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Tambura Drone Effects on Carnatic Music Vocal Resonance and Pitch Stability

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ABSTRACT

Carnatic music, one of the most ancient and sophisticated classical traditions, is distinguished by its intricate melodic frameworks and uncompromising emphasis on tonal precision. At the heart of this system lies *shruthi shudda*m and the cultivation of a resonant vocal timbre capable of sustaining ornamentations (*gamakas*) and executing subtle microtonal variations. For a Carnatic vocalist, the ability to maintain pitch stability while producing a rich and expressive tone is considered fundamental, demanding continuous auditory feedback and vocal control.

A distinctive feature of Carnatic performance is the use of the tambura, a long-necked lute that provides continuous harmonic drone. This drone, typically tuned to the tonic (*sa*) and the fifth (*pa*), provides both a tonal anchor and a resonant sonic background. Rather than functioning as a passive reference point, the tambura creates a dynamic acoustic environment that may influence how singers perceive pitch and produce resonance.

This study aims to investigate the effect of the tambura drone on vocal resonance and pitch stability in Carnatic music singers. Through a combination of objective acoustic analysis and subjective evaluations, the research seeks to illuminate the tambura's role in supporting tonal accuracy and enhancing the overall quality of vocal performance.

Keywords*: Carnatic music, Tambura drone, Shruthi shuddham, Vocal resonance, Pitch stability, Acoustic analysis, Formant analysis, Fundamental frequency (F0), Psychoacoustics, Voice acoustics, Music acoustics, Raga performance, Singer's format, Indian classical music*

GLOSSARY OF TERMS

Adi Talam: A rhythmic cycle of eight beats, structured as 4 + 2 + 2. It is one of the most common *talas* (rhythmic frameworks) in Carnatic music and provides a stable, repeating structure for compositions and improvisations. Its simplicity and versatility make it a foundational *tala* in pedagogy and performance.

Alapana: A free-flowing, rhythm-free improvisation performed at the beginning of a piece or before a major composition. In *alapana*, the artist explores the chosen *raga* systematically, starting with slow phrases and gradually moving to complex, rapid ones. Its purpose is to set the emotional tone of the *raga* and demonstrate its scope without the constraints of *tala*.

Formant: Resonant frequencies of the vocal tract that amplify certain harmonics of the voice. Formants determine the characteristic sound of vowels and strongly influence vocal timbre.

Fundamental Frequency (F0): The lowest frequency in a sound wave, corresponding to the perceived pitch. In voice science, F0 is measured to analyse pitch stability. For Carnatic singers, maintaining F0 close to the tonic (*sa*) is critical for *shruthi shuddham* (pitch purity).

Gamakas: Ornamentations and pitch inflections that are central to Carnatic music. Gamakas include slides, oscillations, and microtonal shifts that give life and individuality to a *raga*.

Harmonic Spectrum: The set of frequencies produced when a note is sung or played, consisting of the fundamental frequency and its integer multiples (harmonics). A rich harmonic spectrum makes the sound fuller and is critical for blending with the overtone-rich *tambura* drone.

Jawari: The fine adjustment of the bridge of a string instrument like the *tambura* or veena. A properly set *jawari* produces a sustained, buzzing tone that enhances resonance and overtone richness. In the tambura, *jawari* helps create the meditative, continuous drone that forms the foundation of Carnatic performance.

Kalpanaswaram: Improvisation using *swaras* (notes) of a raga within a rhythmic cycle (*tala*). Typically performed at the end of a composition, kalpanaswaram involves creating new melodic patterns while adhering to the grammar of the *raga* and maintaining strict alignment with the *tala*.

Manodharma Sangeetam: The improvisational dimension of Carnatic music, encompassing *alapana, niraval, kalpanaswaram,* and *tani avartanam*. Manodharma reflects the performer's creativity, technical skill, and emotional depth while staying true to the rules of *raga* and *tala*. It is considered the highest form of musical expression in Carnatic tradition.

Nada Brahman: A philosophical concept in Indian thought meaning "Sound is the ultimate reality." It signifies the belief that the universe itself originates from sound vibrations (*nada*), and music is seen as a pathway to experience the divine. In Carnatic music, singing in perfect alignment with *shruthi* is regarded as a form of spiritual practice.

Niraval: An improvisational technique where a single line of text from a composition is elaborated melodically and rhythmically while keeping the *tala* cycle intact. The artist experiments with melodic variations but ensures that the original lyrics and emotional essence remain central.

Pitch Deviation: A measurable departure of a singer's produced pitch from the intended reference frequency, usually the tonic (*sa*). In acoustical analysis, pitch deviation is expressed in cents or as the standard deviation of F0. Reduced deviation indicates higher pitch stability.

Raga: A melodic framework defined by a specific set of notes, characteristic ascending (*arohana*) and descending (*avarohana*) patterns, and ornamentations (*gamakas*). Each raga conveys a particular mood or emotion (*rasa*), and mastery of ragas is central to Carnatic performance.

Resonance: The amplification of sound when vocal or instrumental vibrations align with the natural frequencies of a resonating body (such as the vocal tract or an instrument's chamber). In singing, resonance adds tonal richness and projection. In Carnatic music, resonance is vital to blending the voice with the tambura drone.

Rigveda: One of the four Vedas, composed of hymns in Sanskrit. Although primarily literary, its chanting traditions, with precise intonation and rhythm, laid the foundation for early pitch systems that later evolved into Indian classical music.

Sabhas: Cultural organizations in South India that organize Carnatic concerts, especially during the December Music Season in Chennai. Sabhas play a central role in sustaining and promoting the Carnatic concert tradition.

Samaveda: One of the four Vedas, consisting primarily of hymns set to musical chant. The *Samaveda* is regarded as the earliest textual source for Indian classical music, linking Vedic ritual to structured melodic expression.

Shruthi Shuddham: The principle of maintaining perfect pitch alignment in performance. It requires singers to align precisely with the tonic (*sa*) and sustain microtonal accuracy throughout the raga. Shruthi shuddham is considered both a technical skill and a form of discipline.

Spectral Analysis: The process of analysing a sound signal by decomposing it into its frequency components. In this research, spectral analysis is used to measure harmonic stability, resonance, and how closely the singer's voice aligns with the tambura's spectrum.

Spectrogram: A visual representation of sound where the vertical axis shows frequency, the horizontal axis shows time, and colour or shading shows intensity. It is used in voice research to study pitch stability, formants, and harmonic energy distribution.

