

[4] A three vowel height contrast requires at least double the minimal distance of 29% (58%). In addition, as mentioned in footnote 3, 14% of the total vowel height range has been made unavailable. Therefore, we need at least 72% of the available vowel height (58% + 14% = 72%). This means neutralization to a three vowel height system can tolerate a maximum of 28% raising(100% – 72% = 28%). The range, then, tops out at 28%.

[5] A two vowel height contrast requires at least 43% of the vowel height space (29% + 14% = 43%). Neutralization to a two vowel height system, then, can

tolerate a maximum of 57% raising (100% – 43% = 57%). The range, then, is from 29-57%.

[6] First divide the stressed range by the unstressed range and express this as a percent. This number gives the percent of the total range which is occupied by the unstressed range. If we subtract this number from 100%, we are left with the percent of reduction found in the unstressed vowel system.

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