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Emotional and Social Signals in Multimedia: Vibrato Variations in Classical Singing

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Abstract. In acoustic psychology research, many studies have explored how acoustic features enhance emotional expression in singing, but the role of vibrato has been relatively underexamined. This study investigates how variations in vibrato affect emotional perception in singing through two experiments. Recordings of professional classical singers performing notes with different vibrato speeds and amplitudes were analyzed to examine correlations between vibrato features and emotional perception. A perceptual emotional assessment further revealed that changes in vibrato significantly influence the perception of basic emotional categories. Specifically, variations in vibrato speed and amplitude were found to alter how emotions are perceived. The findings indicate that even controlled vibrato variations carry emotional cues recognizable to listeners. The study also highlights that vibrato parameters are independent, and professional opera singers can control these features separately to convey distinct emotions.

Keywords: Vibrato, Acoustic Characteristics, Perception.

1 Introduction

Music is often linked to emotions. Recently, researchers have increasingly focused on how music affects people emotionally. The most noteworthy work in this area is the book 'Music and Emotion' by Juslin and Sloboda [1,2]. They organised four conferences on this topic and collected more than 250 research articles on this phenomenon. Although many fields have studied the emotional power of music, the question of how performers connect emotionally with their audiences remains a mystery. This is because many musicians argue that emotional expression is often regarded as a natural talent or ability of performers that cannot be taught or learned [3]. Therefore, further research to clarify the acoustic characteristics associated with emotions will help vocal students understand the relationship between singing and the audience's perception of their performance.

The expression of emotion is a critical aspect of performance; however, surprisingly little research has been conducted on the psychology behind musical emotion. There is even less research and consequently a lack of consensus, on how emotions are expressed onstage. Music originated from emotional expressions of the human voice. Singing is an especially emotional form, particularly opera [4]. How do opera singers interpret character roles to express emotion during an opera? This question has led researchers to focus on emotional expressions on stage. This research developed from [5] attempt to describe the relationship between acoustic measurements and audience reactions to emotional expression based on the commercial recordings of renowned opera singers. Siegwart did not investigate this in-depth; however, the results suggest that vocal vibrato is an acoustic feature that helps explain emotions. Unfortunately, this acoustic feature is often overlooked in studies on voice and emotion perception. In the Western classical tradition, professional opera singers typically use vibrato when singing, and they generally believe that vibrato is a characteristic of trained singers and that it naturally occurs when the voice is free and well-trained [6]. Vibrato is one of the most commonly used musical performance techniques.

The exploration of vocal vibrato began in the late 1920s and early 1930s and is now an established area of research. Vibrato research was initiated by Carl E.Seashore and colleagues [7], but technological limitations resulted in limited accuracy and precision [7–11]. After Seashore, many researchers developed techniques to improve the accuracy and flexibility of vibrato measurements [12,13]. Researchers also explored the physiological elements of vocal vibrato [14,15]. Subsequent researchers attempted to describe vibrato more comprehensively, with a particular focus on the rate and extent of vibrato. With the development of understanding and measurement techniques for vibrato, some researchers have attempted to study the acoustic characteristics and perceptual relationships of vibrato. One such notable example is the work of [16], who explored these aspects using arias from the renowned opera ‘Lucia di Lammermoor’ and selected soprano arias to express emotions. Overall, most studies on vibrato have focused on acoustic measurements and the perception of vibrato by trained singers, with limited research on emotional perception.

Based on the above points, in this paper, we aim to investigate the role of vibrato in the emotional perception of singing. Although monophonic sounds rarely exist independently in song performance, some studies have provided instances “indicating that singers adjust fine characteristics of vibrato to express emotions, which are reliably transmitted to the audience even in short vowel segments” [17]. To focus on vibrato, We selected experimental vocal recordings, specifically monophonic singing sounds that primarily vary in amplitude and speed of vibrato. This approach will reduce interference from other musical features known to influence emotional perception, such as pitch, rhythm, range, and loudness.

