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The importance of Acoustic Analysis in Linguistic Studies

أهمية التحليل الفيزيائي في دراسة الظواهر اللغوية

Emphasis and Long Vowels in Arabic Language as Model

التفخيم والحركات الطويلة في اللغة العربية أنموذجا

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ABSTRACT

Acoustic analysis provides objective insights into speech production by measuring key acoustic parameters. In Arabic linguistics, it enables precise study of phonetic features such as consonant emphasis and vowel contrast, which are difficult to assess through auditory analysis alone. This article explores the historical evolution of acoustic analysis, its key parameters, and its applications in language learning, speech therapy, and linguistic research. The findings highlight the method's role in improving pronunciation training, diagnosing speech disorders, and advancing Arabic phonetics through AI-driven tools and interdisciplinary collaboration.

KEY WORDS: Acoustic analysis, linguistic phenomena, Arabic phonetics, Arabic vowels, emphatic consonants.

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الملخص

يوفّر التحليل الفيزيائي رؤى موضوعية حول إنتاج الكلام من خلال قياس المعايير الصوتية الرئيسية. يمكّن هذا التحليل، في اللسانيات العربية، من دراسة دقيقة للسمات الصوتية مثل التفخيم والصوائت العربية، وهي سمات يصعب تقييمها من خلال التحليل السمعي وحده. يستعرض هذا المقال التطور التاريخي للتحليل الفيزيائي، وخصائصه الأساسية، وتطبيقاته في تعلم اللغة، وعلاج النطق، والبحث اللساني. تسلط النتائج الضوء على دور هذه الطريقة في تحسين تدريب النطق، وتشخيص اضطرابات الكلام، وتطوير الدراسات في الصوتيات العربية من خلال أدوات مدعومة بالذكاء الاصطناعي والتعاون المتعدد التخصصات.

الكلمات المفتاحية: التحليل الفيزيائي، الظواهر اللغوية، الصوتيات العربية، الصوائت العربية، الحروف المفخمة.

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- Introduction

Acoustic speech analysis is a powerful method for studying speech production by extracting measurable physical characteristics that reflect the physiological processes behind human communication. Widely used in speech pathology, linguistics, and voice research, it provides objective data to assess and diagnose speech impairments. By analyzing specific acoustic parameters, specialists can gain deep insights into voice quality, articulation, and fluency, aiding both clinical evaluations and scientific studies. So acoustic analysis has become an essential method for objectively studying the phonetic characteristics of languages. In the case of Arabic, it enables precise investigation of two crucial linguistic phenomena: consonant emphasis and vowel length contrast. These elements, difficult to grasp through auditory analysis alone, reveal their full complexity when examined through their acoustic correlates.

The applications of this method are vast:

- In phonetics, it allows for the analysis of the characteristics of vowels and consonants.
- In sociolinguistics, it reveals regional or social variations.
- In speech therapy, it aids in diagnosing speech disorders.
- In technology, it is used for speech recognition and voice synthesis.

Acoustic analysis significantly contributes to advancements in modern linguistics (**Grabowski,** 2023). As mentioned above, it allows for precise investigation of two crucial linguistic phenomena in Arabic language: consonant emphasis and vowel length contrast (short vs. long vowels). These features reveal their complexity when examined through acoustic correlates.

The application of acoustic speech analysis in Arabic is particularly relevant for studying:

- Emphatic consonants (ṭ, ḍ, ṣ, ẓ) and their coarticulatory effects (Ferrat, 2024).
- Vowel system and its phonological length contrasts (Alotaibi & Hussain, 2016).
- Dialectal variations across Arab countries (Embarki, 2013; Mitrofanova & Tuller, 2021).

This approach addresses the limitations of traditional auditory analysis through objective measurements (Ladefoged & Johnson, 2014), crucial for:

- Teaching Arabic as a foreign language.
- Diagnosing speech disorders.
- Linguistic engineering.

