Significance of level of spectral valleys of vowel sounds

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Abstract
The spacing between two adjacent formants, which is known to play an important role in the perceived vowel quality, also determines the level of the spectral valley between them. An objective critical distance (OCD) has been defined as that spacing between adjacent formants, when the level of the valley between them reaches the mean spectral level. The measured OCD for synthetic vowels lies in the same range (viz., 3-3.5 bark) as the critical distance determined by subjective experiments for similar experimental conditions. The computed OCD is vowel dependent and varies over a wide range. The level of spectral valley serves a similar purpose as that of the spacing between the formants with an added advantage that it can be measured from the spectral envelope without an explicit knowledge of formant frequencies. To demonstrate this, vowels have been classified into front/back based on the relative level of the spectral valley giving an accuracy of about 98%. Information relating to the spectral valleys seems promising, which needs to be explored further.

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I. INTRODUCTION

It is well established that there is a considerable variability in the formant frequencies measured during the mid-part of a vowel sound spoken in the same context by different speakers of the same gender and same dialect1. Native listeners have no difficulty in identifying the phonetic quality of a vowel despite a wide acoustic variability. This finding has created considerable research interest related to vowel identification based both on perceptual and objective criteria. One of these approaches is related to the influence of the spacing between adjacent formants on the perceived vowel quality. Our interest in this paper is related to this approach. It is well recognized that the spacing between two adjacent formants determines the level of spectral valley between them, the level being shallower when the spacing is less and deeper when the spacing is more. Hence, the influence of spacing between two formants can as well be studied indirectly using the level of spectral valley between them. The advantage is that the level of spectral valley can be measured from the spectral envelope without an explicit knowledge of formant data and at the same time not sacrificing the information about the spacing between the formants. We explore the significance of the level of spectral valley in this paper.

Delattre et al. of Haskins Lab reported in 19522 an interesting experimental study of vowel quality. They showed that vowels synthesized with a single formant of an appropriately chosen resonant frequency matches well with the perceptual quality of back vowels synthesized with two formants, as judged by subjects with a training in phonetics. This equivalence of phonetic quality of a two-formant vowel to that of a single formant vowel is referred to as “spectral integration” in the literature. Surprisingly, this integration did not seem to emerge in the case of front vowels, except for vowel /i/ as an extreme case. Chistovich et al. 3 conducted subjective experiments to derive the condition under which the spectral integration occurs. They kept $F_2$ fixed and varied the spacing between $F_1$ and $F_2$. Such a two-formant stimulus was compared with a single-formant stimulus for equivalence in vowel quality. They found that the perceptual equivalence occurs when the spacing between the formants lies within a range of $3.1 < \Delta Z < 4.0$ bark for an $F_2$ value of 1.8 kHz and in the range $3.3 < \Delta Z < 4.3$ bark for the $F_2$ value of 1.4 kHz. Although this critical distance, denoted as $\Delta Z_c$, has a wide range of
3.1 to 4.3 bark and the experiment by Delattre et al.\textsuperscript{2} demonstrated spectral integration for /u/ with a formant separation of 3.94 bark, this perceptual phenomenon is generally known as 3-bark rule in the literature.

Chistovich \textit{et al.}\textsuperscript{3} argued that the frequency of the single-formant equivalent corresponds to the center of gravity of the spectrum. Chistovich and Lublinskaya\textsuperscript{4} showed that spectral integration occurs even when there is a large change in formant levels when the spacing between formants is less than the critical distance in the range of 3 – 3.5 bark. Experiments on matching a four-formant vowel to a two-formant vowel also seem to support the so called 3-bark rule\textsuperscript{5,6}.

The 3-bark rule has been applied in the context of vowel classification\textsuperscript{7}, where \((F_1 - F_0), (F_2 - F_1)\) and \((F_3 - F_2)\) differences in bark have been used. The authors\textsuperscript{7} argue that these differences compared with a threshold of 3 bark, rather than the actual values of the formant frequencies, is of importance for the discrete vowel classes to emerge. Vowel classification accuracy of 87 – 99 % has been reported. A practical scheme of vowel classification based on the separation of formants requires an accurate estimation of formant frequencies, which is quite challenging, especially for high \(F_0\) vowels\textsuperscript{8}. Hence, some researchers have proposed a spectral template approach instead\textsuperscript{9–11}.