To explore vibrato and emotion in classical singing, two experiments were designed to address this topic step by step. In the first experiment, recordings of two professional classical singers singing the note /la/ with vibrato at different speeds and amplitudes were collected. The main vibrato-related feature quantities and their parameters, as well as their correlations with other acoustic features, were analyzed. The vibrato feature quantities in Experiment 1 are inspired by [18], while other acoustic features are inspired by [19]. In the second experiment, a perceptual emotional assessment was conducted using the singing samples with large, medium, and small vibrato patterns collected in Experiment 1. This explored the role of different vibrato in the perception of basic emotional categories in singing. Participants rated the emotional perception of different vibrato patterns based on basic emotional categories. The experiment referenced the emotion model derived from the basic emotions identified by [20]—anger, disgust, fear, Joy, sadness, and surprise. These emotion models are considered the foundation for all other emotions. In summary, our contributions are three-fold:

– We make a parametric analysis of classical singing voices with varying rates and extents of vibrato.

– We investigate the differences in six basic emotions among vibrato patterns.

– We explore the expected emotional responses from the impact of vocal vibrato.

2 Related Work

So far, in the study of classical singing, the keyword vibrato cannot be ignored. In the literature on the theme of vibrato, there are discussions on historical differences in parameters such as vibrato rate and extent [21,22], differences in breathing techniques [23,24], differences in vocal range, types of vocal music, and volume of vocal training [25,26], as well as the analysis of differences in vibrato acoustic parameters according to different emotions [27,16].

The earliest description of vocal vibrato was by Seashore in [9]. Since then, more and more researchers have attempted to study the vocal vibrato of classical singers from various fields, including physiology, acoustics, vocal pedagogy, and speech pathology [28]. [29] believes that the acoustic characteristics of vibrato are mainly manifested in the rate and extent of frequency and amplitude, pitch, and regularity of modulation. [18] points out that onset delay and note duration are also important parameters of vibrato. All these features can be considered as perception-related and are indicators of a singer's vocal techniques.

It's worth considering whether vibrato influences pitch perception. [30] compared the pitch perception of synthetic vibrato and straight tone, when using vowel to perform vibrato, the pitch with vibrato and the pitch of the straight tone is perceived with the same accuracy. According to [29], Based on his research into the correlation between vibrato parameters and acoustic perception, believes that the vibrato rate should be between 5 and 7 Hz. He noted that vibrato rate below 5Hz sounds slow. If rate is higher than 8 Hz, it will sound tense. If rate is lower than 5 Hz, it would cause listeners to perceive vibrato as choppy.

There are other studies that explore the influence of vibrato and other factors. For example, [31] compared the sustained vowel singing of male and female singers. He considers that gender differences may influence the vibrato rate, and that female singers possess higher values. [32] showed that vibrato rate of the elderly among professional singers was between 5.23 and 7.27 Hz. [33] discovered that untrained singers sung vibrato rate begin with either too fast or too slow, would gradually increase or decrease their vibrato as their vocal training converged on a middle ground. [34] pointed out that the extent of vibrato may be related to loudness. [35]'s study found that the extent of vibrato was negatively correlated with duration and positively correlated with pitch.

Vocal trainers commonly use the terms "rate" and "extent" to define vibrato. Researchers have mainly studied acoustic analysis and perceptual–acoustic correlations of vibrato in trained vocalists; fewer studies have investigated the perception of emotion alone. [36] recommends providing the listener with representative cue information to generate an emotional performance that reflects the cue's characteristics. To investigate the use of vibrato cues, the author selected two cues for emotional evaluation: vibrato rate and extent.

3 EXPERIMENT I

This experiment was designed to describe different variation patterns of vibrato and determine whether the relevant vibrato parameters varied independently. Additionally, it examines the relationship between vibrato variations and pitch, intensity, and spectral centroid.

3.1 Materials and Design

The materials used in this study were recorded by two professional singers (a soprano and a tenor) at the Tokyo University of the Arts. The singers had undergone 16–20 years of vocal training. Both singers gave written consent for their voices to be used in the experiments.