1. History of Acoustic Analysis

Abbot Jean Rousselot was the first to emphasize the importance of acoustic phonetics in his work *Principles of Experimental Phonetics*, published in two volumes (1897 and 1901). His research laid the foundation for experimental phonetics as an empirical science, paving the way for applications in education, pronunciation correction, and speech therapy.

In the early 20th century, researchers such as Gunnar Fant (Sweden) made significant contributions to speech analysis, particularly in the study of formants—resonant frequencies of speech (Fant, 1960). In France, Joseph Fourier's work (1768–1830) on signal processing played a crucial role in the development of spectral analysis techniques. His mathematical models led to the Fourier Transform, a fundamental principle in sonagraphic analysis and a cornerstone of modern acoustic phonetics.

In the United States, pioneering work by Alexander Graham Bell (engineer and speech scientist), Edward Scripture (experimental psychologist and phonetician), and Harvey Fletcher (physicist specializing in auditory perception) led to major advancements in speech research. Their contributions were crucial in developing devices for auditory rehabilitation and speech disorder treatment. Moreover, institutions such as the American Speech-Language-Hearing Association (ASHA), founded in 1925, played a key role in incorporating computational technologies into clinical phonetics.

Despite these advances, our country has lagged in integrating acoustic analysis tools, particularly in speech therapy and linguistics. The first to develop the idea of multidisciplinary research incorporating technology (acoustic analysis for speech and language processing) was undeniably Professor Abderrahmane Hadj Salah (1927-2017). After creating the Institute of Linguistics and Phonetics (ILP) in the 1970s, he significantly contributed to creating the CRSTDLA (Scientific and Technical Research Center for the Development of the Arabic Language) to promote an interdisciplinary scientific approach, bringing together linguists, engineers, and clinicians.

The evolution of acoustic speech analysis can be classified into three important stages:

- 1897–1901: Rousselot lays the foundations of experimental phonetics.
- 1950s: Fant systematizes formant analysis.
- 21st century: Digitalization with Praat and AI tools (Boersma & Weenink, 2023).

2. Acoustic Parameters and Their Importance

Key acoustic speech parameters include:

A. Fundamental Frequency (F0) and Intonation

The fundamental frequency, often called pitch, represents the number of vibrations per second of the vocal cords in the speech apparatus. It corresponds to the voice's pitch and helps distinguish between a low voice and a high voice. It plays a key role in intonation and expressiveness. For example, an interrogative sentence has a rising melody at the end, while a declarative sentence has a descending intonation. It also helps differentiate between a voiced consonant and its unvoiced counterpart. In clinical linguistics, abnormalities in F0 can reveal disorders such as dysphonia or Parkinson's disease, where patients often have a monotone speech.

B. Formants (F1, F2, F3)

Formants reflect vocal tract resonance frequencies. They enable the acoustic analysis of physiological phenomena occurring in the cavities of the vocal tract:

Symbol: Fi, where *i* represents the i-th cavity of the vocal tract.

Relationship to cavity volume: Inversely proportional.

Unit: Hertz (Hz).

- Pharyngeal cavity: F1
- Oral cavity: F2
- Cavity between the teeth and lips: F3

Formants are essential for shaping and distinguishing vowels and contributing to overall speech intelligibility. Vowels are primarily described by their formant frequencies (Harrington, 2010):

- **F1 (first formant):** Reflects mouth opening (higher values = more open vowels like /a/).
- **F2 (second formant):** Indicates tongue position (higher values = front vowels like /i/, lower values = back vowels like /u/).
- Plotting **F1 vs. F2** produces a vowel space diagram, illustrating contrasts between vowels in a language These measurements are also essential for studying dialects or articulation disorders.

Applications of formant analysis include:

- **Language learning:** Identifying and correcting pronunciation errors, particularly for vowels that do not exist in a learner's native language (Fouz-González, 2019).