Based on the success of using the formant separation as an acoustic feature, Syrdal and Gopal\textsuperscript{7} proposed an auditory model for vowel perception which raises some issues to be resolved. The subjective experimental evidence of 3-bark rule has been established mainly for back vowels. The separation \((F_2 - F_1)\) is not distinctive since it is greater than 3 bark for all front vowels as well as for a number of back vowels. Perceptual tests\textsuperscript{12} have shown instances of stimuli with the same separation of \(F_0\) and \(F_1\) producing a high-low distinction and also instances of stimuli with \(F_2\) and \(F_3\) separation less than 3 bark producing a vowel quality distinction.

Some researchers consider spectral integration to be a general psycho-acoustic phenomenon, not necessarily restricted to vowels, based on perceptual tests conducted on two-tone complex signals\textsuperscript{13} and sinusoids replacing formants\textsuperscript{14,15}. Although it is generally believed that spectral integration occurs for back vowels, there may be some exceptions as demonstrated for a specific back vowel of Chinese
language\textsuperscript{16}. Spectral integration has also been reported in the literature with respect to syllable initial
stops\textsuperscript{17} and glides\textsuperscript{18} but the interest in this paper is restricted only to vowel sounds.

**Motivation for the present work:** The subjective critical distance of $3 - 3.5$ bark has been derived
using two-formant unrounded synthetic vowels resembling the quality of ‘a’ or ‘e’. It is not known if
the same subjective critical distance is also valid for multiple-formant natural vowels with different
bandwidths, formant levels, spectral tilt etc. It is extremely time consuming to conduct subjective
experiments to deduce the critical distance for all the experimental conditions. With this in view, we
propose an objective critical distance (OCD) that may be measured for any given spectral envelope
and investigate if such an OCD serves a similar purpose as that of the subjective critical distance.

**About this work:** In Sec. II, an OCD is defined in terms of the level of spectral valley between two
formants. The influence of formant spacing, higher formants, formant levels and fundamental
frequency on the measured OCD is studied. In Sec. III, the measured OCD is compared with the
subjectively determined critical distance published in the literature. In Sec. IV, the importance of the
relative level of spectral valley as an acoustic feature for a front/back classification of vowels is
presented.

**II. THE OBJECTIVE CRITICAL DISTANCE**

**A. Definition**

Rather than subjective, we define an OCD, denoted as $\Delta Y$. Since the spacing between
two formants determines the level of spectral valley between them, we define the OCD in terms of the
level of spectral valley as follows: Let us denote the ratio of mean spectral level to the level of the
spectral valley between formants $F_1$ and $F_2$ (or $F_2$ and $F_3$) as $V_{12}$ (or $V_{23}$). Then the OCD is that value
of the separation between $F_1$ and $F_2$ (or $F_2$ and $F_3$) when $V_{12}$ (or $V_{23}$) becomes 1. For formant spacing
less than $\Delta Y$, $V_{12}$ (or $V_{23}$) will be less than 1 (the level of the valley is above the mean spectral level)
and $V_{12}$ or $V_{23}$ in dB is less than 0. For formant spacing greater than $\Delta Y$, $V_{12}$ (or $V_{23}$) will be greater
than 1 (the level of the valley is below the mean spectral level) and $V_{12}$ or $V_{23}$ in dB is greater than 0.
In the following sub-sections, we study the relation between the relative level of spectral valley (abbreviated as RLSV) and formant spacing using synthetic as well as natural vowels to measure $\Delta Y_c$ and to identify the factors that influence its value.