The singers were asked to sing successive /la/ syllables, pitched at E4(a tenor) and E5(a soprano), with a duration longer than 3000 ms, accompanied by an increase or decrease in the rate and extent of vibrato. Before singing, the singer tuned their voice to the pitch of the piano by listening to it through headphones. The experiment investigated the differences in vibrato (such as the most stable state of the vibrato, the strongest state, etc.), rather than the emotional expression. Additionally, the maximum and minimum vibratos within the range that the singer considered natural were recorded.

Ultimately, 96 sound samples were gathered, including tenor's vibrato sound (N=42) and soprano's vibrato sound (N=54).

The vocal stimulus were recorded at Studio B at the Tokyo University of the Arts, Senju Campus, where the reverberation duration is approximately 0.3 s, using 24-bit recording and a 48 kHz sampling frequency. A Neumann U87Ai unidirectional condenser microphone was placed (5 to 10 cm) directly in front of the singers. Other equipment included Avid Tools and an Avid Mbox2 audio interface.

3.2 Measurement

For the measurement, the characteristic quantities of the following seven acoustic features analyzed in Experiment 1 are presented (Table 1). The vibrato feature quantities referenced the research by [18], including note duration, the onset delay, rate, and extent of vibrato. Additionally, we also include other acoustic features such as pitch, intensity, and spectral centroid inspired by [19].

Table 1. Extracted Acoustic Features, Abbreviations, and Descriptions.

Features (Abbreviations)	Descriptions
Note Duration (DURATION)	The time from the beginning to the end of a note.
Vibrato Onset Delay (DELAY)	The time from the initiation of the note until the first conclusive peak of the vibrato cycle.
Vibrato Rate (RATE)	The frequency at which the pitch oscillates during vibrato indicates how many cycles occur per second.
Vibrato Extent (EXTENT)	The extent to which the pitch deviates above and below the central pitch during vibrato.
Mean Pitch (PITCH)	The average pitch from the beginning to the end of a note.
Mean Energy Intensity (INTENSITY)	The average amount of energy present in the signal.
Spectral Centroid (CENTROID)	It is calculated by averaging the frequencies in a sound, weighted by their energy levels. It helps determine how bright a sound seems to be.

For the acoustic measurement of vibrato, the spectrogram in PRAAT [37] was used to extract vibrato, with a sampling rate of 48kHz and a Fast Fourier Transform (FFT) window size of 2048 samples. If the difference in pitch between adjacent peaks was larger than a predefined threshold (set to 6 Hz), the position was determined to exhibit vibrato. The calculation formula for vibrato extent used the method from [38]. The sound stimuli were annotated and analysed with the TextGrid tool in the Praat software program.

3.3 Results

The correlation of vibrato parameters. A one-way ANOVA test was used to evaluate the relationship between vocal range and acoustic features (Table 2). The means, Standard deviations, F-values, P-values, and 95% confidence intervals are shown in the table below.

The tenor's vibrato rate averages at 5.01 Hz with a standard deviation of 0.41, based on 42 measurements. It varies from 4.22 to 5.93 Hz. The vibrato extent averages at 104.19

cents with a standard deviation of 56.35, ranging from 15 to 231 cents. The onset delay averages at 0.81 seconds with a standard deviation of 0.78, and it varies from 0.18 to 3.66 seconds. The note duration averages at 5.98 seconds with a standard deviation of 1.88, ranging from 3.43 to 14.08 seconds. For the soprano, the vibrato rate averages at 5.19 Hz with a standard deviation of 0.42, based on 54 measurements. It varies from 4.20 to 6.02 Hz. The vibrato extent averages at 75.5 cents with a standard deviation of 18.27, ranging from 29 to 121 cents. The onset delay averages at 0.47 seconds with a standard deviation of 0.34, and it varies from 0.06 to 1.73 seconds. The note duration averages at 6.95 seconds with a standard deviation of 1.03, ranging from 4.81 to 9.01 seconds.

Table 2. Descriptive statistics for ANOVA showing the variation between acoustic features in two different vocal ranges.