- **Clinical diagnostics:** Detecting articulation disorders, such as those associated with cleft palate, dysarthria, or post-stroke aphasia. Formant analysis is also valuable for monitoring speech recovery after surgery or therapy. For example, patients who have undergone a laryngectomy may exhibit altered formant frequencies, requiring specialized speech therapy to regain clarity (Ferrat & Guerti, 2012).

C. Phoneme Duration and Speech Rhythm

This parameter evaluates speech rhythm, fluency, and timing, reflecting a speaker's ability to control airflow and articulation.

- **Rhythmic structures across languages:** Different languages exhibit distinct rhythmic patterns.
- **Common learner difficulty:** Arabic speakers learning English can pronounce all syllables with equal duration, which can negatively impact fluency and comprehension. Acoustic analysis, by measuring syllable and pause duration, helps learners adapt their rhythm to the target language.
- **Clinical significance:** Irregular phoneme duration is often associated with speech disorders such as stuttering, dysarthria, or apraxia of speech. These conditions are frequently observed in individuals with stroke or neurodegenerative diseases. For instance, someone with dysarthria may produce prolonged vowel sounds due to difficulties in coordinating speech muscles, resulting in slow and effortful speech (Zeroual et al., 2021).

D. Intensity and Stress Patterns

The amplitude of speech sounds determines how loud or soft speech is perceived, playing a key role in speech clarity and emphasis.

- **Importance of syllable stress:** In languages like Arabic, English, Spanish, or German, syllable stress is crucial for meaning and intelligibility. Stress placement in Arabic is predictable and depends on syllable structure. Misplaced stress can lead to misunderstandings, as stress patterns are integral to word recognition (Domahs et al., 2014).
- **Common learner difficulty:** French speakers often struggle to emphasize stressed syllables adequately, as French has a more even syllable stress pattern compared to languages like English or Arabic. So acoustic analysis can visually demonstrate where stress should be placed and help learners improve their modulation of intensity, leading to more natural and accurate pronunciation.
- **Clinical significance:** Disorders related to amplitude and stress include:
  - **Hypophonia** (reduced loudness), commonly observed in Parkinson's disease. Many Parkinson's patients progressively lower their speaking volume, often without realizing it, making everyday conversations challenging (Ferrat, 2009).

- **Excessive loudness**, which may indicate vocal hyperfunction or compensatory speech mechanisms in individuals with hearing impairments.

While stress in Arabic is not as prominent as in English, it still significantly affects pronunciation and clarity. Misplacing stress can lead to misunderstandings or make speech sound unnatural. In language learning, mastering Arabic stress patterns is essential for achieving accurate pronunciation and fluency.

3. Acoustic analysis Tools

The most commonly used tool in acoustic analysis is the spectrogram, which visually represents speech sound frequencies over time.

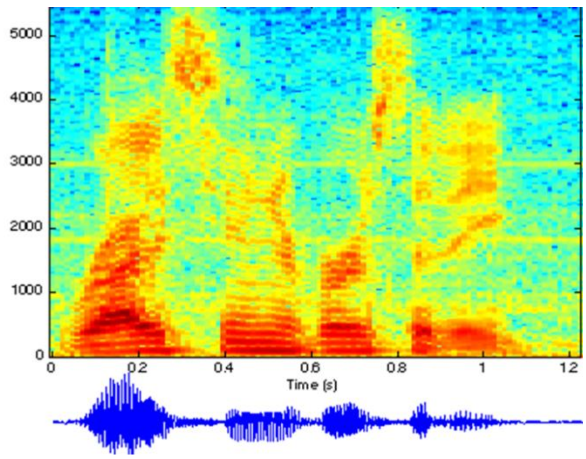

Figure 1. Spectrogram representation of speech

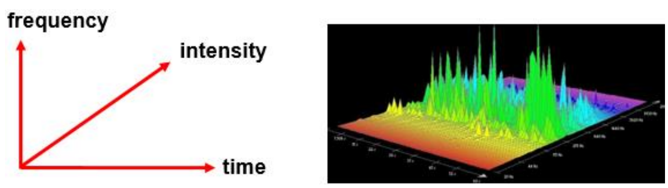

Figure 2. Three-dimensional (3D) representation of the spectrogram

Currently, many software programs facilitate speech analysis, including:

- **Kay Elemetrics** (commercial software);
- **Praat** (free software);
- **Vocalab, WinSnoori, WinPitch** (speech analysis tools available online).

