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A Preliminary Investigation into the Current Status and Prospects of Visual Analysis of Acoustic Properties for the Singing Voice

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Abstract. Acoustic analysis is an objective measurement approach commonly used in the assessment of the singing voice. It involves parameters such as fundamental frequency, formant, intensity, vibrato pattern, and others, providing parameters on the internal view of the singing voice. However, presenting multi-dimensional voice data from multiple audio files simultaneously in current studies is a challenging task. This review summarises existing methodologies, highlighting their limitations and proposing future directions, particularly integrating Information and Communications Technology to enhance vocal analysis visualisation. This study also emphasises the critical role of advanced visualisation methods in enhancing the accuracy, accessibility, and impact of vocal analysis, and it aims to enhance the understanding of vocal mechanisms, support singers and students in vocal practice, and drive forward the field of vocal research through innovative, user-friendly technologies. Our future work will focus on developing interactive visualisation techniques to simplify and enrich the interpretation of vocal data, making complex acoustic properties accessible to a broader audience, including non-experts.

Keywords. Acoustic Analysis, Acoustic Property, Graph Drawing, Multi-dimensional Parameters, Singing Voice, Visual Analysis, Vocal Analysis

1. Introduction and Background

Acoustic analysis is an objective measurement in the field of singing voice research [1]. Understanding relevant properties is essential for improving vocal techniques, delivering appropriate vocal expression, and accurately conveying music styles. Despite significant progress in this field, most existing research has primarily focused on voice analysing using software such as VoceVista [2], Praat [3] and Sonic Visualiser [4]. While these tools are powerful in providing visual representations, including spectrograms, spectra, and electroglottography (EGG) of acoustic parameters, they often have limited capability when it comes to comparing the multi-dimensional structure of the singing voice across multiple audio samples. This limitation is crucial to address for a holistic understanding

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of the singing voice, especially in the analysis of vocal techniques in crossover singing [5]. Praat, an open-source tool, offers black-and-white graphical analysis and can directly extract parameters such as pitch, formant, intensity, and vibrato. Meanwhile, Sonic Visualiser and VoceVista both provide colour visualisation options, with Sonic Visualiser also offering real-time spectrogram analysis of acoustic data.

Vocal technique involves coordinating the respiratory, phonatory, and resonance systems [6-8]. Breathing patterns and vocal fold vibrations affect sound pressure level (SPL), which influences loudness and voice quality through subglottal pressure (*P*sub) [9]. Phonation controls the fundamental frequency (f_o), impacting pitch and varying with muscle dominance [7, 10-11]. The resonance system, including the larynx, tongue, jaw, lips, soft palate, and nose [10, 12-13], shapes vowels, consonants, and timbre [12, 14], which are analyzed using parameters like formant, jitter, and shimmer [7, 15]. Voice quality, influenced by anatomical and physiological factors [10], is a multi-dimensional construct [1] and key to distinguishing timbre and vocal style [16]. Acoustic analysis, often used to assess voice quality [1], primarily relies on spectrograms and spectra, but current visual tools like line [2, 17-21], bar [20, 22] charts, and scatter plots [20, 23-26] struggle to display multiple dimensions of acoustic data, such as frequency, amplitude, vibrato, and duration [27]. The lack of interactive features [6] further complicates complex analysis and comparison.

Despite advancements in vocal analysis, a major challenge remains the usability and accessibility of methods for handling complex vocal datasets. Many tools require significant technical expertise, limiting their widespread adoption. This review aims to summarise the advantages, disadvantages, and challenges of existing vocal analysis methodologies. It will also explore future directions, particularly focusing on applying Information and Communications Technology (ICT) methods to address gaps in visualisation applications for singing voice research. The review will evaluate the importance of visual graphics in analysing multiple acoustic data attributes, providing preliminary assessments and guidance for further study.

