Using entropy to determine vowel spaces

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Abstract

Vowel spaces are often illustrated with the first and second formants plotted against each other on X-Y plots. The numerical values of vowel F1, F2, and F3 were evaluated using Pearson correlations and results often show inconsistencies, indicating that some F1-F2 plots might not provide the best vowel space depiction. The same formant values were examined using conditional entropy methodology and determinations were made which formants should be the independent X variable, and which formants should be the dependent Y variable for plotting. This research describes the examination of relationships between formants to determine optimal, more accurate vowel space plots.

Keywords: vowel space, entropy, correlation, formant

Introduction

Vowels have been one of the most well studied aspects of phonetics in most languages worldwide. Traditionally, studies on vowels are concentrated on the distribution of F1 vs. F2, which define the acoustic space of a given language. As a general rule, the F1 variability represents the high vs. low distinction of the vowels whereas the F2 represents the front vs. back of the vowels distinction of the vowels. Most usually, the F1 vs. F2 distribution is shown in vowel charts which define at the same time the shape of the acoustic space of the language under investigation. Additionally, vowel formant charts exhibit in one single diagram the interrelation of the first two formants (Ladefoged 2003, Johnson 2004, Story, Bunton 2017).

This research is motivated by two questions: The first question concerns the variability of vowel space as a method to display vowel distribution and vowel characteristics. The second question concerns the possibility of measuring the relationship between the formants in a language.

In a recent study (Anderson, Botinis, Goertz, Kontostavlaki 2022), the acoustic space of Greek as well as the centroid of the vowel spaces were investigated. It was shown that the vowel space of Greek was considerably smaller that the acoustic space of American English, whereas the center the acoustic space of Greek was considerably dissimilar to American English.

Correlations of vowel formants

The speech data for this research comes from three sources: 1) Linguists provide examples of the 28 IPA vowels on several academic websites (see references) and a total of 112 vowel examples were used in this evaluation. 2) A total of 908 CVC and CV words read by native English speakers (two female, 1 male) using a Røde N microphone in a GretchKen™ Industries acoustic sound booth. 3) The third portion of the speech data was 426 speech tokens from 29 languages downloaded from the IPA and UCLA websites.

All vowels and vowel portions of the words were evaluated using PRAAT (standard settings of 5,500 Hertz ceiling and 5 formants), to produce F1, F2, and F3. Formants were them evaluated using Pearson correlation methods.

Correlations varied widely for the 112 vowels found that approximately 15% have strong correlations and 50% have low or negative correlations. Many correlations indicated F1-F3 formants would be preferable.

The word list correlations varied from very low values such as -0.263 (man) and -0.067 (key) to higher values 0.901 (pet) and 0.842 (put). Some F1-F3 correlations were found to be stronger than F1-F2 correlations.

The correlations for the tokens of the 29 languages also varied from very low to high values and did not support a general F1-F2 plotting scheme.

Correlations did not produce clear indications for vowel space plotting, prompting the investigation to the suitability of conditional entropy.

Conditional entropy for vowel formant pairs

Conditional entropy was developed from Information Theory. Entropy is used to detect patterns in data, and to establish their relationships by providing numerical values that shows their relative degree of overlapping information (see MacKay 2003, Haglund, Jeppsson, & Strömdahl 2010, Goodfellow et al. 2016). Conditional entropy is the amount of data needed for one variable to describe another variable: their suitability for plotting one against the other. The conditional entropy was calculated with the Mutual Info 0.9 cross-platform program package (Peng 2002) operating in Matlab.

Results

The entropy data shows which formant is the independent variable (X) and which formant is the dependent variable (Y) for plotting.

The left bolded column shows the six pairs of the formants that were compared for the analysis. F1F2, for example, is notation for the test of the suitability of F1 as the dependent variable and F2 as the independent variable. Lower entropy values show better suitability for vowel space plotting. In the case of '*kid*', plotting F2-F3 would provide optimal results. '*Boat*' and '*cot*' indicate the dominance of F2. The results for 'out' shows that F1 should be plotted on the X-axis. The zero values of *nem* shows that F2 and F3 are independent, *světlo* shows that F3 is the independent variable, and the UCLA vowel /æ/ spoken in isolation shows that F2 is the independent variable. *Ship* data, having all zero values, indicates that the vowel formants are combined or related to each other.

Some vowel formant pairs have zero entropy values as seen in the four right columns of Table 1. Conditional entropy has a unique defined mathematical property: *if and only if* conditional entropy is equal to zero *then* the value of one variable (dependent) is a direct function of the input variable (independent). This property was noted in samples taken from both male and female speakers, and sometimes does not appear consistently in words that speakers repeated words. These zero or near zero values mean that two formants are linked and perhaps one formant generates the other. Rather than being distinct formants, the two zero formants could be considered a combined wide band of formants.

Table 1. Entropy values of vowel portions of speech samples. Data from female speakers are indicated in italics. The Bulgarian word *nem* translates to 'five' and the Czec*h word světlo* translates to 'light'. Other words are English.

	kid	boat	cot	out	*nem*	*světlo*	/æ/	*ship*
F1F2	*0.3185*	**0.024**	**0.0606**	0.1086	***0***	*0.3419*	**0**	***0***
F2F1	*0.1757*	0.0481	0.101	**0.0869**	*0.0952*	*0.0408*	0.1609	***0***
F1F3	*0.2471*	0.1204	0.1414	0.1304	***0***	***0***	0.1006	***0***
F3F1	*0.1757*	0.0481	0.101	**0.0869**	*0.0952*	*0.0408*	0.1379	***0***
F2F3	***0.0952***	0.1204	0.1414	0.1304	***0***	***0***	0.1236	***0***
F3F2	*0.1667*	**0.024**	**0.0606**	0.1086	***0***	*0.3419*	**0**	***0***

Discussion

Conditional entropy determines which formants would be most accurately displayed on the x-axis and which formant would be plotted on the y-axis. In some cases, F2-F3 or F3-F2 plots would convey more complete information than F1-F2 plots. Assumptions about vowel depictions may have to be modified, according to entropy data that defines the appropriate X-Y vowel space plot.

The discovery of zero entropy values of some formant pairs should be investigated further. Hopefully additional research will show if zero value formant pairs should be plotted against each other, or against a third value. Furthermore, this line of research is expected to advance our knowledge on crucial aspects of cross-linguistic as well as cross-dialectal vowel characteristics.

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