The Praat software is widely used in phonetic research and acoustic analysis (Boersma & Weenink, 2023).

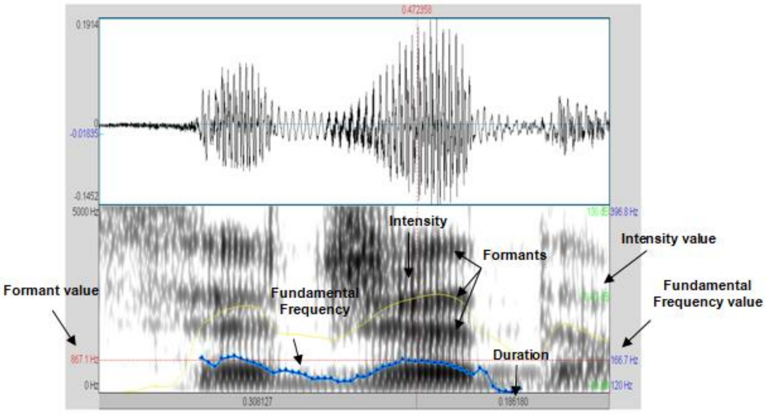

Figure 3. Extracting the acoustic properties of speech using Praat

4. Notions of Vowels and Emphasis in Arabic Language

In this section, we provide a brief overview of long and short vowels in Arabic and the distinction between these two phonetic and phonological characteristics, emphasis in Arabic from an articulatory perspective, and the difference between an emphatic consonant and its non-emphatic counterpart, having the same place of articulation and manner of articulation (voiced/unvoiced, plosive/fricative).

4.1. Short vs. Long Vowels

The phonetic system of the Arabic language has six vowels, three short vowels (/a/, /i/, /u/) and three long vowels (/aː/, /iː/, /uː/). Arabic has a crucial phonological contrast between the short and long vowels, which can change word meanings:

- /kataba/ (كَتَبَ) "he wrote" vs. /kaːtaba/ (كَاتَبَ) "he corresponded."
- /d͡ʒamal/ (جَمَل) “camel” vs /d͡ʒaːmal/ (جَامَلَ) “he flattered”

4.2. Emphasis in Standard Arabic

Emphasis (tafχiːm in arabic) is a distinctive feature of standard Arabic that affects a set of consonants called "emphatic". These emphatic consonants are: /ṭ/ ط, /ḍ/ ض, /ṣ/ ص, /ẓ/ ظ.

This phenomenon results from a complex configuration of the vocal tract involving (Embarki, 2013; Al-Tamimi & Khattab, 2018; Ferrat, 2024):

- Primary articulations : Coronal tongue placement, tongue retraction, slight lip rounding.
- Secondary articulations: Pharyngealization and velarization (Zawaydeh & de Jong, 2021; Heselwood, 2023).

This feature is phonemically distinctive (e.g., /tara/ (ثار) "to rebel" vs. /ṭara/ (طار) "to fly").

5. Acoustic Analysis of Arabic Vowels and Emphasis

In this article, we show some results of acoustic analysis conducted on these two linguistic features in Arabic and their importance in language learning.

5.1. Vowel Characteristics

The spectrographic analysis of some studies reveals quantifiable differences:

Table 1. Comparison between acoustic values of short/long vowels.

