RESONANCE AND FREQUENCY CHARACTERISTICS OF VOWELS: A COMPARATIVE ACOUSTIC STUDY OF SUNDANESE AND NON-SUNDANESE SPEAKERS

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ABSTRACT

This study investigates vowel production from the perspective of acoustic resonance in the human vocal tract. Fundamental frequency (F_0) and formant frequencies (F1–F4) were measured for selected vowels (/u/, /eu/, and /e/) produced by Sundanese and non-Sundanese speakers and analyzed as resonant modes of a variable-length air column. Speech recordings were obtained under controlled conditions and processed using Praat software, while statistical analysis was employed to evaluate inter-speaker variability. The results show that the measured formant frequencies fall within comparable ranges for both speaker groups. For the vowel /u/, F1 values were found in the range of approximately 420–440 Hz, while F2 values ranged from about 900–1230 Hz. For the vowel /e/, F1 values were observed at 550–580 Hz, and F2 values at 1880–1900 Hz. Statistical testing indicated no significant differences in formant frequencies between the two groups ($p > 0.05$ for all vowels). From a physical standpoint, these results indicate that vowel-specific resonance characteristics are governed primarily by shared biomechanical and acoustic constraints of the vocal tract. Lower formant frequencies correspond to longer effective cavity lengths and more constricted configurations, whereas higher formants reflect shorter-wavelength resonances that are less sensitive to global tract geometry. Overall, the findings support the universality of acoustic wave principles underlying human sound production and demonstrate the relevance of vowel analysis as an applied problem in acoustic physics.

Keyword**:** *Acoustic resonance; Formant frequencies; Vocal tract acoustics; Source-filter model; Speech acoustics*

INTRODUCTION

Human voices serve as a primary medium of communication, carrying not only linguistic but also emotional and cultural information. From a linguistic perspective, the acoustic features of speech, such as fundamental frequency and formant values, are crucial for distinguishing languages and dialects. Formants, the resonance frequencies shaped by the vocal tract, play a vital role in the production of vowel sounds (Algaraady et al., 2025). Consequently, analyzing formants provides deeper insights into the acoustic structure and linguistic characteristics of a particular language or dialect (Chakraborty et al., 2024).

A critical approach to understanding language and cultural identity is through bioacoustics analysis. By measuring features such as formant frequencies, researchers can uncover phonetic distinctions characteristic of specific language groups (Calvacanti et al., 2021). This method enables precise mapping of vowel sound patterns, which is essential for identifying differences between languages or dialects (Tomaschek and Ramscar, 2022). For instance, previous research analyzing the Nias and Batak languages using Praat revealed variations in vowel formant values (F1, F2, and F3), highlighting distinct acoustic features between the two languages (Harahap and Lubis, 2022).

Sundanese is one of the many regional languages in Indonesia, known for its relatively stable corpus and widespread usage among native speakers. However, the decline in the number of Sundanese speakers in recent years underscores the urgency of documenting and preserving the language (Alhammad, 2023). Scientific studies, particularly those involving bioacoustics analysis, can contribute significantly to this effort by deepening our understanding of its phonetic system. Such research not only adds academic value but also supports broader efforts to preserve and revitalize regional languages at risk of extinction (Fadhli & Yusanto, 2019).

Although numerous studies have examined vowel characteristics across languages, there remains a lack of detailed acoustic comparisons between Sundanese and non-Sundanese speakers. Much of the existing literature has focused on phonemic descriptions without examining formant-based acoustic differences arising from diverse linguistic and cultural backgrounds (Lestari et al., 2023). This study seeks to address that gap by examining whether there are significant differences in the fundamental frequency and formant values of vowels produced by Sundanese versus non-Sundanese speakers.

By conducting a comparative analysis of vowel acoustics, this study aims to identify acoustic patterns that may be influenced by speakers' native language. Specifically, it investigates the fundamental frequency of speech and measures formant values to determine whether these acoustic features vary significantly between the two groups. Previous studies have noted that Sundanese has seven vowel phonemes, compared with the five found in standard Indonesian (Faznur & Nurhamidah, 2020), suggesting a potential source of variation in vocal resonance. The outcomes of this research are expected to contribute not only to the fields of phonetics and regional linguistics but also to ongoing efforts to preserve Indonesia's linguistic diversity.