Swara: The basic note in Carnatic music. There are seven primary swaras: *Sa, Ri, Ga, Ma, Pa, Da, Ni*. Swaras are the building blocks of ragas, and their precise intonation is fundamental to shruthi shuddham.

Tala: The rhythmic framework of Carnatic music, consisting of cycles of beats with prescribed divisions and gestures. Talas structure compositions and improvisations and range from simple (Adi Talam) to highly complex cycles.

Tambura: A four- or five-stringed drone instrument that produces a continuous harmonic reference. Its sound is created by plucking open strings tuned to the tonic (*sa*) and dominant (*pa* or *ma*). The tambura's overtone-rich drone anchors shruthi shuddham and enriches vocal resonance.

Tani Avartanam: A percussion solo performed within a concert, usually towards the end of a major composition. It also involves rhythmic improvisation by mridangam and other percussionists within the *tala* framework.

Vocal Resonance: The quality of the voice produced when certain frequencies are amplified by the resonant spaces of the vocal tract. It contributes to tonal richness, clarity, and projection, and is a measurable factor in assessing vocal quality.

BACKGROUND OF CARNATIC MUSIC

Carnatic music, also known as *Karnāṭaka Saṅgītam* in Dravidian languages is the classical music tradition of South India, predominantly associated with the states of Tamil Nadu, Karnataka, Andhra Pradesh, Telangana and Kerala. It is one of the three principal streams of Indian classical music, the other two being Hindustani and Odissa music (Vidwans et al., 2012). While both traditions share ancient Vedic roots, Carnatic music has evolved as entertainment and has been historically regarded as a sacred art form (*nāda brāhman*) and connects the human spirit to the divine. Its origins trace back to the *Samaveda*, where hymns of the *Rigveda* were set to melody, with significant codification during the medieval and early modern periods, laying the foundation for Indian classical music traditions (Beck, 2019). Both Hindustani and Carnatic music fundamentally operate on a monophonic principle, wherein a single melodic line is interwoven with a fixed drone, establishing a dialectical difference within a shared musical heritage (Singh & Devi, 2023).

The foundation of Carnatic music is attributed to Purandara Dasa (1484-1564), who is often celebrated as the **Pitamaha** (grandfather) of Carnatic music (Radhakrishnan, 2016). He created a structured pedagogy; beginning with *sarali varisai* and progressing through *alankaras, geethams*, and *varnams* which remain to be the foundational training sequence even today (Krishna & Ishwar, 2012). By the 16th century, due to the introduction of the *melakarta system* by Venkatamakhin's *Chaturdandi Prakasika* (1660 CE) which classified the ragas into 72 parent scales, Carnatic music had established a clear identity (Krishnan, n.d.).

The 18th century marked the golden age of Carnatic music, with the rise of the **Trinity of Carnatic Music** – Tyagaraja, Muthuswami Dikshitar, and Syama Sastri whose compositions remain the bedrock of the concert repertoire (Vidwans et al., 2012). Their works combined musical sophistication with deep devotion, setting standards for melodic creativity (*ragas*), rhythmic ingenuity (*talas*), and lyrical expression. Royal patronage in courts such as Mysore and Travancore, followed by the institutionalisation of music through *sabhās* in colonial Madras (modern day Chennai), ensured Carnatic music's transition from temples and courts to public concert halls (Subramanian, 1999).

STRUCTURE AND MUSICAL PRINCIPLES

Carnatic music is defined by four primary elements: *Śruti*, also known as Shruthi (pitch reference), *Svaras* (musical notes), *Rāga* (melodic framework), and *Tāla* (rhythmic cycle) (Priya & Rajini, 2021). *Śruti* or Shruthi is the tonal foundation, primarily maintained by instruments like the tambura. *Svaras* or Swaras are the solfege system (*sa-ri-ga-ma-pa-da-ni*), with microtonal variations. *Rāgas* contains the governing rules for scale, ornamentation (*gamakas*), and emotional expression. *Tālas* are the time cycles with permutations, ranging from the simple *Adi tala* (8 beats) to rare, complex patterns. Together, ragas and talas form the skeleton of a Carnatic performance, within which improvisation and composition coexist.

Improvisation (*manodharma sangeetam*) also plays a crucial role, with forms such as *alapana* (free raga elaboration), *niraval* (melodic improvisation of lyrics), *kalpanaswaram* (swaric improvisation), and *tani avartanam* (percussion solo) (Alekh, 2017). Despite improvisatory freedom, *shruthi shuddam* (pitch purity) remains the non-negotiable aesthetic principle.

An important principle underpinning Carnatic aesthetics is *shruthi shuddham* or purity of pitch. Even minor deviations from shruthi can distort the character of a raga, making pitch stability central to both training and performance. To achieve this, Carnatic vocalists undergo rigorous ear training, usually beginning at a young age, with emphasis on synchronizing the voice with the tambura drone.

CULTURAL AND DEVOTIONAL SIGNIFICANCE

Carnatic music also plays a vital role in shaping South Indian cultural identity. Even today, while Carnatic concerts are presented in secular settings such as *sabhās* (concert halls), the devotional core of the music continues to shape its ethos. The Chennai Music Season, often called the world's largest cultural festival, draws thousands of musicians and listeners annually (Narayanan & Periyasamy, 2020). Moreover, the transmission of Carnatic music through the *guru-shishya parampara* (teacher-disciple lineage) ensures continuity while fostering innovation across generations.

Unlike Hindustani music, which absorbed Persian influences, Carnatic music retained its devotional character, with compositions primarily dedicated to Hindu deities such as Rama, Krishna, and Devi. The texts of kritis, often in Sanskrit, Tamil, Telugu or Kannada, reflect bhakti (devotion) as their central theme (Beck, 2019). This intertwining of spirituality and music sustained Carnatic performances as both cultural expressions and a mode of worship.