Parameter	Short Vowels	Long Vowels	Reference Study
Duration	80—100 ms	200—250 ms	Al-Ani (1970)
Formant stability	±15%	±5%	Khattab & Al-Tamimi (2013)
Intensity	68 Db	72 dB	Embarki (2013)

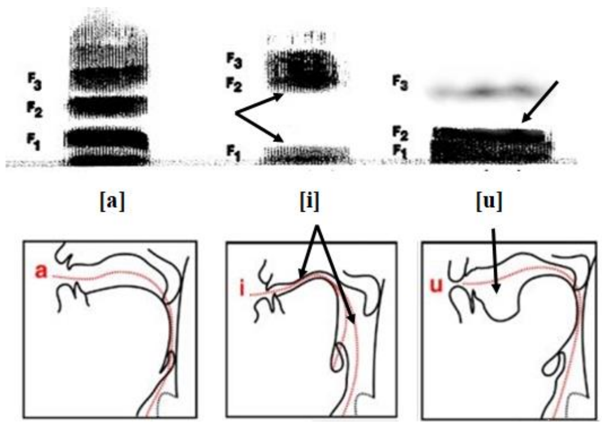

Figure 4. Spectral representation of the Arabic vowels

5.2. Emphasis Characteristics

The spectrographic analysis of some studies reveals:

Table 2. Comparison between acoustic values of emphatic/non emphatic consonants.

Parameter	Typical Values	Reference Study
F2 Frequency	↓ 300-400 Hz vs non-emphatic	Ferrat (2004)
Low Frequency Energy	↑ 800-1500 Hz	Khattab & Al-Tamimi (2013)
Consonantal Duration	↑ 15-20%	Zawaydeh & de Jong, 2021)

So Emphatic consonants show :

- Lower F2 (300–400 Hz drop vs. non-emphatics).
- Longer duration (15–20% increase).

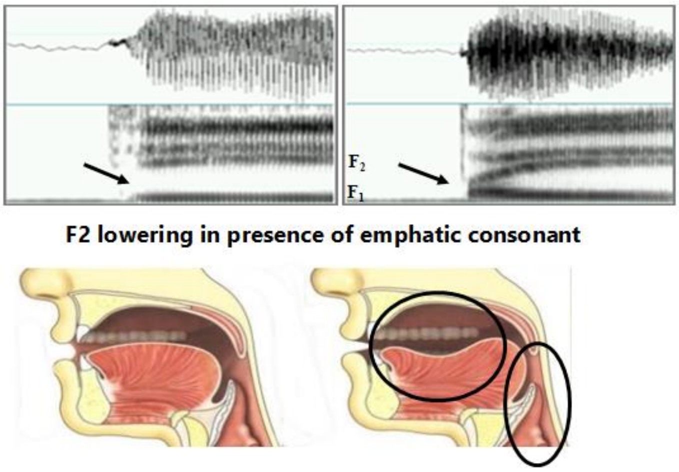

Figure 5. Lowering of the formant F2 in presence of emphatic consonant

5.3. Interaction Between Emphasis and Vowel Length

- Vowels after emphatics have lower F2 and longer duration (Ferrat, 2024).
- The effect is stronger on long vowels (ΔF2 = 120 Hz) than short vowels (ΔF2 = 80 Hz) (Ferrat, 2024).

6. Challenges for Learners

Language learning relies not only on understanding and acquiring vocabulary and grammar but also on mastering correct pronunciation, prosody, and intonation. Acoustic speech analysis helps identify and correct pronunciation errors, intonation differences, and rhythm variations among foreign language learners. Indeed, non-native learners of Arabic often find difficulties to pronounce the emphatic consonants. Thus, to learn Arabic, learners can visualize, using acoustic analysis software like Praat, the difference between an emphatic consonant and its non-emphatic counterpart (e.g., [t] vs [ṭ]), where the emphatic context shows a lower F2 formant in the following vowel. Also studies show that 78% of French speakers initially confuse /a/ and /aː/ in minimal pairs (Boula de Mareüil & Zeroual, 2015). Acoustic feedback training (using Praat software) helps reduce confusion errors to 22% in 5 weeks (Boula de Mareüil & Zeroual, 2015).