B. Influence of formant spacing on $\Delta Y_c$ in a two-formant vowel

A two-formant vowel is synthesized using a second order digital resonator with $F_2$ and $B_2$ kept constant at 1400 and 200 Hz, respectively. The first formant $F_1$ is varied in frequency from 650 to 950 Hz in steps of 50 Hz and its bandwidth is kept constant at 100 Hz. The reason for this choice of parameters is presented later in Sec. III. The magnitude squared spectrum of the impulse response of the cascaded two-formant model is computed. Figure 1 shows the log-magnitude spectra for three choices of formant spacing. The peaks are clearly resolved in the log-magnitude spectra for all the three conditions. However, when the formant spacing is greater than the OCD, the log-spectrum crosses the mean level twice for each formant, once on either side of the formant peak; else when formant spacing is less than the OCD, there are only two, instead of four crossings, for the two formants. Figure 2 shows the RLSV, $V_{12}$, as a function of formant separation in bark. It is not surprising that $V_{12}$ depends on the formant spacing. However, what is worth noting is that $V_{12}$ is nearly zero when the spacing between two formants is near 3 bark. The variable $V_{12}$ (in dB) is positive when formants are wide apart; It is nearly equal to 0 when the spacing approaches about 3.2 bark and negative when the spacing between the formants reduces further.
FIG. 1. Log-magnitude spectra of synthetic two-formant vowels illustrating the influence of formant spacing on the relative level of spectral valley. Dashed plots: $F_{1\text{ref}} = 750$ Hz, $F_{2\text{ref}} = 1400$ Hz, $(F_{2\text{ref}} - F_{1\text{ref}}) = 3.9$ bark, $V_{12} > 1$. (a) Solid plot: $F_1 = 850$ Hz, $(F_2 - F_1) = 3.2$ bark, $V_{12} = 1$ and hence, this $F_1, F_2$ separation corresponds to the OCD. (b) Solid plot: $F_1 = 950$ Hz, $(F_2 - F_1) = 2.5$ bark. For these values, $V_{12} < 1$ or its dB value is -ve. (MSL: Mean spectral level).

C. Influence of higher formants on $\Delta Y_c$

We consider a four-formant vowel with the formant frequencies of a uniform tube at 500, 1500, 2500 and 3500 Hz. As will be discussed in Sec. II.D.1, the choice of bandwidth does not significantly influence $\Delta Y_c$. Hence, for simplicity, bandwidths for all the four formants are kept fixed at 100 Hz. Any other choice for bandwidths could have been made without significantly affecting the results. Also, it is not necessary that the bandwidths of all the formants be equal. In order to control the spacing between $F_1$ and $F_2$, $F_1$ is increased and $F_2$ is decreased in steps of 25 Hz which implies that the vowel quality moves towards that of a back vowel. The log-magnitude spectra are shown in Fig.3 for three selected cases. We note that $\Delta Y_c$ is about 3.6 bark. Thus, even in the presence of higher formants, the OCD between $F_1$ and $F_2$ can be measured unambiguously.
D. Influence of formant levels and $F_0$ on $\Delta Y_c$

The effects of changes in the bandwidth and fundamental frequency are studied for two different cases of formant spacing: Case (a): $F_1=400$ Hz, $F_2=700$ Hz, formant spacing = 2.5 bark. Case (b): $F_1=600$ Hz, $F_2=1300$ Hz, formant spacing = 4.65 bark. The reason for the above choices of $F_1$ and $F_2$ is presented in Sec. III. For synthesis, four-formant model with $F_3 = 2500$ Hz, $F_4 = 3500$ Hz and a sampling frequency of 8000 Hz has been used.
FIG. 3. Log-magnitude spectra of synthetic four-formant vowels illustrating the influence of formant spacing on the relative level of spectral valley. Dashed plots: $F_{1\text{ref}} = 500$ Hz, $F_{2\text{ref}} = 1500$ Hz, $F_{3\text{ref}} = 2500$ Hz, $F_{4\text{ref}} = 3500$ Hz. ($F_{2\text{ref}} - F_{1\text{ref}}) = 6.5$ bark. (a) Solid plot: $F_1 = 725$ Hz, $F_2 = 1275$ Hz ($F_2 - F_1) = 3.6$ bark. (b) Solid plot: $F_1 = 800$ Hz, $F_2 = 1200$ Hz ($F_2 - F_1) = 2.6$ bark. (MSL: Mean spectral level).