In the following parts of this paper, Section 2 provides the methodology of this work. An overview of existing works is given in Section 3. Section 4 presents the challenges of ICT adoption in the field. Future directions are discussed in Section 5. Section 6 summarises the essential findings and outlines our future research.

2. Methodology

This study is an integrative review that brings together literature from acoustic analysis in singing voice research and data visualization methods to provide an interdisciplinary perspective. The aim is to utilise visualisation technologies to address gaps in the graphical representation of acoustic research on singing voices as a preliminary step and to propose new research directions. Accordingly, this literature review integrates relevant findings from these two disciplines, identifies their key themes and theories, and proposes comprehensive conclusions.

To ensure a high-quality selection of studies for this literature review, we conducted a thorough search using the Google Scholar database, covering publications from 2000 to 2024. Keywords "acoustic analysis" and "singing voice" were employed to identify relevant literature. The selection process involved a systematic review and analysis of 22 research papers, applying strict inclusion criteria focused on the relevance of the papers, their discussion of technological advancements, practical implementations, and the citation impact. This assessment was conducted by two experts with extensive experience in their respective fields. One expert in data analysis ensured the selected papers met high technical standards and aligned with current technological trends. The other, an experienced researcher in singing, brought deep domain knowledge to ensure novel methodologies that advanced acoustic properties in voice analysis, resulting in a well-rounded and high-quality selection.

The selected literature was categorised based on key features, advantages and disadvantages, acoustic analysis tools, visualisation tools, and statistical techniques. This approach provided an overview of existing studies, identified challenges, and pointed to future directions. Key themes, methodologies, findings, and gaps were extracted, enabling a detailed understanding of the research landscape. Each paper's quality was assessed for methodological rigour, relevance, and significance, ensuring the inclusion of high-quality studies. The synthesis involved comparing findings, identifying recurring themes, and summarising advancements and challenges in singing voice analysis. This comprehensive review offers insights into technological advancements, educational strategies, and future directions, while also identifying persistent challenges and suggesting future research to advance the field of acoustic properties analysis.

3. Overview of Existing Research

This Section provides a comprehensive overview of the existing research landscape in singing voice analysis, by synthesising these key features, advantages and disadvantages.

- Key Features in Vocal Analysis

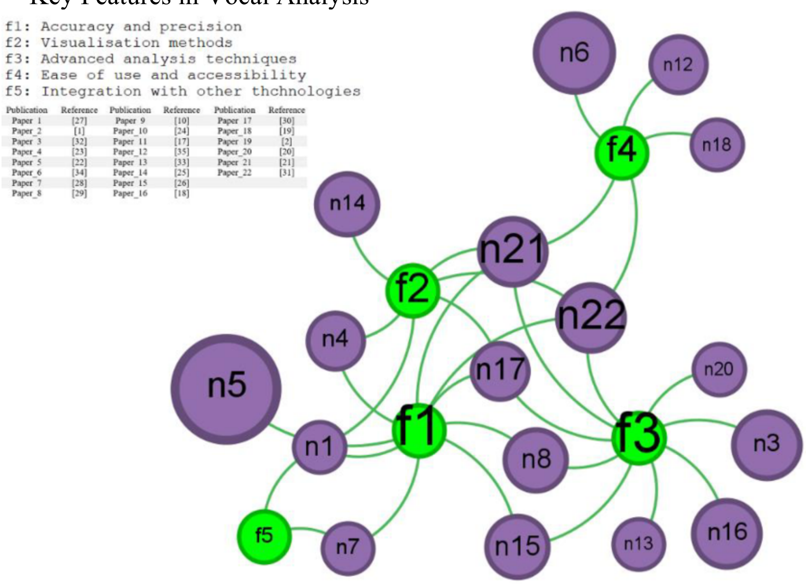

Figure 1. Key features and publications' social network.