With advancements in speech technology and artificial intelligence (AI), modern learning tools can now analyze and provide real-time feedback on key speech parameters, making language acquisition more efficient and personalized. Today its applications span across phonetics, dialectology, sociolinguistics, psycholinguistics and language learning, and speech technology:

A. Phonetics, Dialectology and Sociolinguistics

Acoustic analysis compares vowel systems across languages/dialects. For example, Arabic vowels /a/, /i/, /u/ have distinct realizations in different regions (Al-Ani, 1970).

In dialectology and Sociolinguistics, which the comparison of vowel formants or intonation patterns can reveal regional or social variations (e.g., differences between Algerian and Tunisian Arabic) (Zawaydeh, 1999). In language acquisition, the acoustic analysis can track the development of phonetic contrasts in children, and detect pronunciation errors (e.g., /s/ (س) vs. /ṣ/ (ص) confusion).

B. Clinical Linguistics

Acoustic analysis offers several advantages. It enables the classification and characterization of speech disorders based on concrete data and facilitates objective assessments of impairment severity through measurable acoustic parameters (Kent & Kim, 2003). Advances in technology have made computational tools and online software increasingly accessible, providing valuable insights into the nature and degree of speech impairments (Duffy, 2020). So this method helps:

- Diagnose disorders such as dysarthria or stuttering.
- Evaluate therapy effectiveness by tracking acoustic parameter changes.

C. Language Learning

Acoustic analysis tools, like Praat software, help learners correct their pronunciation through visual feedback, allowing learners to compare their pronunciation to native speakers on a sonagramm (e.g., English speakers adjusting Arabic vowel articulation to distinguish between short and long vowels, articulation of emphatic consonants, geminate consonants, ...).

Also, it helps to improve sentence melody and rhythm, which are crucial for natural-sounding Arabic, such as the rising intonation in questions like **الولد ذاهب ؟** (al waladu đāhib ?, Is the boy going?) in figure 6.

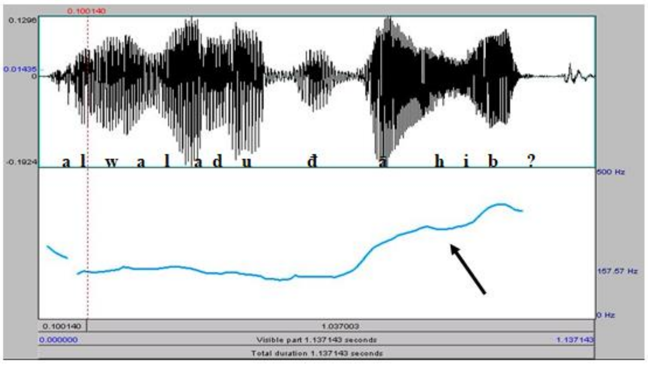

Figure 6. Intonation curve rising from low to high pitch

- Conclusion and Future Directions

Many concrete applications can stem from studies made possible by acoustic analysis. Notable examples include the Education by pronunciation training using acoustic feedback, and innovative pronunciation methods based on acoustics analysis, Speech therapy with rehabilitating articulation disorders in Arabic-speaking children and non native's learners, and Technology: Improving speech recognition and speech synthesis systems for Arabic.

Acoustic analysis has an important contribution to Arabic linguistics by objectifying subtle phonetic features (emphasis, vowel length, germination, ...), quantifying inaudible variations, and enabling new research and teaching methods.

To maximize benefits, we must:

- Train clinicians/linguists in acoustic software.
- Strengthen researcher-engineer collaborations.
- Adapt methods to understudied languages (e.g., Arabic dialects).

With Artificial Intelligence advancements, these tools will become even more accessible, opening new research and teaching possibilities.

Future directions that may arise from acoustic analysis include interlingual comparative studies and inter-dialectal variations, the development of interactive educational tools and e-learning exercises in the field of Arabic language learning, and the development of specific clinical tools in language pathology.

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