	Vocal Range(Mean±SD)		F-value	P-value	95% CI
	Tenor(n=42)	Soprano(n=54)			
Duration(s)	5.98±1.88	6.95±1.03	10.191	0.002*	-1.62~-0.32
Delay(s)	0.81±0.78	0.47±0.34	7.899	0.006 *	0.10~0.57
Rate (Hz)	5.01±0.41 1	5.19±0.42	4.235	0.042 *	-0.35~-0.01
Extent(cents)	0104.19±56.35	75.50±18.27	12.076	0.001 *	12.30~45.08
Intensity(dB)	779.10±2.50	79.60±1.90	0.032	0.859	-4.41~3.69
Pitch(Hz)	324.80±10.00	655.20±9.50	1.633	0.204	-1.52~0.36
Centroid(Hz)	1936.50±129.60	2105.80±144.00	2.629	0.108	-5.82~53.16

*The significance is also reported for *p<0.05

The result indicated the mean “RATE” for the tenor was significantly lower than that for the soprano (F = 4.235, p = 0.042, <0.05). The lower standard deviation for the vibrato “RATE” of the tenor (SD = 0.409) compared to the soprano (SD = 0.417) suggests that vocalists with a lengthy history of vocal training are more consistent. The mean vibrato “EXTENT” was significantly higher for the tenor than the soprano (F = 12.076, p = 0.001, <0.05). The tenor produced a wider range of vibrato “EXTENT” (SD = 56.34) than the soprano (SD = 18.27).

The mean Onset “DELAY” of the vocal range of the tenor was significantly higher than the vocal range of the soprano (F =7.899, p = 0.006, <0.05). Additionally, the mean “DURATION” of the vocal range of the tenor was significantly lower than the soprano (F

= 10.191, p = 0.002, <0.05). However, there were no significant differences between the mean “INTENSITY”, “PITCH” or Spectral “CENTROID” of the tenor and soprano (p = 0.859; p = 0.204; p = 0.108, respectively).

The Pearson correlation coefficients of the pairwise variables among the seven acoustic parameters are given in Table 3. To interpret the correlations, referring to Cohen’s [39] standard, an absolute value of $|r| \geq 0.5$ indicates a moderate relationship. The results between vibrato “EXTENT” and Spectral “CENTROID” were statistically significant (p<-0.001) and moderately correlated (tenor r = 0.796, soprano r = 0.501).

Table 3. Summary of Pearson’s bivariate correlations between variables (seven acoustic features) in correlation analysis.

Types	Variable	Duration	Delay	Rate	Extent	Intensity	Pitch
Tenor	Delay	0.031 (0.845)					
	Rate	0.212 (0.178)	-0.286 (0.067*)				
	Extent	-0.072 (0.652)	-0.617 (0.000*)	0.122 (0.441)			
	Intensity	-0.348 (0.024*)	-0.182 (0.248)	-0.172 (0.277)	0.26 (0.097*)		
	Pitch	0.285 (0.067*)	0.039 (0.805)	0.1 (0.530)	-0.114 (0.474)	-0.104 (0.512)	
	Centroid	0.312 (0.044*)	-0.527 (0.000*)	0.266 (0.088*)	0.796 (0.000*)	0.018 (0.910)	0.03 (0.849)
Soprano	Delay	0.441 (0.001*)					
	Rate	-0.256 (0.061*)	-0.076 (0.586)				
	Extent	-0.35 (0.009*)	-0.068 (0.624)	0.285 (0.037*)			
	Intensity	-0.4 (0.003*)	-0.277 (0.098*)	-0.025 (0.858)	0.154 (0.266)		
	Pitch	-0.118 (0.394)	0.021 (0.879)	-0.074 (0.596)	-0.233 (0.090*)	-0.227 (0.043*)	
	Centroid	-0.1 (0.474)	0.065 (0.638)	0.273 (0.046*)	0.501 (0.000*)	0.187 (0.176)	-0.181 (0.191)

*The significance is also reported for *p<0.05

Additionally, the tenor Onset "DELAY" and vibrato "EXTENT" had a moderately negative relationship ($r = -0.617$ $p<0.001$), as did onset "DELAY" and spectral "CENTROID" ($r =-0.527$, $p <0.001$). This result was not observed for the soprano ("DELAY" and "EXTENT": $r = -0.068$, $p = 0.624$), which may be due to her lengthier background of vocal training.