METHODS

The study involved 40 participants, comprising 20 native Sundanese speakers and 20 non-Sundanese Indonesian speakers, aged 15–30 years. Speech data were elicited by instructing each participant to produce two standard vowels (/u/ and /e/) together with one vowel specific to Sundanese (/eu/).

The research was conducted at four educational institutions in Cirebon, Indramayu, Serang, and Banten, chosen to capture variation across different educational environments and speaker backgrounds. All procedures were carried out by trained personnel, and informed consent was obtained from each participant. Ethical clearance was granted by the Research Ethics Committee of Bandung Institute of Technology (Approval No. KEP/II/2025/X/M050625GRF-SSDF, dated August 11, 2025).

A quantitative approach using the experimental method was adopted, as it enables controlled investigation of the cause-and-effect relationships between ethnicity and acoustic parameters (Fletcher, 2025). The purpose of this experimental design was to analyze the fundamental frequency (F0) and formant structures (F1, F2, F3) of vowel sounds produced by Sundanese and non-Sundanese speakers. Voice recordings were processed and analyzed using Praat software version 6.4.25, a widely recognized tool for phonetic and acoustic analysis (Boersma & Weenink, 2023).

The samples were selected randomly from the population of female speakers aged 15 to 30 years. The inclusion criteria were being a native speaker of Sundanese or a non-Sundanese ethnic group, having no speech disorders, and regularly using Indonesian in daily communication. Random sampling was employed to ensure that each member of the population had an equal probability of selection, thereby enhancing the representativeness of the sample (Ahmed, 2024).

Data collection was carried out in a controlled environment to minimize external noise interference. Participants were instructed to pronounce the vowels a, i, u, e, o, and eu on the fundamental tone "do," each sustained for approximately 3 seconds. Recordings were made using an external microphone placed 15 cm from the participant's mouth, with the participant seated to minimize body movement and ensure consistent vocal tract positioning (Lim & Choi, 2009).

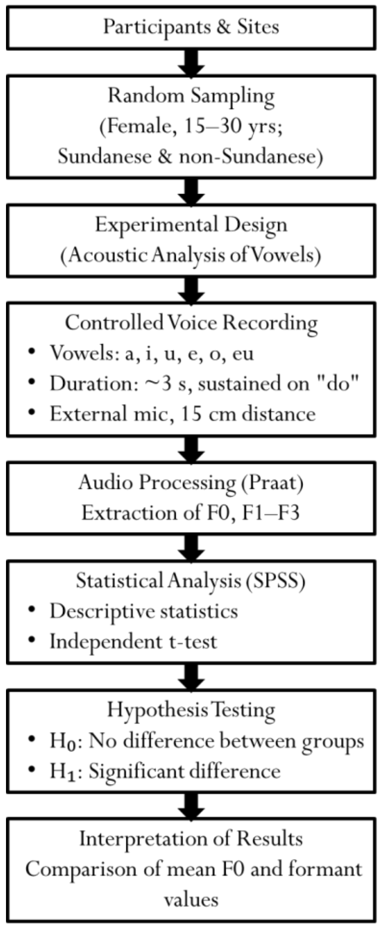

Figure 1. Research Workflow: Sampling, Recording, Processing, and Analysis.

Table 1. Formant frequency of Sundanese dan non-Sundanese Speakers

Vowel	Formant	Frequency (Hz)				t-test error margin
		Sundanese Speakers		Non-Sundanese Speakers		
		Mean	SD	Mean	SD	
/u/	F1	434.38	52.45	423.55	59.15	0.41
	F2	1229.11	245.75	926.90	202.15	0.32
	F3	2704.93	361.32	2771.24	410.29	0.65
	F4	4001.86	464.41	4028.14	411.00	0.84
/eu/	F1	528.65	67.33	547.63	77.23	0.41
	F2	1457.69	191.16	1443.21	223.43	0.75
	F3	2835.17	321.58	2824.55	450.63	0.92
	F4	4114.83	531.64	4065.38	502.74	0.73
/e/	F1	579.97	72.62	550.40	78.11	0.19
	F2	1887.78	556.15	1896.91	601.37	0.96
	F3	2788.92	307.29	2806.61	308.62	0.87
	F4	3847.28	455.13	3848.26	517.19	0.88

The data analysis was conducted in two stages: descriptive and inferential analysis. Descriptive statistics were used to provide an overview of the collected data. At the same time, inferential analysis applied an independent t-test to determine whether there were significant differences in vowel formants between Sundanese and non-Sundanese speakers. All statistical analyses were conducted using SPSS version 22, a standard statistical software in social and linguistic sciences (Yang, 2022).