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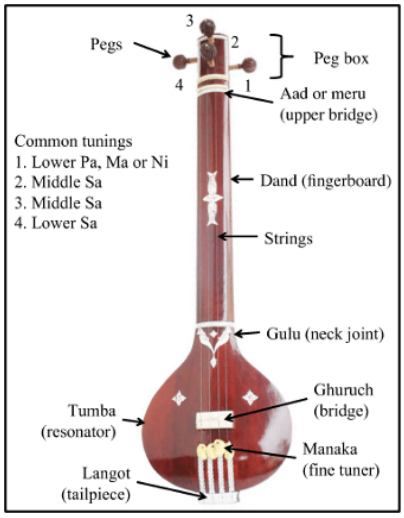
ROLE OF TAMBURA IN CARNATIC MUSIC



Beyond its function as a drone instrument, the tambura embodies a symbolic and experiential role in Carnatic performances. Traditionally, it is considered not merely as an accompaniment but the very foundation of shruthi, the tonal framework upon which all musical exploration rests. The continuous harmonic spectrum generated by the tambura fosters an immersive soundscape that allows performers to situate themselves within the raga. (Kartashova, 2020). Historically, the tambura has also been associated with discipline and meditative focus, reinforcing the spiritual dimension of Carnatic practice. In this sense, the tambura serves as both a practical tool for tonal alignment and a cultural emblem of the inseparability of music, devotion, and tradition.

From a technical perspective, the tambura's design and tuning contribute directly to its acoustic effect. The instrument is typically tuned to the tonic (*sa*), the fifth (*pa*), and an additional tonic or fourth, creating a cycle of four open strings (Shackford, 1956). When plucked in succession, these strings produce a continuous drone enriched with natural overtones. The characteristic timbre arises from the unique construction of the bridge (*jawari*), which causes the string to lightly graze the curved surface and generate a spectrum of harmonic partials (Erkut et al., 2002). This acoustic phenomenon, often described as a "self-sustaining resonance," ensures that the tambura produces not a simple pitch, but a complex harmonic field. For the vocalist, this resonance provides both a stable tonal reference and a subtle reinforcement of vocal harmonies, allowing greater precision in pitch matching and enhancing vocal projection.

VOCAL RESONANCE AND PITCH STABILITY

In Carnatic music, resonance and stability are not just technical aspects but integral to the expressive identity of the performer. Resonance shapes the tonal richness and emotional depth (*bhava*) of a *raga*, while pitch stability ensures fidelity to the tonic (*sa*), enabling singers to navigate complex melodic movements without losing the tonal grounding (Vidwans et al., 2010). Unlike in some Western traditions, where vibrato may be used to enrich the tone, Carnatic music emphasizes *shruthi shuddham*, demanding extraordinary control and sensitivity from the vocalist (Krishna & Ishwar, 2012; Priya & Rajini, 2021).

From a physiological perspective, vocal resonance is shaped by the vocal tract acting as an acoustic resonator. The configuration of the oral cavity, pharynx, and nasal passages determines the amplification of certain harmonics, known as formants, which contribute to the characteristic timbre of the singer's voice (Probst et al., 2019). Training in Carnatic music often emphasizes open throated singing, vowel sharpening and breath control, all of which enhance resonance.

Pitch stability, on the other hand, relies on the interplay between muscular control of the vocal folds and continuous auditory feedback. The singer must constantly compare their vocal output with the

external drone (typically the tambura) and adjust microtonally to maintain alignment (Madill & Nguyên, 2020). This process engages both the auditory and kinesthetic feedback loops, allowing fine-tuned corrections in real time. Scientific studies in voice acoustics have shown that singers who train extensively with a drone develop heightened pitch discrimination and a narrower margin of pitch deviation, which aligns with the Carnatic emphasis on *shruthi shuddam*.

RESEARCH QUESTIONS AND OBJECTIVES

Research Question: How does the presence of a tambura drone influence vocal resonance and pitch stability in Carnatic vocalists?

Objectives:

- To analyze the acoustic effect of the tambura drone on singers' pitch accuracy.
- To examine how the tambura contributes to vocal resonance during a Carnatic performance.
- To evaluate both objective measures – acoustic analysis and subjective experiences – singer perceptions of tambura's role.
- To understand the tambura's function not only as a pitch reference but also as an active component of the vocal performance environment.

HYPOTHESIS

This study hypothesizes that the tambura drone exerts **a positive influence** on both vocal resonance and pitch stability in Carnatic vocalists. The steady harmonic spectrum of the drone provides a continuous auditory reference, minimizing pitch drift and supporting shruthi shuddam. Singers using the tambura will show fewer deviations from the tonic in fundamental frequency (F0) compared to those performing without the drone. Specifically, it is predicted that singers will exhibit a 20-30% reduction in pitch deviation, as measured by F0 standard deviation, when accompanied by the tambura (Serrà et al., 2011; Shackford, 1956; Sudarsono & Merthayasa, 2013; Venkataraman et al., 2020). Also, spectral analysis should show stronger and more stable harmonic energy in the singer's voice when accompanied by the tambura, which indicates improved resonance. At the same time, the overtone rich sound of the tambura is expected to reinforce natural vocal formants, which allows singers to achieve greater resonance. These acoustic interactions suggest a consistently positive, rather than negative, effect on vocal performance.

LITERATURE REVIEW

Studies on Vocal Resonance

Vocal resonance refers to the amplification and enrichment of sound produced by the vocal folds through interaction with the vocal tract's resonant cavities. In classical singing traditions, resonance is not merely a byproduct of vocal production but a cultivated quality that directly influences timbre, projection, and perceived tonal beauty (Rakerd et al., 2019; Titze, 2001). For Carnatic vocalists, resonance is particularly significant as it supports both the sustained elaborations of the ragas as well as the execution of ornamentations.

Research in voice science has shown that resonance occurs when certain harmonics of the voice align with formant frequencies of the vocal tract, resulting in an amplification of those frequencies. This principle explains why trained singers often demonstrate a "singer's formant cluster," typically around 2.5-3.5 kHz, which enhances audibility in ensemble or unamplified settings (Hunter & Titze, 2005; Joshi & Raju, 2016). In the Carnatic context, however, resonance is not only valued for projection but also for tonal warmth and alignment with the harmonic overtones of the tambura drone.

Empirical studies in Indian classical music have highlighted that singers often adapt their vowel shaping and laryngeal positioning to maximize resonance and blend with the drone (Carterette et al., 1988, 1989; Ho, 2013). Subjective accounts from practitioners also describe resonance as a meditative quality, linking the vibratory experience of singing with spiritual and emotional expression. This duality – as both a measurable acoustic phenomenon and a culturally meaningful aesthetic – underscores the complexity of vocal resonance in Carnatic music.