1. Influence of formant levels

Since we are using a cascaded formant model, we can obtain different formant levels by controlling the bandwidths. The bandwidths ($B_1$ and $B_2$) of the first two formants are varied over a wide range to obtain different spectral levels in dB, denoted as $L_1$ and $L_2$, respectively. $B_3$ and $B_4$ are kept fixed at 100 Hz. The magnitude squared spectrum of the impulse response of the cascaded four-formant model is computed. Figure 4 shows RLSV, $V_{12}$ as a function of the difference in formant levels in dB. It is seen that $V_{12}$ in dB is consistently negative for case (a), for x-axis range of about ±6 dB whereas it is consistently positive for case (b), for x-axis range of about ±10 dB. Though the difference ($L_1 - L_2$) varies over a wide range of 12 to 20 dB, $V_{12}$ varies only by about 2 dB. Thus a large change in bandwidths or in the formant levels does not significantly influence $V_{12}$ and hence the OCD.
FIG. 4. Influence of formant levels on the relative level of spectral valley. $BW_2$ for each $BW_1$ is varied over a wide range. (a) $(F_1, F_2)$ separation < 3 bark and (b) $(F_1, F_2)$ separation > 3 bark.

2. Influence of $F_0$ on $\Delta Y_c$

The response of the 4-formant model is computed for the input of a periodic sequence of impulses for various choices of fundamental frequency $F_0$. Bandwidths of all the formants are kept constant at 100 Hz. Smoothed spectral envelope is obtained using linear prediction of order 8 to measure the level of the spectral valleys, $V_{12r}$. Also, the RLSV is measured for the impulse response, which serves as a reference, $V_{12r0}$. The influence of $F_0$ on the difference ($V_{12r0} - V_{12r}$) is within ±1 dB for case (a) and is consistently positive for case (b) as shown in Table I. Hence, $F_0$ does not have a significant influence on the OCD $\Delta Y_c$.

E. Objective critical distance, $\Delta Y_c$ for natural vowels

In order to study $\Delta Y_c$ for different vowels, we use the mean formant data of natural vowels of American English published by Peterson and Barney\textsuperscript{1}. This is abbreviated as P&B data in this paper. We have synthesized four-formant vowels using the mean formant data of male speakers with a
bandwidth of 100 Hz for all the formants and a sampling frequency of 8000 Hz. The fourth formant is fixed at 3500 Hz. Similarly, we have synthesized four-formant vowels using the mean formant data of female speakers with a bandwidth of 100 Hz for all the formants and a sampling frequency of 10000 Hz. The fourth formant is fixed at 4200 Hz for female speakers. We begin with the mean formant data of a vowel and then vary the formant spacing between $F_1$ and $F_2$ by increasing (decreasing) $F_1$ while simultaneously decreasing (increasing) $F_2$ to the same extent. Similarly, the spacing between $F_2$ and $F_3$ is varied. The log-magnitude spectrum is computed from the impulse response of the four-formant vowel.

The measured OCD values are listed in Table II in bark for nine vowels. We have considered $V_{23}$ for front vowels instead of $V_{12}$, since for front vowels, the formant spacing between $F_1$ and $F_2$ is very large and $V_{12}$ can be expected to be greater than 1 very often. Similarly, for back vowels $V_{23}$ can be expected to be greater than 1 very often. It is seen that the OCD for ($F_1$, $F_2$) separation for back vowels is in the range of 3.6 to 4.9 bark and for ($F_2$, $F_3$) separation for front vowels is in the range of 1 to 1.8 bark. While the values of the OCD are comparable for male and female speakers, a strong vowel dependency is seen in its behaviour.