4 EXPERIMENT 2

To understand how sound affects how we perceive emotions in music, researchers have proposed the idea that people can tell what feelings are being expressed in a song just by listening to the vibrato. Our experiment evaluated this hypothesis. This study aimed to determine whether listeners' perception of vibrato affected their perception of emotions in singing. Specifically, the author hypothesized that the variations of vibrato would not influence listeners' evaluation of the underlying emotion of the singing voice.

4.1 Method

Brief nonverbal vocalizations (a sustained /a/ syllable produced as the vibrato rate and extent increased or decreased) produced by two professional opera singers singing in vibrato patterns of varying rates and extents were recorded. These different vibrato patterns were used as the sound stimuli in emotional evaluation experiments. Recordings with differing vibrato rates and extents were selected as the sound stimuli in the Experiment to clarify the relationship between the perception of emotions and vibrato in classical singing.

Participants The participants included 15 students, both Japanese and international, at the Tokyo University of the Arts. All participants were in excellent health, with no history of speech or hearing impairment. Verbal and written instructions for the experiment were provided and informed consent was obtained from all participants.

Before beginning the experiment, participants were asked to provide their name, age, gender, and musical experience, as well as their field of study and number of years of musical experience, if applicable. The ages of the participants ranged from 19 to 27, with an average age of 24. The study involved nine female and six male participants.

Stimuli In the evaluation experiment, 18 stimulus patterns were selected from 96 recorded sound stimuli, including three extent and three rate levels for the soprano and tenor. The fade-in/fade-out durations were set to 10 ms to reduce noise at the start and end of the sound sources. To eliminate the impact of the vocal stimuli changing in volume, the sound pressure level was set to 60 dB.

A total of 18 sound stimuli from two vocal registers were used for the evaluation experiment (2 registers × 3 vibrato rates × 3 vibrato extents), with 9 sound stimuli from each register forming a separate experimental group.

The distribution of vibrato extents and rates for the 18 sound stimuli in the two register types is shown in Figure 1. L1 indicated a large extent and a slow rate (L2: a large extent and a medium rate; L3: a large extent and a fast rate; M1: a medium extent and a slow rate; M2: a medium extent and a medium rate; M3: a medium extent and a fast rate; S1: a small extent and a slow rate; S2: a small extent and a medium rate; S3: a small extent and a fast rate).

Procedures The investigation was comprised of two distinct parts, each lasting from 10 to 15 minutes. The first consisted of nine tenor stimuli followed by nine soprano stimuli. Before the experiment, the participants were prompted with a test sound stimulus of 60 dB, the basic emotion evaluation experiment began at this volume.

Referring to [40], six basic emotions (joy, anger, disgust, fear, sadness, and surprise) were selected as the subject of the emotion evaluation experiment, using a bipolar 7-point rating scale. All operations were performed using a graphical user interface created with Max/MSP. Figure 2 shows the interface of Experiment 2. The investigation was conducted in a 24-square-metre room in complete silence. The experiments were conducted independently. Two speakers (NSBP200) and a Windows 8 (64-bit) notebook PC (ASUS-N550J) were used for the sound-source playback.