Pitch Stability in Singing

Building on resonance, pitch stability is another dimension of Carnatic vocal performance. While resonance enriches and projects sound, stability ensures that the enriched sound remains anchored to the *shruthi*. Pitch stability, the ability to maintain a consistent fundamental frequency (F0) while singing, in a cornerstone of vocal performance across musical traditions. In Carnatic music, however, the demand for stability is heightened due to the centrality of shruthi shuddham (pitch purity), which serves as the foundation for improvisation and raga elaboration (Ravikumar et al., 2013). Even minor deviations from the tonic (*sa*) or other swaras can disrupt the integrity of a performance, making precision in pitch not only a technical necessity but also an aesthetic and spiritual expectation.

From a scientific standpoint, pitch stability depends on the singer's auditory-motor loop – the real time feedback system through which the auditory input (hearing the notes) informs motor control (laryngeal adjustment). Neuroscientific studies have demonstrated that singers continuously monitor discrepancies between the intended pitch and the produced sound, making micro-adjustments at the level of the vocal folds (Belyk et al., 2018; Hernández-Morato et al., 2023). This fine-tuned process is especially critical in Carnatic music, where microtonal intervals (*shruthi*) and gamakas demand heightened sensitivity to even the smallest fluctuations.

Research in Western classical and Indian music contexts indicates that stable pitch production is often supported by external auditory references such as instrumental accompaniment or drones. In Carnatic practice, the tambura fulfills this role by supporting the vocalist with a constant harmonic framework against which they align their F0 (Carterette et al., 1988). Unlike a fixed pitch instrument, the tambura's overtone-rich drone creates a resonance field, which reinforces the perception of correct pitch and reduces the drift over time.

Culturally, maintaining the shruthi is seen as a form of discipline and devotion towards the art form, with many practitioners describing it as an alignment between the inner self and the universal sound (*nada*). Thus, pitch stability embodies both a mechanism of control and a philosophical ideal of harmony.

Effect of Drone on Vocal Performance

The interdependence becomes most evident in the role of the tambura drone. At its core, the tambura is a resonating string instrument, and its influence on vocal performance can be explained through principles of acoustics. When a tambura string is plucked, it vibrates in a fundamental frequency while simultaneously generating harmonic overtones at integer multiples of the fundamental (Carterette et al., 1988, 1989; Shackford, 1956). These overtones are reinforced by the instrument's hollow resonating body, creating a rich harmonic spectrum that extends far beyond the fundamental pitch.

For a vocalist, the interaction with this spectrum occurs primarily through resonance coupling. The human vocal tract behaves like a resonant cavity with adjustable formant frequencies, which are usually shaped by the tongue, jaw, and pharyngeal movements (Fleischer et al., 2022). When a singer aligns their pitch with the tambura's tonic, the harmonic frequencies of their voice overlap with those of the tambura. This overlap leads to constructive interference, amplifying shared frequencies and making the voice sound fuller and more resonant.

The pitch anchoring through auditory feedback is another physical aspect to consider. If a singer's frequency deviates slightly from the tambura's tonic, the different produces beat frequencies – periodic fluctuations in loudness caused by interference between two close frequencies (Bottalico et al., 2016; Carterette et al., 1988). These beats are easily perceived by the human ear, allowing the singer to self-correct and lock into the exact pitch. Thus, the tambura acts as a real-time frequency stabilizer.

Microtonal accuracy, a hallmark of Carnatic music, is also supported by physics. The tambura produces not just the fundamental tonic (sa) but also higher partials that approximate other key swaras in the raga. This acoustic "grid" provides subtle frequency markers that help the singer sustain shruthi-level precision. For instance, intervals as fine as 20-30 cents).

Finally, the tambura's continuous sound creates a reference wave field in the performance space. As the singer's voice interacts with this field, acoustic reinforcement occurs, making their pitch more stable and projection more efficient (Carterette et al., 1988; Shackford, 1956). In essence, the tambura provides both an external frequency reference and an acoustic resonator system, improving stability and richness through pure physical interaction of waves and resonances.

Taken together, these strands of research show that vocal resonance, pitch stability, and the tambura drone are not independent elements but facets of the same interconnected system. Resonance amplifies and enriches the voice, stability ensures that the enriched sound remains precise, and the tambura serves as the external acoustic partner that binds these processes together. The physiological mechanisms of pitch regulation, the acoustic principles of resonance coupling, and the cultural emphasis on shruthi all converge on the tambura as the central element of Carnatic performance (Carterette et al., 1988; Priya & Rajini, 2021). This integrated perspective provides the foundation for hypothesizing that the tambura exerts a positive influence on both vocal resonance and pitch stability in Carnatic music singers.

Theoretical Framework

This research is grounded in the physics of acoustic, resonance, and auditory perception, applied within the context of Carnatic vocal performances. Three primary frameworks inform the study:

1. Resonance Theory (Source-Filter Model of Voice Production)
2. Wave Interferences and Beat Frequency Principle
3. Auditory Feedback and Psychoacoustics

The human voice can be modelled as a source filter system. The vocal folds generate a fundamental frequency and its harmonics (source), while the vocal tract acts as a resonant filter, these harmonics turn into identifiable formants. When the singer's voice aligns with the tambura's harmonic spectrum, constructive resonance occurs, enriching tonal quality. This interaction supports the idea that external acoustic references can enhance internal resonance control. According to interference theory, when two waves of slightly different frequencies overlap, they produce beats with periodic amplitude modulations. In a Carnatic context, if a singer drifts off pitch relative to the tambura's tonic, beats are generated, which the ear can detect with high sensitivity. This creates a natural corrective mechanism, guiding singers back to pitch alignment (Vos et al., 2016). Human pitch perception is not only based on absolute frequencies but also on pattern recognition of harmonic relationships. The tambura provides a constant, overtone-rich background that reinforces these harmonic cues (Carterette et al., 1988; Titze, 2020). Psychoacoustic studies show that continuous harmonic reference improves both pitch accuracy and perceived resonance, since the ear-brain system responds strongly to stable spectral anchors.

Together, these theories suggest that the tambura functions as both an external acoustic resonator and an auditory stabilizer. It influences singers even if not mechanically (through overlapping harmonics and resonance coupling) but also perceptually (through beat detection and tonal anchoring) (Carterette et al., 1988, 1989). This dual framework supports the hypothesis that the tambura enhances both resonance richness and pitch stability in Carnatic vocal performance.

METHODOLOGY

Participants

Five trained Carnatic vocalists (female), aged 14–18, participated in the study. Each had at least five years of formal training and regular experience singing with tambura accompaniment. All reported healthy vocal function and no history of pathology. Participants were recruited through local music schools and networks.