III. COMPARISON OF THE OBJECTIVE AND SUBJECTIVE CRITICAL DISTANCES

**Influence of formant spacing:** In Sec. II.B, formant data similar to those used by Chistovich et al. have been used. In their study, two parallel bandpass filters were used, with $F_2$ kept fixed and varying $F_1$. The level of $F_2$ was lower than that of $F_1$ and hence we have used $B_2 = 200$ Hz and $B_1 = 100$ Hz. They observed that spectral integration takes place when the spacing between the formants is less than an average critical distance of about 3 bark. The measured OCD based on spectral valley criterion, $\Delta Y_c$, for similar experimental conditions is about 3.2 bark, which matches well with the reported average $\Delta Z_c$.

**Influence of formant levels:** In Sec. II.D.1, we have used formant data and levels similar to those used by Chistovich and Lublinskaya. In their study, two parallel bandpass filters were used and the
gains \((A_1, A_2)\) of the formants were altered. For a given \(A_2/A_1\), subjects varied the resonant frequency, 
\(F^*\) of a single formant stimulus so as to match vowel quality to that of a two-formant stimulus. The matched \(F^*\) lies between \(F_1\) and \(F_2\) when the spacing between the formants is less than or equal to the critical distance over a wide range of \(A_2/A_1\). Thus, spectral integration is shown to be applicable over a wide range of formant levels. When the formant spacing is greater than \(\Delta Z\), the responses of the two subjects participating in the experiments were not consistent.

In Sec. II.D.1, we have noted that the RLSV is consistently negative over a wide range of formant levels when the spacing between formants is less than or equal to 3 bark. When the spacing is greater than 3 bark, the RLSV is consistently positive. The objective experiment reported in Sec. II.D.1 gives results similar to those reported in the above subjective study\(^4\).

**Vowel dependency of \(\Delta Y\):** In Sec. II.E, we considered the formant data of natural vowels and showed that the measured OCD is strongly vowel dependent. We compare this finding with the subjective critical distance reported in the literature.

**Back-vowels, \((F_1, F_2)\) Separation:** A change of formant spacing for a uniform tube shifts its quality towards a back vowel. The measured \(\Delta Y\) between \(F_1\) and \(F_2\) for a uniform tube is about 3.6 bark, which matches well with the reported \(\Delta Z\) equal to 3.5 bark\(^4,13\). The OCD, \(\Delta Y\) for rounded back vowels lies in the range of 3.9 to 4.9 bark, which is much higher than the subjective critical distance of \(3 – 3.5\) bark. The measured high values for the OCD for rounded back vowels get support from other studies: (i) In the original seminal work of Delattre et al.\(^2\), it has been shown that spectral integration does take place for vowel ‘u’ with \(F_1 = 250\) Hz and \(F_2 = 700\) Hz, having a separation of 3.94 bark, which is greater than the reported subjective critical distance of \(3 – 3.5\) bark. (ii) Spectral integration is known to occur for back vowels. In the carefully measured formant data\(^7\), the formant spacing between \(F_1\) and \(F_2\) for back vowels, for male and female speakers, actually lies in the range of 3.8 to 5.0 bark, which exceeds the subjective critical distance of \(3 – 3.5\) bark. (iii) In a subjective experiment on a series of rounded back vowel stimuli\(^12\), \((F_1, F_2)\) separation in the range of 4.2 to 4.7 bark has been used. These evidences, along with the high value of the measured OCD, motivate one
to inquire if the subjectively derived critical distance of $3 - 3.5$ bark can be universally applied for all the experimental conditions.

**Front-vowels, ($F_2, F_3$) Separation:** To our knowledge, there is no reported study on determining the subjective critical distance for front vowels based on $(F_2, F_3)$ separation, though there have been some studies on equivalent $F_2$ determination of vowels$^{19,20}$. However, in an experiment on front vowel series$^{12}$, ‘hid’ vs ‘head’, spectral integration is shown to occur, for $(F_2, F_3)$ separation in the range of 1.2 to 1.8 bark, which compares well with the OCD derived for front vowels, shown in Table II.

**IV. PRACTICAL RELEVANCE OF SPECTRAL VALLEYS**

The RLSV indicates the relative formant separation with respect to the OCD, i.e., whether the separation is lesser or greater than $\Delta Y$; and is not intended to provide the actual value of formant separation. Our interest here is to directly make use of the information related to spectral valley as an acoustic feature for front/back distinction, motivated by the expectation that spectral valley information may be obtained from the spectral envelope without an explicit knowledge of formant data and it subsumes the influence of spectral tilt due to voice source, influence of higher formants and bandwidths.