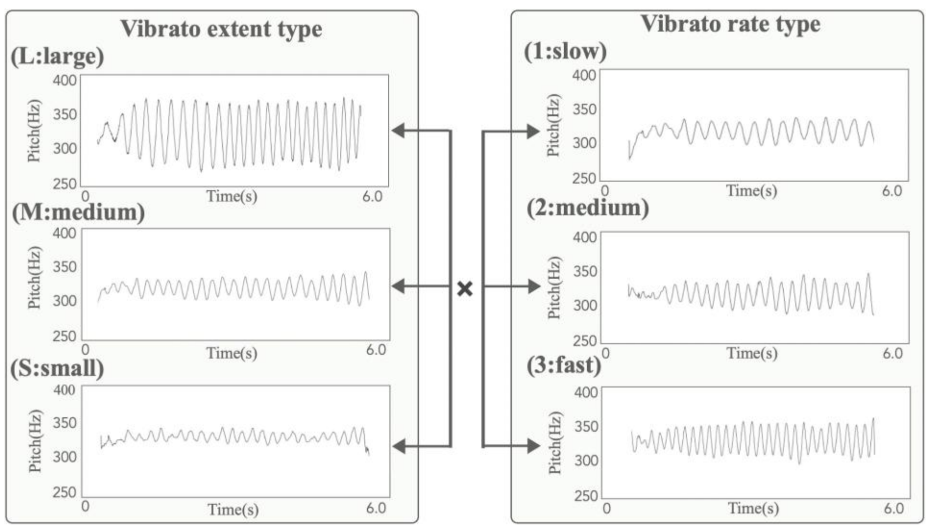

Fig.1. Sound stimuli were created with nine patterns each for tenor (T) and soprano (S) (three patterns of vibrato extent × three patterns of vibrato rate). The three patterns of extent are: L (Large), M (Medium), and S (Small). The three patterns of rate are: 1 (Slow), 3 (Medium), and 3 (Fast).

4.2 Results

The impact of vibrato on emotion perception. The results of the PCA analysis are visualized in Figure 3, which presents the evaluations of 18 sound stimuli according to the six basic emotions. In the biplot of the first and second principal components (varimax rotation), the points correspond to the distribution of the 18 sound stimuli, with the directions of the arrows corresponding to the six basic emotions.

The first principal component, “Fear-Anger”, had a variance of 1.85, constituting 30.8% of the total variance. The second principal component, “Joy-Sadness”, constituted 24.7%. The variance of the two principal components totalled 55.5%. More than 90% of the variance was accounted for by the four principal components. As the data should have at least two principal components to determine the trend of the main variability, the number of principal components was set to two.

The first principal component, “Anger”, had a negative direction, while “Fear” and “Joy” were positive. In the second principal component, “Joy”, “Fear” and “Anger” had a positive direction, and “Sadness” had a negative direction.

The results demonstrate that the L2 and L3 of the tenor were distributed in “Anger”. As indicated in Figure 3(right), the rate of the vibrato was 5 to 6 Hz, and the vibrato extent was 150 to 200 cents, indicating that the large extent and fast rate correspond most closely to “Anger”. The soprano’s sound stimuli, L1 and M1, as well as the tenor’s S1, were distributed in “Fear”, with a rate of vibrato around 4.5 Hz and a medium extent of vibrato at 50 to 100 cents. The soprano’s sound stimulus, M3, was distributed in “Joy”, indicating that a medium extent and fast rate of singing vibrato corresponds to “Joy”. The sound stimuli, S2, by both the soprano and tenor, were distributed in “Sadness”. The rate of vibrato was 5 to 5.5 Hz and the parameter value of extent was 0–50 cents, indicating that a small extent and medium rate of vibrato corresponded to “Sadness”.

Table 4. In the emotional evaluation experiment of Experiment 2, 18 sound stimuli were used, and their sound pressure levels were standardized to 60 dB to control for volume variations. The left column represents the vocal registers and vibrato patterns, whereas the right column details the vibrato extent and rate parameters.

Registers	Extent type	Range	Rate type	Extent(cents)	Rate(Hz)
Tenor(T)	L	150~200cents	1	163.03	4.85
			2	176.63	5.16
			3	171.61	5.65
	M	50~150cents	1	107.66	4.39
			2	109.53	5.02
			3	135.83	5.54
	S	0~50cents	1	32.19	4.22
			2	30.01	5.20
			3	38.41	5.60
Soprano(S)	L	90~130cents	1	95.47	4.51
			2	101.37	4.92
			3	121.29	5.46
	M	50~90cents	1	65.44	4.34
			2	61.96	4.88
			3	75.84	5.52
	S	0~50cents	1	42.90	4.50
			2	38.83	4.97
			3	47.85	5.52

5 Discussion

The average vibrato "RATE" was 5.11 Hz, ranging from 4.20 to 6.02 Hz, aligning with prior studies such as Prame’s 6.0 Hz range (5.5–6.7 Hz) [24] and Hirano’s 4.1–6.6 Hz range for 23 singers [41]. The soprano’s vibrato “EXTENT,” limited to 4–7 Hz and 30–200 cents, reflected traditional vibrato boundaries, likely due to extensive training and controlled vocal technique. A strong positive correlation was observed between vibrato “EXTENT” and spectral “CENTROID,” indicating broader neuromuscular and aerodynamic adjustments with increased extent. However, no significant correlations were found between vibrato parameters and “PITCH” or “INTENSITY,” consistent with earlier findings [42].