The hypotheses tested in this study were as follows. The null hypothesis (H_0) stated that there were no significant differences in vowel formants between Sundanese and non-Sundanese speakers. The alternative hypothesis (H_1) proposed that significant differences did exist between the two groups. This hypothesis testing served as the basis for determining whether the acoustic characteristics of vowels differed statistically between the two ethnic groups (Ranganathan & Pramesh, 2019).

The results of the analysis were evaluated by comparing the mean fundamental frequency and formant values between the two groups. Any significant differences found served as the basis for concluding about the acoustic characteristics of Sundanese and non-Sundanese speakers.

To provide a more straightforward overview of the research stages, a flow chart is presented in Figure 1. This diagram illustrates the study's sequential procedures, beginning with participant recruitment, data collection, data processing using Praat, statistical analysis in SPSS, and, finally, interpretation of results.

RESULTS AND DISCUSSION

The measured formant frequencies (F1–F4) of the vowels /u/, /eu/, and /e/ are interpreted here within the framework of acoustic resonance in a variable-length air column. The human vocal tract functions as a dynamic resonator analogous to a closed–open organ pipe, with the vocal folds forming the closed boundary and the lips approximating an open boundary. Standing acoustic waves are established in this system, and their resonance frequencies are determined by the effective cavity length, the distribution of cross-sectional areas, and the acoustic boundary conditions.

Table 1 summarizes the mean and standard deviation of the formant frequencies for Sundanese and non-Sundanese speakers. Overall, the independent t-test results indicate that no statistically significant differences were observed for any of the measured formants across all vowels ($p > 0.05$). The margin-of-error values approaching unity suggest that the differences in mean frequencies between the two groups are relatively small. For instance, for the vowel /u/, the mean F1–F4 values are comparable between groups, with the largest t-test statistic still below the critical threshold. Similar trends are observed for the vowels /eu/ and /e/.

Figure 2 further illustrates these results by presenting the mean formant frequencies with corresponding standard deviations. The distributions show a high degree of overlap between Sundanese and non-Sundanese speakers, particularly for the higher formants (F3 and F4). Slightly larger variability is observed for F2 in the vowel /u/ among Sundanese speakers, as reflected by a larger standard deviation. This variability suggests inter-speaker differences in articulation rather than systematic group-level divergence (Suwandi et al, 2025).