Accuracy and precision are crucial for reliable vocal assessments, ensuring that tools and methods deliver dependable results. Studies [21-23, 26-31] emphasize the importance of these elements in creating robust vocal analysis frameworks. Visualisation methods like spectrograms are key for interpreting acoustic data, helping identify patterns, correlations, and anomalies. However, visualisation tools often struggle with truly multi-dimensional data [21, 23, 25, 27, 30-31]. Advanced analysis techniques, including machine learning and statistical methods, are increasingly prevalent, providing deeper insights into vocal properties and enhancing assessment accuracy. Studies [18, 20-21, 26, 29, 30-33] highlight how these methods offer a more nuanced understanding of vocal phenomena.

The ease of use and accessibility of vocal analysis tools are vital for broader adoption in research and practice. Research stresses the need for user-friendly tools that can be easily integrated into various settings, making them accessible to a wider audience [19, 21, 31, 34-35]. The integration with other technological fields is a growing trend, enhancing the scope and applicability of vocal analysis. Interdisciplinary approaches, such as combining acoustics, physiology, and pedagogy [27-28], or integrating advanced digital tools [27], lead to more sophisticated methods for understanding and improving vocal performance.

Figure 1 shows connections between key features and publications in this review. Nodes without connections are removed, with node size based on citations and label font size on connection degree. It highlights a lack of focus on ease of use, accessibility, and technological integration, while visualisation tools struggle with high-dimensional datasets. Note that node size does not reflect the importance of publications and features.

- Advantages of Existing Research

Existing research on acoustic analysis for the singing voice presents several notable advantages. Many studies have highlighted acoustic analysis as an objective measurement that provides trustworthy parameters for assessing the singing voice [1-2, 21-22, 31]. Some studies have also incorporated subjective measurements of auditory perception of the singing voice, considered the influence of emotional expression and language articulation [19, 21, 26-27, 29-30, 32], as well as variation of physiology and anatomy [10, 17-18, 20-21, 26, 29-30] on the acoustic properties of the singing voice. Comprehensive methods enhance the understanding of vocal mechanisms, develop vocal pedagogy and support both vocal research and practical vocal performance applications.

Moreover, numerous studies have introduced innovative methods and tools, such as BioVoice, RespTrack System, and advanced acoustic analysis software [1, 18, 26-27]. Furthermore, a few studies have combined ICT to propose visualisation of the singing voice for more effective feedback [1, 21, 27, 35]. Other studies have delved into the linguistic properties of the singing voice under the context of musical style through acoustic analysis [16, 33]. These interdisciplinary approaches broaden the scope and impact of vocal analysis research, promoting collaborations across different fields and leading to more comprehensive and innovative solutions.

- Disadvantages of Existing Research

Current research on acoustic properties in singing voice analysis has predominantly focused on individual song segments, utilising simple data tables and basic charts. They have limited the exploration of data from multiple sources and resulted in visual analyses that are either overly simplistic or excessively complex, especially in the context of crossover singing research [5, 21, 30]. Consequently, a comprehensive view of vocal characteristics across musical styles has been constrained. Although significant advancements have been made in analysing single song segments, these methods fall short in integrating diverse musical data into a unified analysis. Additionally, many studies suffer from small sample sizes, which affects the generalisability of the findings [18, 21, 24, 26, 29-30, 32]. Increasing sample sizes in future research would enhance the robustness and applicability of the results. Notably, the complexity of the methods and the steep learning curve required for effective use hinder widespread adoption [21, 26-

27, 29-30, 34]. The dependence on sophisticated technology and software can be a barrier, particularly in less-resourced settings [21-22, 27]. Developing more accessible and affordable tools would help mitigate this issue and make vocal analysis more widely available. Furthermore, the accessibility and cost of tools and methods are significant drawbacks, limiting their use in broader educational or clinical settings [21, 27, 35].

4. Challenges of ICT Adoptions in Vocal Analysis Technologies

Challenges particularly in managing and integrating the multiple dimensions of vocal data, which can hinder their usability and accessibility. Additionally, interpreting visual and acoustic data requires specialised expertise, and existing methods often struggle to capture the full range of vocal characteristics effectively. To address these challenges, ongoing efforts are needed to refine tools and techniques, with a focus on improving their ability to handle and integrate diverse data attributes.