Fig.2. The graphical user interface of our experiment.

6 Conclusion

This study examined how vibrato and other acoustic characteristics contribute to emotional perception in singing. The experiment confirmed that variations in vibrato rate and extent allow listeners to infer emotions, with significant differences observed across the four basic emotions: Anger, Fear, Joy, and Sadness. Principal component analysis revealed that "Fear–Anger" and "Joy–Sadness" were the primary dimensions, with Anger showing greater vibrato extent and Sadness showing less. Vibrato rate for Fear, around 4 Hz, induced significant pitch variation, potentially evoking feelings of dread. Additionally, the study found a positive correlation between vibrato extent and spectral centroid, while other vibrato parameters, such as rate, extent, onset delay, and note duration, were largely independent. Exceptions, like the negative correlation between vibrato onset delay and extent in tenors, were attributed to differences in training. These findings suggest that professional opera singers can independently manipulate vibrato parameters to convey nuanced emotional expressions.

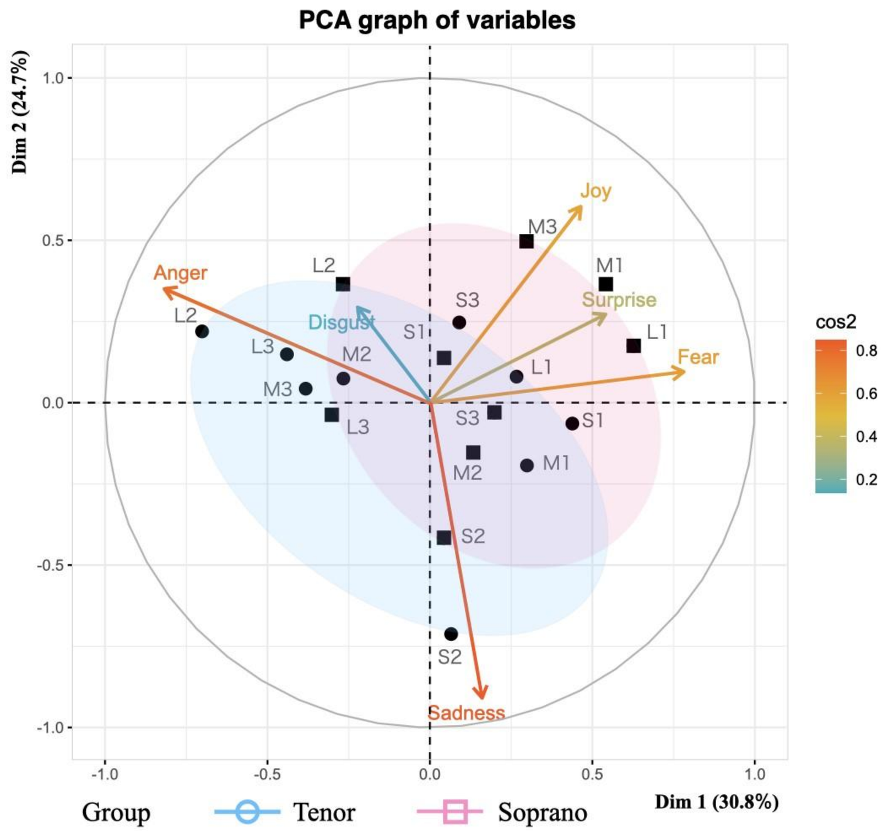

Fig.3. The left figure shows a PCA biplot for the first and second principal components, showing a scatterplot of loadings (arrows), correlations, and sentiment for each variable. The length of the arrows approximates the variance of each variable, while the angle between variables indicates their correlation. Dim 1: first principal component 1; Dim 2: second principal component 2. The relevant numerical values can refer to Table 4.

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