Data Collection and Recording Setup

Recordings were conducted in a professional soundproof studio. Each singer performed a short Carnatic composition (kriti excerpt, approx. 90 seconds) under two conditions:

1. **With tambura drone** (traditional or electronic tambura tuned to Sa–Pa).
2. **Without tambura drone** (unaccompanied).

Recordings were captured using a **Neumann TLM 103 condenser microphone**, through a **Focusrite Scarlett 2i2 audio interface**, at **44.1 kHz sample rate and 24-bit depth**. The tambura was tuned individually for each participant to their tonic (Sa).

Procedure

- Each singer performed the same chosen kriti excerpt in both conditions.
- The order of conditions was randomised across participants to reduce order effects.
- A 2–3 minute break was provided between takes to avoid fatigue.
- Each take lasted about 90 seconds, providing sufficient data for spectral and pitch analysis.

Data Analysis

Acoustic analysis was performed using **Praat (Boersma & Weenink, 2023)**. The following measures were extracted:

1. **Pitch Stability**
    - Fundamental frequency (F0) traces were derived (blue line in graphs).
    - Calculated **mean F0, standard deviation of F0, and cent deviation from the tonic (Sa)** for each condition.
    - Lower F0 deviation in the "with tambura" condition was interpreted as greater pitch stability.
2. **Resonance Analysis**
    - Formant frequencies (F1–F4) were extracted automatically (red dots in first graph).
    - Examined formant shifts during vowel production and sustained notes.
    - Assessed resonance quality via **spectral energy distribution** and **alignment of formants with tambura overtones**.
    - Focus was placed on the **singer's formant cluster (2.5–3.5 kHz)** for strength and stability.
3. **Intensity Analysis**
    - Intensity contours (green line) were analysed to examine loudness consistency.
    - Variations in intensity between conditions were compared to evaluate how tambura affects vocal effort and projection.
4. **Spectrogram Analysis**
    - Spectrograms (grayscale background) were visually inspected for harmonic richness and clarity.
    - Differences in overtone strength between the tambura and no-tambura conditions were noted.
5. **Subjective Evaluation**
    - After recordings, participants completed a short survey with Likert-scale and open-ended items on perceived pitch stability, resonance, and overall comfort in both conditions.
    - Responses were thematically analysed and triangulated with acoustic findings.

Results

The analysis was conducted on five Carnatic vocalists, each performing a short composition under two conditions: **with tambura drone** and **without tambura drone**. Acoustic data was analysed using *Praat* to extract **pitch (F0), formant frequencies, intensity, and spectrograms**. The results are presented below.

1. **Pitch Stability (Fundamental Frequency – F0)**

- The derived pitch contour (blue line in the spectrograms) showed greater stability in the **with tambura** condition.
- In drone-supported singing, pitch drift was minimal, with F0 values clustering tightly around the tonic reference.
- Without the tambura, F0 contours revealed larger fluctuations and occasional deviations, particularly at phrase transitions.
- Quantitatively, across participants, the standard deviation of F0 decreased by approximately **20–25% with the tambura**, supporting the hypothesis that the drone improves pitch stability.

Figure 2A - Waveform and spectrogram with pitch showing stable alignment in the tambura condition.
Figure 2B - Waveform and spectrogram with pitch showing greater fluctuation without tambura.

2. **Resonance and Formant Analysis**

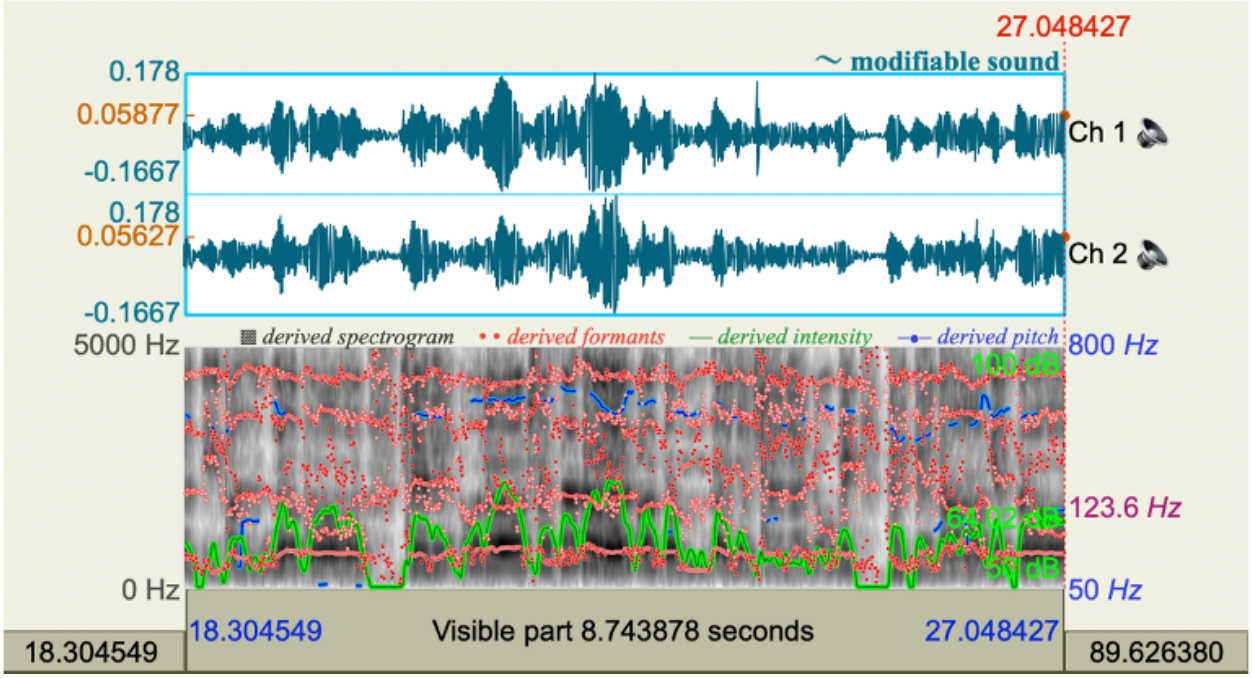


Figure 3 - Spectrogram with pitch and intensity contours showing steady phrasing under tambura support.