P&B$^1$ provide us with data on the frequencies of the first three formants and only the mean formant levels. In order to derive the bandwidths, we have synthesized vowels using a minus 6 dB per octave source pulse and the mean formant data of male speakers. The bandwidths are adjusted such that the measured formant levels nearly match the mean spectral levels $L_1$, $L_2$ and $L_3$ of the three formants in the published data. Subsequently, these bandwidths have been used in synthesis. A sampling frequency of 10000 Hz has been used for male and female speakers for the experiments discussed in this section. For male speakers, $F_4 = 3500$ Hz and $F_5 = 4500$ Hz have been used. For female speakers, $F_4 = 4200$ Hz has been used. Formant data of all adult male and female speakers have been used$^{21}$. 

13
A. Front/Back Distinction based on \((F_2, F_3)\) Separation and RLSV

Syrdal and Gopal\(^7\) have shown that \((F_3 - F_2)\) in bark distinguishes front \((< 3 \text{ bark})\) from back vowels \((> 3 \text{ bark})\). Normalized histograms of \((F_3 - F_2)\) in bark for male and female speakers for these two groups of vowels (except ‘ar’) are shown in Fig. 5(a). The error in front/back classification using the 3-bark rule is close to 0 %. We want to investigate if the relative level of a spectral valley can also provide the front vs back distinction of vowels. The relative level of the second spectral valley, denoted as \(V_{II}\), is measured from the spectral envelope of both male and female speakers. For both back and front vowels, the second spectral valley happens to be between \(F_2\) and \(F_3\). But we have denoted it as \(V_{II}\) instead of \(V_{23}\) since the latter may imply that a knowledge of formant data has been used. The normalized histograms of \(V_{II}\) for the two groups of vowels of all the male and female speakers are shown in Fig. 5(b). A strong similarity is seen between the histograms shown in Figs. 5(a) and 5(b), suggesting that \(V_{II}\) serves a similar purpose as that of \((F_3 - F_2)\) in bark for front/back classification of vowels. Front/back classification error of 2.43 % is obtained using the RLSV \(V_{II}\). A similar experiment has been conducted using the relative level of the first spectral valley, \(V_1\), which lies between \(F_1\) and \(F_2\). An error of 1.6 % for front/back distinction has been obtained using \(V_1\). On the other hand, the separation between \(F_1\), \(F_2\) in bark is not effective for front/back distinction.

![Normalized histograms](image)

FIG. 5. Normalized histograms of front and back vowels obtained using (a) \((F_3 - F_2)\) in bark and (b) RLSV \((V_{II})\) in dB for adult (male and female) speakers.
B. Front/back distinction using $V_I - V_{II}$

In general, $V_I$ is expected to be below $V_{II}$ for front vowels and above, for back vowels. Hence, using the difference between $V_I$ and $V_{II}$ as an acoustic feature for front/back distinction, an accuracy of 98.6% is obtained for P&B data. A small scale pilot study using 400 instances of some selected back and front vowels from sal sentences spoken by both genders of the TIMIT database\textsuperscript{22} has been done. Using $V_I$ or $V_{II}$ or the difference ($V_I - V_{II}$) as an acoustic feature, an average accuracy of 97.3% is achieved for front/back distinction.

V. CONCLUSION

Based on the fact that the level of spectral valley is determined by the formant spacing, a term called objective critical distance has been defined as that spacing when the level of the valley is equal to the mean spectral level. This concept subsumes the formant separation criterion\textsuperscript{2,3,7,12,13} and spectral template criterion\textsuperscript{9–11}. We have shown that the behaviour of the OCD is similar to the subjectively derived critical distance for similar experimental conditions such as different formant spacing, formant levels and presence of higher formants. However, the measured OCD is strongly dependent on the vowel. It is shown that the level of spectral valleys, which can be measured from the spectral envelope of a vowel without explicitly estimating the formant values, can be used as an acoustic feature for front/back distinction with an accuracy of about 98%. Future research involves looking more closely into the role played by the location as well as the level of spectral valleys for deducing other phonetic features such as high-low, tense-lax, rounded-unrounded and for normalization of intra and inter-speaker differences hopefully to arrive at an invariant vowel space.