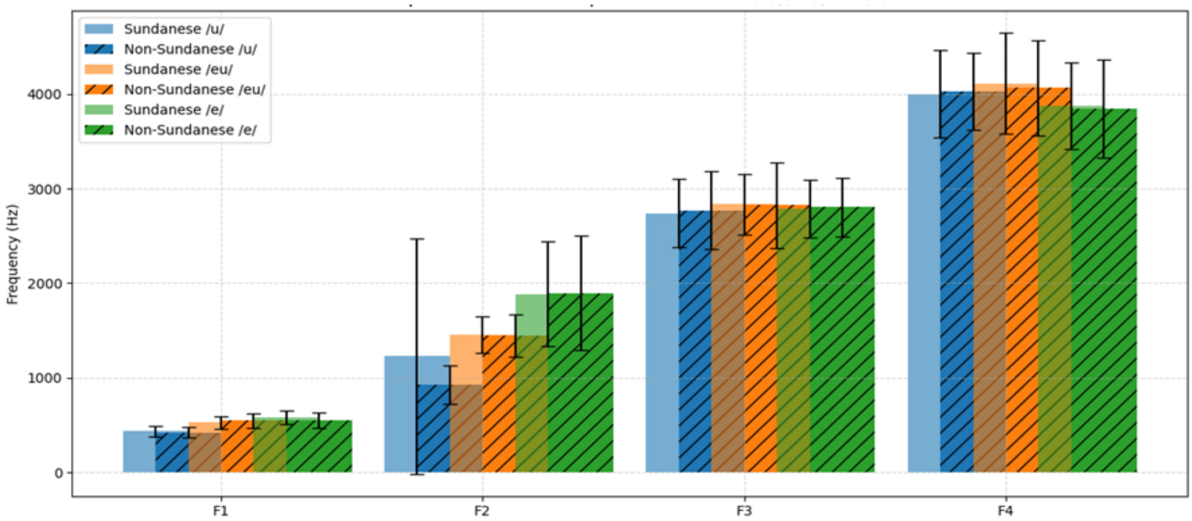

Figure 2. Comparative formant frequencies (F1–F4) for vowels /u/, /eu/, and /e/ between Sundanese and non-Sundanese speakers. Colors represent different vowels, and error bars indicate standard deviation

The acoustic patterns observed in the formant data can be interpreted within the framework of acoustic resonance in a variable-length air column, where the human vocal tract acts as a dynamic resonator analogous to a closed–open organ pipe. In this physical model, the vocal folds constitute the closed boundary, while the lips represent the open boundary. Standing acoustic waves are generated in this system, and their resonance frequencies depend on the effective cavity length, the distribution of cross-sectional areas, and the vocal tract boundary conditions.

From classical acoustic wave theory, the resonance frequencies of a closed–open tube are approximately given by:

$$f_n = \frac{(2n-1)c}{4L_{eff}} \quad (1)$$

where c is the speed of sound in air and L_{eff} denotes the effective length of the resonating air column. Variations in vowel articulation modify L_{eff} as well as the tract's spatial impedance profile, thereby shifting the observed formant frequencies (Zhang, 2016).

Physical Interpretation of F1 and F2

The first formant (F1) is primarily associated with vowel height and, from a physical perspective, reflects the degree of mouth opening and vertical tongue displacement. A more open articulation increases the effective cross-sectional area of the oral cavity, reducing acoustic stiffness and leading to higher F1 values. Conversely, more constricted articulations lengthen the effective resonator and lower F1.

This relationship is clearly evident in the present data. The vowel /u/ consistently exhibits lower F1 values compared to /e/ and /eu/ in both speaker groups, as shown in Table 1 and Figure 2. This pattern reflects the longer effective cavity length and narrower constriction characteristic of /u/, in agreement with predictions from the organ-pipe resonance model.

The second formant (F2) is governed by the front–back positioning of the tongue, which redistributes the vocal tract into coupled front and back cavities. Advancing the tongue shortens the front cavity while lengthening the back cavity, thereby increasing F2. In contrast, tongue retraction lengthens the front cavity and lowers F2. Accordingly, the relatively low F2 values observed for /u/ arise from its retracted tongue position and elongated front cavity, whereas the higher F2 values for /e/ correspond to a shortened front cavity and stronger high-frequency resonance.

Although the mean F2 value of /u/ appears higher for Sundanese speakers than for non-Sundanese speakers, this difference should be interpreted cautiously from a physical standpoint. The second formant is highly sensitive to local variations in vocal-tract shaping, such as tongue advancement and lip rounding. The relatively large standard deviation of F2 indicates that inter-speaker variability dominates group-level effects, suggesting that local cavity fluctuations do not translate into systematic differences in global resonance behavior.

In both organ pipes and the vocal tract, resonance occurs when the length of the air column matches specific wavelengths, resulting in the formation of standing waves. The configuration of the tongue, lips, and jaw continuously alters the shape