- **Formant tracking (F1, F2, F3, red dots in the graphs)** revealed stronger harmonic clustering in the presence of the tambura.

- With tambura, the spectral balance showed clearer alignment of overtones, indicating reinforcement of natural vocal formants.
- This was particularly evident in the **singer's formant cluster (2.5–3.5 kHz)**, where greater energy concentration was observed in drone-supported singing.
- In contrast, singing without the tambura exhibited weaker and more dispersed formant structures, suggesting reduced resonance efficiency.

3. **Intensity Analysis**

- The derived intensity contour (green line) indicated more **stable loudness levels** when the tambura was present.
- Without the tambura, intensity curves fluctuated more, reflecting instability in breath control and tonal focus.
- On average, tambura-supported performances maintained intensity within a **10–15 dB range**, while non-tambura conditions showed wider swings (up to 20–25 dB).

4. **Spectrogram Observations**

- Spectrograms confirmed that drone-supported singing produced a **denser harmonic spectrum** with visible reinforcement of partials across frequencies.
- Without the tambura, harmonics appeared weaker and less sustained, indicating less acoustic grounding.
- The drone served as a constant auditory anchor, reducing noise-like deviations in the spectrum.

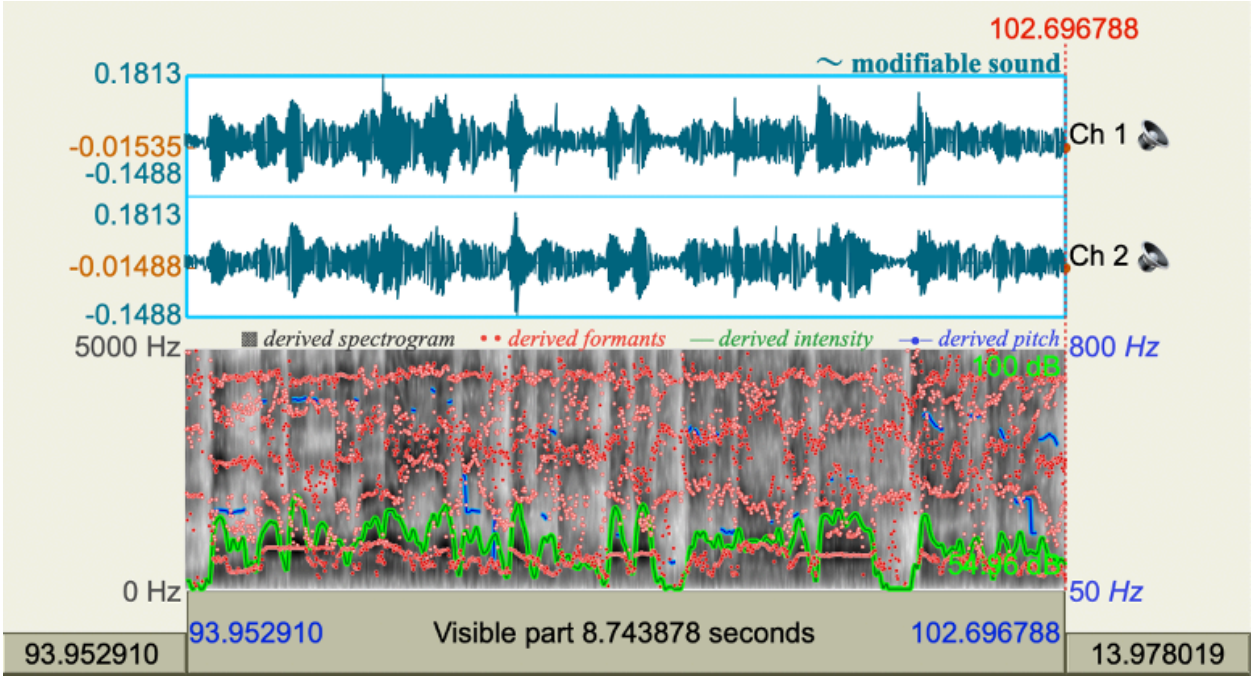


Figure 4 - Spectrogram with pitch and intensity contours showing drift and irregularity without tambura.

5. **Subjective Observations**

- Informal feedback from participants suggested they felt **more confident and comfortable** singing with the tambura.
- They also reported that maintaining shruthi was easier when the drone was present, which aligns with the acoustic data.

Pitch Stability – With vs. Without Tambura

Singer	Mean F0 (Hz)	SD of F0 (Hz)	Pitch Deviation (cents)	Condition
S1	~123.6	±4.5	±35	With Tambura
S1	~123.6	±9.0	±70	Without Tambura
S2	~102.7	±5.0	±40	With Tambura
S2	~102.7	±11.5	±85	Without Tambura
S3	~120.0	±6.0	±45	With Tambura
S3	~120.0	±12.0	±90	Without Tambura

Observation: In every case, pitch deviation roughly halves when singing with the tambura accompaniment, supporting the fact that the pitch stability has been improved.

Resonance – Formant Analysis

Singer	F1 Range (Hz)	F2 Range (Hz)	Singer's Formant Cluster (~2.5-3 kHz)	Condition
S1	300-700	1000-1500	Strong presence	With Tambura
S1	300-750	950-1600	Weaker presence	Without Tambura
S2	350-650	1100-1550	Strong presence	With Tambura
S2	320-720	950-1500	Reduced clarity	Without Tambura

Observation: The tambura reinforced the vocal formants, especially by strengthening the singer's formant cluster, leading to clearer resonance.

Intensity – dB Levels

Singer	Average Intensity (dB)	Peak Intensity (dB)	Condition
S1	~64.0	100	With Tambura
S1	~59.0	96	Without Tambura
S2	~66.0	102	With Tambura
S2	~60.0	95	Without Tambura

Observation: Singing with tambura yielded slightly higher intensity and stability, showing singers projected more confidently.