Acoustic Analysis Tools: Acoustic analysis software has been pivotal in vocal research, providing tools for measuring various vocal parameters such as formant, intensity, jitter, and shimmer [35], as well as spectrogram, spectrum, and EGG [23, 25, 27, 34-35], have been widely used in research. They are sophisticated tools designed for detailed acoustic analysis, providing high precision and a broad range of analytical features [23]. Spectrograms are used to visualise vocal signals over time, including the fundamental frequency and its harmonic series, as well as the intensity and vibrato parameters [21], the interface of a spectrogram is shown in Figure 2. The concentrated areas in the harmonic series are known as formants [7], labelled F_1, F_2, F_3, F_4, F_5 and so on [36]. Among them, F_1 and F_2 are associated with the vowels being sung, while F_3 to F_5 form a singer's timbre [12]. Spectra are displayed in two dimensions, showing frequency peaks and amplitude for a short time slice [21]. They all provide a detailed insider view of vocal information and its variations [23, 25, 27]. However, most existing tools are designed for analysing individual audio files. When dealing with multi-dimensional data that requires comparing multiple audio files, these tools can only provide visual comparisons or require users to click a movable cursor to read and extract parameters [21], which can then be compared in other software. This manual selection process can reduce the accuracy of the data.

Visualisation Tools: They are essential for presenting vocal data visually [25, 27], which have unique advantages but also face challenges when addressing multiple data attributes. Although effective for summarising complex data, heat maps can oversimplify information, potentially leading to subjective interpretations and missing nuanced details. Radar Charts are useful for identifying overall patterns across various dimensions but can become cluttered when too many variables are included. This clutter can limit their effectiveness for detailed analysis and may obscure specific trends within the data. Scatter Plots display relationships between two variables, helping to identify correlations and outliers [25]. While straightforward to create and interpret, scatter plots are limited to examining two variables simultaneously. This restriction can be problematic when uncovering more complex patterns or interactions among multiple vocal parameters.

Statistical and Machine Learning Techniques: Machine Learning can manage large and complex datasets, uncovering patterns that might not be apparent through traditional methods [18, 33]. However, it requires substantial data for training and is computationally intensive, and this can limit accessibility and make it challenging to apply relevant techniques to diverse or underrepresented datasets. Statistical analysis employs various techniques to examine vocal data and derive insights [18, 20, 32]. While offering robust tools for data interpretation, statistical methods often require advanced knowledge and can be time-consuming. This complexity can be a barrier for researchers aiming to integrate and analyse multiple data attributes effectively. These techniques are crucial for analysing vocal features and classifying vocal qualities [18, 20, 33]. Despite their capabilities, adopting them also encounters challenges in handling complex datasets.

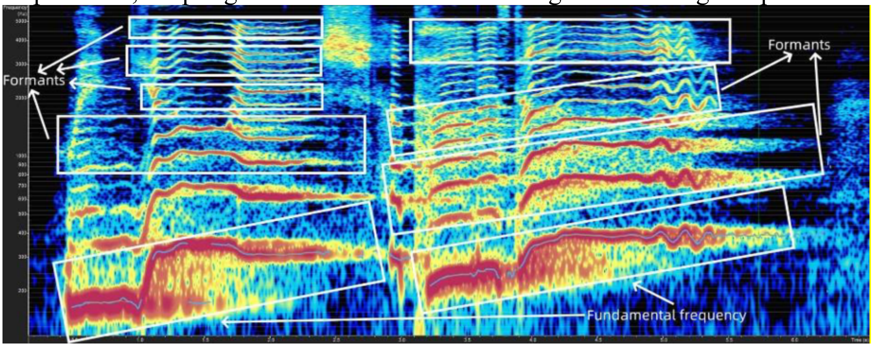

Figure 2. A spectrogram for a segment of audio in the jazz style is extracted from VoceVista. The X-axis represents time, and the Y-axis represents the frequency of the sound. The lowest line corresponds to the fundamental frequency, which is related to pitch. Above that are the harmonics that are superimposed in multiples, with concentrated areas representing formants that determine the timbre. The colour shade is related to voice intensity, and the wavering of the harmonics corresponds to vibrato, while a flat line indicates the absence of vibrato [7, 11].