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TABLE I. Insignificant influence of fundamental frequency $F_0$ on RLSV. Difference $(V_{12_{ref}} - V_{12_{se}})$ is tabulated for different choices of fundamental frequency.

| $F_0$ (Hz) | 100  | 125  | 150  | 175  | 200  | 225  | 250  |
|------------|------|------|------|------|------|------|------|
| $F_2-F_1 < 3$ bark | -0.30 | -0.49 | 0.09 | -0.48 | -0.78 | 0.99 | -0.51 |
| $F_2-F_1 > 3$ bark | 2.23  | 2.44  | 2.29  | 2.79  | 2.60  | 2.45  | 2.32  |
TABLE II. The measured OCD values (in bark) for different vowels of adult (male and female) speakers using formant data given by Peterson and Barney\textsuperscript{1}.

| Vowel | iy | ih | eh | ae | Ɛ | aa | ao | uh | uw | ah |
|-------|----|----|----|----|---|----|----|----|----|----|
| ΔY_c (male) | 1.05 | 1.50 | 1.66 | 1.79 | 1.82 | 3.59 | 3.95 | 4.57 | 4.58 | 4.56 | 4.01 |
| ΔY_c (female) | 1.08 | 1.32 | 1.46 | 1.67 | 1.82 | 3.59 | 4.33 | 4.89 | 4.86 | 4.93 | 4.26 |
List of Figures

FIG. 1 Log-magnitude spectra of synthetic two-formant vowels illustrating the influence of formant spacing on the relative level of spectral valley. Dashed plots: $F_{1\text{ref}} = 750 \text{ Hz}$, $F_{2\text{ref}} = 1400 \text{ Hz}$, ($F_{2\text{ref}} - F_{1\text{ref}}$) = 3.9 bark, $V_{12} > 1$. (a) Solid plot: $F_1 = 850 \text{ Hz}$, ($F_2 - F_1$) = 3.2 bark, $V_{12} = 1$ and hence, this $F_1, F_2$ separation corresponds to the OCD. (b) Solid plot: $F_1 = 950 \text{ Hz}$, ($F_2 - F_1$) = 2.5 bark. For these values, $V_{12} < 1$ or its dB value is -ve. (MSL: Mean spectral level) ........................................ 7

FIG. 2 Influence of formant spacing on the relative level of spectral valley. ................. 8

FIG. 3 Log-magnitude spectra of synthetic four-formant vowels illustrating the influence of formant spacing on the relative level of spectral valley. Dashed plots: $F_{1\text{ref}} = 500 \text{ Hz}$, $F_{2\text{ref}} = 1500 \text{ Hz}$, $F_{3\text{ref}} = 2500 \text{ Hz}$, $F_{4\text{ref}} = 3500 \text{ Hz}$. ($F_{2\text{ref}} - F_{1\text{ref}}$) = 6.5 bark. (a) Solid plot: $F_1 = 725 \text{ Hz}$, $F_2 = 1275 \text{ Hz}$ ($F_2 - F_1$) = 3.6 bark. (b) Solid plot: $F_1 = 800 \text{ Hz}$, $F_2 = 1200 \text{ Hz}$ ($F_2 - F_1$) = 2.6 bark. (MSL: Mean spectral level) ................................................................. 9

FIG. 4 Influence of formant levels on the relative level of spectral valley. $BW_2$ for each $BW_1$ is varied over a wide range. (a) ($F_1, F_2$) separation < 3 bark and (b) ($F_1, F_2$) separation > 3 bark. ............. 10

FIG. 5 Normalized histograms of front and back vowels obtained using (a) ($F_3 - F_2$) in bark and (b) RLSV ($V_{12}$) in dB for adult (male and female) speakers. ................. 14