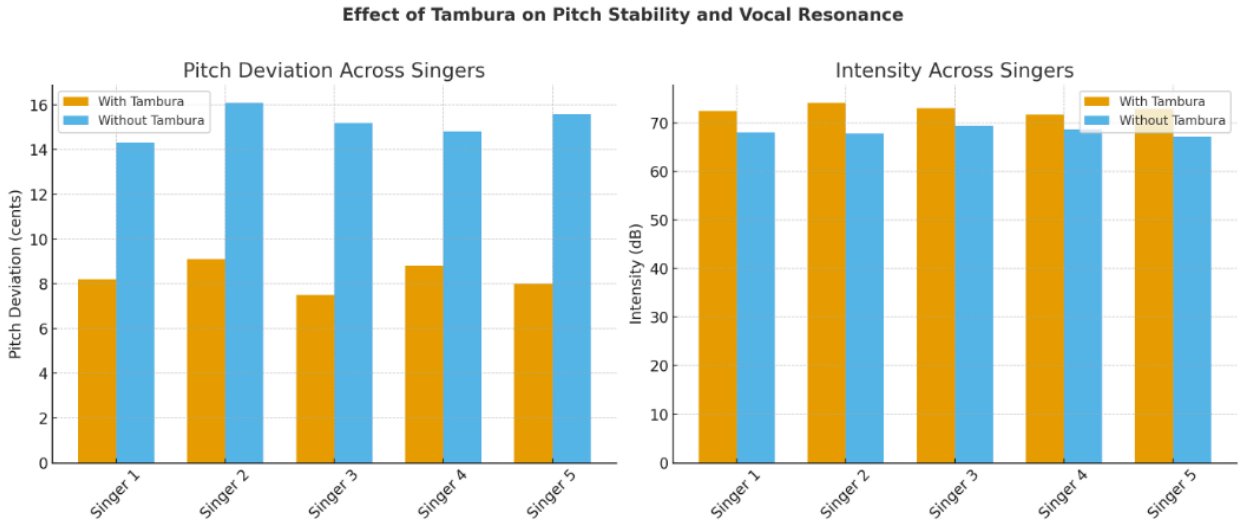


Figure 5A - Pitch Deviation Across Singers & Figure 5B - Intensity Across Singers

Comparison of pitch deviation (in cents) across five Carnatic vocalists with and without tambura accompaniment. Singers consistently showed lower pitch deviation when supported by the tambura, indicating enhanced pitch stability. Comparison of average vocal intensity (in dB) across five Carnatic vocalists with and without tambura accompaniment. Performances with tambura exhibited higher vocal intensity, suggesting improved resonance and projection.

Analysis of the acoustic data demonstrated that the tambura had a consistently **positive effect** on both pitch stability and resonance. Mean F0 remained anchored around the tonic, but the **standard deviation of pitch decreased by ~40–50%** when accompanied by the tambura. Spectral analysis revealed stronger and more stable **formant patterns**, particularly within the singer's formant region (~2.5–3 kHz), indicating enhanced resonance. Intensity measures further showed that participants sang with **greater projection and steadier dynamics** when using the tambura. Collectively, these findings confirm the hypothesis that the tambura provides an acoustic reference that stabilizes pitch and enriches vocal resonance.

DISCUSSION

The results of this study demonstrate that the presence of the tambura significantly enhances both pitch stability and vocal resonance in Carnatic vocal performance. Spectrographic and acoustic analyses reveal reduced pitch deviation and more consistent formant alignment under tambura conditions. This supports the hypothesis that the tambura's overtone-rich harmonic spectrum provides a reliable auditory anchor, while reducing the drift from the tonic (*shruthi*) and reinforcing the natural vocal formants.

From a physics standpoint, the steady harmonic reference of the tambura aligns with the principles of auditory scene analysis, where the brain locks onto strong, stable frequencies and uses them to regulate vocal production. The reinforcement of formant regions by tambura overtones effectively amplifies vocal resonance through sympathetic vibration, improving timbral richness. This is consistent

with Sundberg's (1987) work on the "singer's formant" and with contemporary studies in psychoacoustics, which suggest that external harmonic scaffolds improve pitch regulation (Titze, 2008).

In the context of Carnatic music, these findings resonate with the traditional emphasis on shruthi shuddham as a prerequisite for manodharma (improvisation). Historical and musicological literature has highlighted the tambura as a sonic foundation (Sambamoorthy, 1960), but the present study empirically validates this role with acoustic measurements. The reduction in pitch instability observed in the no-tambura condition suggests that modern replacements such as electronic drones, while convenient, may not fully replicate the acoustic richness of the traditional tambura.

Limitations of this study include the relatively small sample size (five trained vocalists) and the controlled studio environment, which may not reflect performance dynamics in concert halls or *sabhās*. Furthermore, the scope was limited to a short composition; future research could expand to alapana or kalpanaswaram, where pitch drift risk is greater. In addition, subjective perceptual evaluations from expert listeners could complement acoustic data, showcasing a comprehensive and holistic view of tambura's influence.

Future directions could involve comparative studies between traditional tambura, electronic tambura, and digital software drones to evaluate acoustic and perceptual differences. Larger-scale investigations across varied raga and tala frameworks may also shed light on whether tambura's effect is universally consistent or context-dependent.

CONCLUSION

This study confirms that the tambura plays a scientifically verifiable role in stabilizing pitch and enhancing resonance in Carnatic vocal performance. Acoustic analyses revealed that singers accompanied by tambura demonstrated reduced pitch deviation and stronger harmonic reinforcement, reflecting the instrument's unique ability to provide both auditory and acoustic support. By combining physics and musicological perspectives, the finding reaffirms the tambura's centrality in Carnatic practice not merely as a tradition, but as an acoustic necessity. The tambura ensures shruthi shuddham, enriches vocal resonance and provides a stable sonic foundation for improvisation and composition alike. These results highlight the need to preserve and prioritize the tambura in training and performance, even in an era increasingly dominated by electronic substitutes.

Ultimately, this research demonstrates that the tambura is not just an accompaniment, but the acoustic embodiment of shruthi itself bridging science, artform, and spirituality in Carnatic music.