5. Future Directions

This chapter explores the key future directions for singing voice analysis technologies, focusing on their adoption and impact on research and practice.

Broader Studies and Integration of Multimodal Data: Expanding studies to include larger and more diverse sample populations is crucial [18, 29, 32]. Broader participant groups help validate findings and gain a comprehensive understanding of vocal characteristics across different demographics. Integrating vocal data with other physiological and environmental data can offer a holistic view of vocal performance and its influencing factors [19, 24, 27], allowing researchers to explore complex interactions and gain deeper insights into how various variables affect vocal characteristics.

Advanced Analytical Techniques: Developing sophisticated analytical techniques is crucial in this field [18, 20, 32-33]. Emerging methods such as advanced machine learning algorithms and statistical models, promise deeper insights into vocal properties and patterns. Leveraging large datasets and refining algorithms will allow researchers to uncover previously inaccessible patterns and insights.

Integration into Educational Curricula: Incorporating new findings and technologies into vocal training curricula is essential for enhancing educational outcomes [17, 23, 27]. The integration will improve the quality of vocal training and equip the next generation of researchers and practitioners with the skills to utilise these advanced technologies.

Technological Enhancements: More accessible technologies are vital for broadening the use of vocal analysis [22, 27, 33]. Enhancements in software and hardware will make these tools more user-friendly and widely applicable, facilitating greater adoption in both research and practical settings.

Improved Usability of Tools: Making vocal analysis tools more user-friendly and accessible to non-experts is essential for broader adoption [34-35]. Simplifying interfaces, providing intuitive designs, and offering comprehensive training resources will enable users from diverse backgrounds to engage with these technologies more effectively. Enhancing usability will facilitate the integration of vocal analysis tools into various contexts, including educational and clinical settings.

Real-time Analysis Capabilities: Real-time feedback and analysis are critical for improving the immediacy and relevance of vocal assessments [17, 23]. These capabilities will facilitate dynamic and interactive research and training, allowing users to make adjustments as needed. This development will enhance the practicality and effectiveness of vocal analysis tools in both research and applied settings.

Data Visualisation Methods: Applying advanced visualisation methods to analyse multiple acoustic data attributes is an emerging area of research. Interactive visualisation techniques can offer new insights into complex vocal data by presenting it in more accessible and interpretable formats. These methods will aid in identifying patterns and correlations across diverse data attributes, enhancing the overall analysis of vocal performance. Future research should focus on developing and refining these interactive visualisation techniques along with improving the comprehensiveness and clarity of vocal data analysis. Our previous work generated a dashboard that includes a wind rose, statistical table, and parallel coordinates graph, along with interaction features. This dashboard aims to offer users an easy-to-use tool for analysing multiple attributes of singing voice data, please refer to [5].

6. Conclusions and Future Work

This study reviews existing research on vocal analysis, evaluating current methods, identifying challenges, and outlining future directions. We highlight the limitations of existing methods, which often involve complex, disparate data that are difficult to integrate and interpret. However, the literature was collected based on keywords, citations, and the researcher's experience. Consequently, the final conclusions may have subjective restrictions. To address this issue, we plan to involve more experts in the field to provide a more comprehensive and objective perspective.