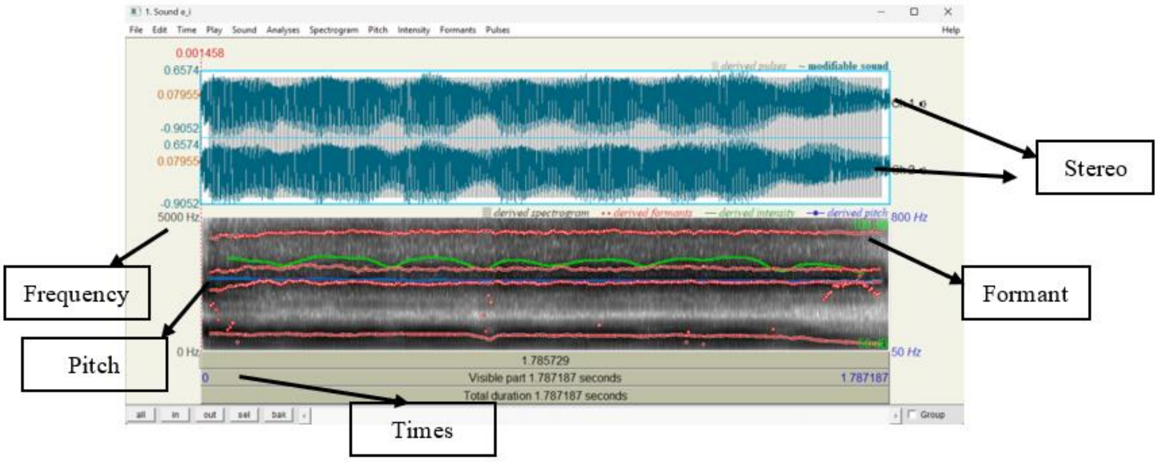

Figure 3. Spectrogram Analysis to Determine the Formant Frequencies.

and effective length of this resonating column, thereby determining the formant frequencies and the resonant frequencies that define vowel quality. Each vowel corresponds to a unique spatial configuration of the vocal tract, which modifies the first formant (F1) and second formant (F2). For instance, the vowel /i/ exhibits a narrow front cavity and an elongated back cavity, yielding a low F1 and a high F2 (Lammert & Narayanan, 2015; Patil & Shah, 2015).

In the case of the vowel /e/, which belongs to the category of front vowels, the tongue is positioned forward in the oral cavity with a mid-level height. This articulatory posture can be interpreted using the organ-pipe resonance model, in which variations in cavity length produce different resonant frequencies. During the articulation of /e/, the tongue advances and slightly elevates, creating a shorter front cavity (between the tongue and lips) and a longer back cavity (between the tongue and pharyngeal wall). According to the resonance principles of organ pipes, the shorter the resonating air column, the higher the resulting frequency, while a longer air column yields lower frequencies. Thus, for /e/, the short front cavity elevates F2, whereas the extended back cavity lowers F1 (Oganian et al., 2023; Auracher et al., 2020).

Higher Formants (F3 and F4): Resonance Stability and Energy Distribution

Higher formants (F3 and F4) correspond to shorter-wavelength resonances and are less sensitive to gross articulatory changes. Instead, they are influenced by finer geometric details, including side cavities, lip rounding, and pharyngeal wall configuration. The near-uniformity of F3 and F4 across Sundanese and non-Sundanese speakers indicates that mid- to high-frequency resonances are acoustically robust and dominated by shared physical constraints of the human vocal tract.

The near-uniformity in F3 and F4 across groups underscores the robustness of acoustic convergence in mid- to high-frequency components of vowel production, which are often less susceptible to regional and linguistic variation than the lower formants that encode vowel height (F1) and backness (F2). These findings reinforce the hypothesis that long-term contact and phonetic accommodation between Sundanese and Indonesian speakers have yielded homogenized vowel realizations, even though Sundanese phonology formally posits a larger vowel inventory than standard Indonesian (Faznur & Nurhamidah, 2019).

Figure 3 illustrates this behavior through spectrographic analysis, where acoustic energy is concentrated around the lower formants, with diminishing intensity at higher frequencies. This distribution is consistent with the source–filter theory of speech production, in which the glottal source provides broadband excitation and the vocal tract selectively amplifies specific resonant modes.

Empirical acoustic analyses using Praat support this pattern: the vowel /e/ typically exhibits F1 values around 400 - 500 Hz and F2 values between 1900 - 2300 Hz, consistent with its classification as a mid-front vowel. This demonstrates how vowel quality emerges from the interaction between the source (vocal fold vibration) and the filter (vocal tract resonance), analogous to the behavior of air columns in organ pipes, which produce harmonic overtones based on their length and boundary conditions.

When comparing Sundanese and non-Sundanese speakers, the acoustic measurements of /e/ reveal subtle yet meaningful differences. The average F1 for Sundanese speakers is slightly higher (579.97 Hz) than that of non-Sundanese speakers

(550.40 Hz), indicating a somewhat lower tongue position and a more open vowel among Sundanese speakers. Meanwhile, the F2 values - reflecting the degree of frontness are slightly lower for Sundanese speakers (1887.78 Hz) compared to non-Sundanese speakers (1896.91 Hz), suggesting a marginally less fronted articulation in Sundanese pronunciation.