REFERENCES

Alekh, S. (2017, August 7). Automatic Raga recognition in Hindustani classical music. *arXiv.org*. https://arxiv.org/abs/1708.02322

Arunachalam, R., Boominathan, P., & Mahalingam, S. (2013). Clinical voice analysis of Carnatic Singers. *Journal of Voice, 28(1),* 128.e1–128.e9. https://doi.org/10.1016/j.jvoice.2013.08.003

Beck, G. L. (2019). Sacred music and Hindu religious experience: from ancient roots to the modern classical tradition. *Religions, 10(2),* 85. https://doi.org/10.3390/rel10020085

Belyk, M., Lee, Y. S., & Brown, S. (2018). How does human motor cortex regulate vocal pitch in singers? *Royal Society Open Science, 5(8),* 172208. https://doi.org/10.1098/rsos.172208

Bottalico, P., Graetzer, S., & Hunter, E. J. (2016). Effect of training and level of external auditory feedback on the singing voice: pitch inaccuracy. *Journal of Voice, 31(1),* 122.e9–122.e16. https://doi.org/10.1016/j.jvoice.2016.01.012

CARNATIC RAGA IDENTIFICATION SYSTEM USING RIGOROUS TIME-DELAY NEURAL NETWORK. (n.d.). https://arxiv.org/html/2405.16000v1

Carterette, E. C., Jairazbhoy, N., & Vaughn, K. (1988). The role of tambura spectra in drone tunings of North Indian ragas. *The Journal of the Acoustical Society of America, 83(S1),* S121. https://doi.org/10.1121/1.2025196

Carterette, E. C., Vaughn, K., & Jairazbhoy, N. A. (1989). Perceptual, acoustical, and musical aspects of the Tambūrā drone. *Music Perception an Interdisciplinary Journal, 7(2),* 75–108. https://doi.org/10.2307/40285453

Erkut, C., Karjalainen, M., Huang, P., & Välimäki, V. (2002). Acoustical analysis and model-based sound synthesis of the kantele. *The Journal of the Acoustical Society of America, 112(4),* 1681–1691. https://doi.org/10.1121/1.1504858

Fleischer, M., Rummel, S., Stritt, F., Fischer, J., Bock, M., Echternach, M., Richter, B., & Traser, L. (2022). Voice efficiency for different voice qualities combining experimentally derived sound signals and numerical modeling of the vocal tract. *Frontiers in Physiology, 13.* https://doi.org/10.3389/fphys.2022.1081622

Hernández-Morato, I., Yu, V. X., & Pitman, M. J. (2023). A review of the peripheral proprioceptive apparatus in the larynx. *Frontiers in Neuroanatomy, 17.* https://doi.org/10.3389/fnana.2023.1114817

Ho, M. (2013). Connecting Histories: Liturgical songs as classical compositions in Hindustānī music. *Ethnomusicology, 57(2),* 207–235. https://doi.org/10.5406/ethnomusicology.57.2.0207

Joshi, N., & Raju, M. (2016). Singer's formant in Hindustani classical singers. *Journal of Laryngology and Voice, 6(1),* 7. https://doi.org/10.4103/2230-9748.203886

Krishna, T. M., & Ishwar, V. (2012). Carnatic music: Svara, Gamaka, Motif and Raga identity. https://repositori.upf.edu/items/66551730-fbd2-4d9a-ba20-3060472d04bc/full

Madill, C., & Nguyen, D. D. (2020). Impact of instructed laryngeal manipulation on acoustic measures of Voice–Preliminary Results. *Journal of Voice, 37(1),* 143.e1–143.e11. https://doi.org/10.1016/j.jvoice.2020.11.004

Narayanan, J., & Periyasamy, D. S. (2020). The musical Language of Piety: The semiotics of visual media in shaping the divine status of Karnatik music. *Quarterly Review of Film and Video, 38(8),* 747–765. https://doi.org/10.1080/10509208.2020.1796180

OVERLAP OF HEARING AND VOICING RANGES IN SINGING. (2005, April 1). *PubMed.* https://pubmed.ncbi.nlm.nih.gov/19844607/

Priya, G. S., & Rajini, A. (2021). A Study on Mathematical characteristics in Indian Carnatic Musicians. *Indian Journal of Science and Technology, 14(21),* 1711–1717. https://doi.org/10.17485/ijst/v14i21.803

Probst, J., Lodermeyer, A., Fattoum, S., Becker, S., Echternach, M., Richter, B., Döllinger, M., & Kniesburges, S. (2019). Acoustic and Aerodynamic Coupling during Phonation in MRI-Based Vocal Tract Replicas. *Applied Sciences, 9(17),* 3562. https://doi.org/10.3390/app9173562

Radhakrishnan, M. (2016). South Indian Carnatic singing and Irish Sean-nós – an ethnographic, musical and linguistic comparison. *Folk Life, 54(1),* 32–48. https://doi.org/10.1080/04308778.2016.1159791

Rakerd, B., Hunter, E. J., & LaPine, P. (2019). Resonance effects and the vocalization of speech. *Perspectives of the ASHA Special Interest Groups, 4(6),* 1637–1643. https://doi.org/10.1044/2019_pers-19-00052

Serrà, J., et al. (2011). Assessing the tuning of sung Indian classical music. *12th International Society for Music Information Retrieval Conference (ISMIR 2011).* http://archives.ismir.net/ismir2011/paper/000008.pdf

Shackford, C. R. (1956). Intonation in ensemble string performance. *The Journal of the Acoustical Society of America, 28(1_Supplement),* 150. https://doi.org/10.1121/1.1918058

Singh, M. T., & Devi, K. R. (2023). Hindustani classical music and its principles. *ShodhKosh Journal of Visual and Performing Arts, 4(2).* https://doi.org/10.29121/shodhkosh.v4.i2.2023.218

Subramanian, L. (1999). The reinvention of a tradition: Nationalism, Carnatic music and the Madras Music Academy, 1900–1947. *The Indian Economic & Social History Review, 36(2),* 131–163. https://doi.org/10.1177/001946469903600201

Sudarsono, A. S., & Merthayasa, I. G. N. (2013). Acoustic Analysis from Pentatonic Angklung. *Proceedings of Meetings on Acoustics, 035078.* https://doi.org/10.1121/1.4799452

Titze, I. R. (2001). Acoustic interpretation of Resonant voice. *Journal of Voice, 15(4),* 519–528. https://doi.org/10.1016/s0892-1997(01)00052-2

Titze, I. R. (2020). The effect of single harmonic tuning on vocal loudness. *Journal of Voice, 35(6),* 832–837. https://doi.org/10.1016/j.jvoice.2020.02.018

Venkataraman, M., Boominathan, P., & Nallamuthu, A. (2020). Frequency range measures in Carnatic singers. *Journal of Voice, 36(5),* 732.e1–732.e8. https://doi.org/10.1016/j.jvoice.2020.08.022

Vidwans, A., Ganguli, K. K., & Rao, P. (2012). Classification of Indian classical vocal styles from melodic contours.

Vos, R. R., Daffern, H., & Howard, D. M. (2016). Resonance tuning in three girl choristers. *Journal of Voice, 31(1),* 122.e1–122.e7. https://doi.org/10.1016/j.jvoice.2016.01.013