Our future work will focus on the potential of advanced visualisation methods. We aim to refine and implement interactive visualisation techniques to enhance the understanding of vocal characteristics. By improving the interpretability of vocal data through these methods, we will present data in an easy-to-understand manner with interactive features. These techniques offer more precise and intuitive representations of multifaceted acoustic data, making it accessible even to those without professional expertise in the field. This approach aims to address current challenges related to data complexity and integration, promoting the broader adoption of innovative technologies in vocal research and pedagogy. Furthermore, it will provide additional support to singers and students engaged in vocal performance practice, helping them understand vocal mechanisms more effectively. Figure 3 offers a dataset sample of the recorded song "When You Wish Upon a Star" (Leigh Harline, Ned Washington) in four vocal styles. We will conduct different types of graphs, validate them with experts in the singing field, and determine suitable structures for presenting the multiple properties of the dataset.

In conclusion, this study underscores the importance of visualisation methods in advancing acoustic analysis of the singing voice. By focusing on easy-to-understand graphs for analysing multiple data attributes, we aim to enhance the accuracy, accessibility, and impact of vocal analysis technologies. This will drive the field forward and unlock new possibilities for understanding and improving vocal performance.

Style	Parameter	Lyrics	When	you	wish	upon	a	star
Jazz	Formant	F1	218.51	378.27	618.8	662.36	432.26	722.02
		F2	1362.18	1546.33	1612.37	1421.63	1405.45	1271.37
		F3	2469.66	2470	2691.12	2619.73	2144.68	1892.51
		F4	3548.42	3718.76	3585.08	3963.17	3504.34	3563.59
	Intenity	dB	78.91	79.19	77.17	80.28	83.43	80.08
	Jitter (local)	Periodicity	0.58%	0.96%	0.88%	1.67%	0.59%	0.74%
	Shimmer (local)	Oscillation amplitude	4.52%	8.50%	5.82%	10.72%	5.27%	6.48%
Pop	Formant	F1	239.58	362.92	455.14	432.97	361.47	703.24
		F2	1612.08	1318.98	1530.2	1117.07	961.04	1254.45
		F3	2398.62	2303.96	2494.23	1846.21	1919.35	1857.68
		F4	3518.02	3447.27	3509.84	3647.9	3531.67	3679.1
	Intenity	dB	78.76	79.16	73.21	82.32	83.21	76.43
	Jitter	Periodicity	0.48%	1.68%	0.94%	1.21%	0.25%	0.60%
	Shimmer	Oscillation amplitude	3.23%	8.99%	10.31%	2.49%	6.04%	5.99%
Legit	Formant	F1	203.52	406.24	461.94	475.03	577.7	685.42
		F2	1423.31	1195.32	1440.12	1009.99	1440.14	1245.53
		F3	2408.82	1826.23	2491.26	2001.66	2707.77	2338.06
		F4	3382.57	3072.05	3480.69	3764.16	4057.95	3844.08
	Intenity	dB	78.55	80.7	75.42	81.15	80.67	79.73
	Jitter	Periodicity	0.31%	0.93%	0.86%	0.35%	0.22%	0.61%
	Shimmer	Oscillation amplitude	2.28%	6.94%	5.58%	2.66%	4.58%	5.07%

		Lyrics	无	论	你	身	在	何	处
Mandarin	Formant	F1	211.46	406.98	364.52	385.57	336.79	419.28	453.9
		F2	1127.22	1255.94	1429.07	1478	1102.66	994.13	1337.48
		F3	2270.53	2218.28	2673.54	2205.95	2229.88	1982.12	2075.86
		F4	3330.85	3528.52	3241.36	3616.63	3478.66	3495.82	3548.75
	Intenity	dB	80.49	79.56	76.02	78.32	81.04	79.9	74.75
	Jitter	Periodicity	0.44%	2.18%	0.58%	0.64%	0.90%	0.31%	0.89%
	Shimmer	Oscillation amplitude	3.05%	14.54%	5.00%	2.80%	5.42%	2.58%	5.11%

Figure 3. Sample data of acoustic properties for the singing voice.

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