These variations align with phonological tendencies in Sundanese, which feature a relatively symmetrical vowel system with mild centralization in certain mid vowels, including /e/. By contrast, non-Sundanese speakers, such as native speakers of Standard Indonesian or Javanese, tend to produce /e/ with a slightly more fronted or centralized articulation, reflecting their respective L1 phonetic norms. Cross-linguistic studies (e.g., Ladefoged & Johnson, 2015; Van Zanten & van der Molen, 2005) have documented such dialectal and L1-influenced variation, confirming that formant frequencies, particularly F2, are highly sensitive to regional phonetic patterns.

The vowel sound /u/ is categorized as a back vowel, produced with the tongue retracted toward the posterior part of the oral cavity and raised near the soft palate (velum), accompanied by rounded lips. From an acoustic perspective, this vowel's production aligns with the closed-open organ pipe resonance model, where the vocal folds function as the closed end and the mouth as the open end of the pipe. As air flows upward from the lungs through the vibrating vocal folds, it generates a fundamental sound wave that resonates within the vocal tract, forming the basis of the vowel's distinctive acoustic quality.

This resonance process becomes more apparent during the articulation of /u/, where the tongue's backward and elevated position shapes the vocal tract into a configuration with a long and narrow front cavity and a shorter back cavity. According to the principles of organ pipe resonance, a longer resonating air column results in lower resonant frequencies. Consequently, the first (F1) and second formant (F2) values of/u/ are typically low. Acoustic measurements using Praat typically indicate F1 around 300–350 Hz and F2 around 800–900 Hz, confirming that the dominant resonances correspond to longer wavelengths than those of front vowels such as /e/. These findings illustrate how subtle articulatory adjustments, such as tongue retraction and lip rounding, directly modify the effective length of the resonating air column, yielding the characteristic "dark" or low auditory quality of /u/ (Suwandi et al., 2020).

Although the statistical analysis indicates no significant differences in formant frequencies between Sundanese and non-Sundanese speakers, this outcome carries important physical implications. The similarity of formant patterns suggests that, under controlled phonation conditions, the physical configuration of the vocal tract converges across speaker groups despite differences in phonological systems. This convergence reflects shared biomechanical constraints and acoustic optimization of vowel production.

Thus, the absence of statistical significance should not be interpreted as a lack of physical relevance. Instead, it demonstrates that acoustic resonance mechanisms dominate vowel realization, reinforcing the universality of physical principles governing human sound production.

Overall, the results suggest that vowel production in both speaker groups is primarily governed by shared biomechanical and acoustic constraints, with resonance frequencies arising from the same underlying physical principles despite differences in linguistic background.

CONCLUSION AND RECOMMENDATION

The results for F1 show that the vowel /u/, in both Sundanese and non-Sundanese speakers, has lower frequency values compared to the vowels /e/ and /əu/. This may be attributed to the relatively more closed articulation of /u/ compared to the more open vowel articulation of /e/ and /əu/. For F2, the vowel /u/ also displays lower values than /e/ and /əu/, which can be explained by the deeper tongue position during the articulation of /u/. Additionally, a more constricted mouth posture during /u/ production likely contributes to the lower F2 frequency.

Based on the analysis, the t-test results indicate that there were no statistically significant differences in the formant frequencies between Sundanese and non-Sundanese speakers for all vowels analyzed (/u/, /eu/, and /e/), with t-values ranging from 0.32 to 0.96, all below the critical threshold ($p > 0.05$). Mean F1 values for both groups were closely aligned, with Sundanese speakers showing 434.38 Hz and non-Sundanese speakers showing 423.55 Hz for the vowel /u/, as were higher formants such as F4 (/u/), which showed 4001.86 Hz and 4028.14 Hz, respectively. The average standard deviations across formants were also comparable, indicating similar acoustic variability within each group. These quantitative findings confirm that native language background (Sundanese versus non-Sundanese) exerts no significant acoustic influence on vowel formant production under the tested conditions.

Future research should use samples from speakers with homogeneous regional backgrounds to minimize data variation. When conducting a comparative analysis, it is advisable to select samples from similar linguistic or regional backgrounds. Moreover, future studies should also consider age homogeneity, as age-related variability may influence the frequency characteristics of vowel production.

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