

Acoustic-Phonetic Characteristics in Children with Cerebral Palsy and Deaf Children Using PRAAT Software: A Comparative Exploratory Study

Caractéristiques acoustico-phonétiques chez les enfants atteints d'infirmité motrice cérébrale et les enfants sourds à l'aide du logiciel PRAAT: une étude comparative exploratoire

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Abstract:

This comparative acoustic study investigates the physical and phonetic characteristics of speech production in children diagnosed with cerebral palsy (CP) and profoundly deaf children compared against typically developing peers. Employing an exploratory descriptive-comparative multi-case design, acoustic data were elicited from a stratified cohort of six pediatric subjects ($N=6$) aged 7 to 8 years across three matched dyads: neurotypical controls, children with cerebral palsy presenting with dysarthric speech, and deaf children enrolled in specialized pedagogical rehabilitation. Sustained vocalizations of three cardinal vowels—[a], [o], and [i]—were recorded under standardized acoustic conditions and processed using PRAAT software. Evaluated parameters comprised fundamental frequency (F_0 / pitch), mean intensity, perturbation metrics (local jitter% and local shimmer%), vocal tract resonance formants (F_1 , F_2 , and F_3), and harmonics-to-noise ratio (HNR).

The empirical findings demonstrate pronounced acoustic divergences across clinical groups: children with cerebral palsy displayed aerodynamic instability, elevated shimmer, and restricted formant dispersion attributable to neuromotor spasticity and impaired speech-breathing coordination. Conversely, deaf children exhibited vocal destabilization characterized by marked pitch drift, elevated jitter and shimmer, and depressed HNR, reflecting the disruption of auditory feedback. Pronounced intra-group heterogeneity was documented, demonstrating that compensatory phonatory adaptations remain individualized. These outcomes validate the operational hypotheses, underscoring the necessity of integrating computerized acoustic assessment into speech-language therapy for diagnostic profiling and targeted rehabilitation.

Keywords: Acoustic-phonetic characteristics; Cerebral palsy; Deafness; PRAAT software; Formant analysis; Speech-language pathology.

Résumé:

Cette étude acoustique comparative examine les caractéristiques physiques et phonétiques de la production de la parole chez des enfants atteints d'infirmité motrice cérébrale (IMC) et des enfants profondément sourds, comparés à des pairs au développement typique. En adoptant un devis descriptif-comparatif exploratoire d'études de cas multiples, les données acoustiques ont été recueillies auprès d'une cohorte stratifiée de six sujets pédiatriques ($N=6$) âgés de 7 à 8 ans, répartis en trois dyades appariées : des témoins neurotypiques, des enfants atteints d'infirmité motrice cérébrale présentant une parole dysarthrique, et des enfants sourds bénéficiant d'une rééducation pédagogique spécialisée. Des vocalisations prolongées de trois voyelles cardinales — [a], [o] et [i] — ont été enregistrées dans des conditions acoustiques standardisées et traitées à l'aide du logiciel PRAAT. Les paramètres évalués comprenaient la fréquence fondamentale (F_0 / hauteur tonale), l'intensité moyenne, les indices de perturbation (*jitter* local % et *shimmer* local %), les formants de résonance du conduit vocal (F_1 , F_2 et F_3), ainsi que le rapport harmoniques-sur-bruit (HNR).

Les résultats empiriques révèlent des divergences acoustiques marquées entre les groupes cliniques : les enfants atteints d'infirmité motrice cérébrale ont présenté une instabilité aérodynamique, un *shimmer* élevé et une dispersion formantique restreinte, imputables à la spasticité neuromotrice et à une altération de la coordination pneumo-phonique. À l'inverse, les enfants sourds ont manifesté une déstabilisation vocale caractérisée par une dérive marquée de la hauteur tonale, des valeurs élevées de *jitter* et de *shimmer*, ainsi qu'un HNR abaissé, reflétant la rupture de la boucle de rétroaction auditive. Une forte hétérogénéité intra-groupe a été constatée, démontrant que les adaptations phonatoires compensatoires demeurent hautement individualisées. Ces résultats valident les hypothèses opérationnelles, soulignant la nécessité d'intégrer l'évaluation acoustique informatisée en orthophonie pour l'établissement de profils diagnostiques et la mise en œuvre d'une rééducation ciblée.

Mots-clés : Caractéristiques acoustico-phonétiques ; Infirmité motrice cérébrale ; Surdit   ; Logiciel PRAAT ; Analyse formantique ; Orthophonie.

1. Introduction

Human language constitutes the primary cognitive and semiotic medium distinguishing our species, operating as the foundation for inter-subjective social cohesion and higher-order cognitive processing. Spoken communication relies fundamentally on vocal production, translating neuro-cognitive linguistic programming into measurable physical sound waves. Vocal production can be evaluated through objective acoustic indices, including fundamental frequency (F_0), vocal intensity, phonatory duration, harmonic structures, and resonance formants, utilizing digital signal processing platforms such as PRAAT.

Physiologically, voice production represents an aerodynamic-acoustic phenomenon wherein a pressurized transpulmonary airstream egresses from the lungs to induce self-sustained,

quasi-periodic vibratory oscillation within the laryngeal vocal folds. The generated glottal acoustic spectrum is filtered and shaped within supraglottic resonating cavities (pharyngeal, oral, and nasal), radiating into ambient air as complex longitudinal pressure waves¹

Analyzing acoustic-phonetic markers provides objective insights into motor-speech control and auditory integration across clinical cohorts affected by neuromotor or sensory deficits. Children with cerebral palsy (CP) confront structural sensorimotor, tone, and postural impairments affecting the respiratory, phonatory, and articulatory musculature, compromising vocal quality and intelligibility. Concurrently, deaf children experience a severe deficit or absence of auditory biofeedback, restricting their capacity to monitor pitch, amplitude, and phonetic articulation.

A review of the empirical literature highlights a scarcity of objective acoustic investigations targeting pediatric cerebral palsy in regional clinical settings, contrasting with research on cochlear implant recipients. Abar and Belhouchat (2023) conducted an exploratory acoustic evaluation of motor-impaired children ($N=6$; aged 6–10 years) utilizing PRAAT, reporting phonetic perturbations, hypernasality, spastic resonance, and pitch instability².

In hearing-impaired cohorts, early investigations demonstrated that deaf children exhibit altered fundamental frequencies and dysprosody compared to normally hearing controls (Col & Kuhn-Mounier, 1967, as cited in Arar & Attal, 2022, p. 479). Arar and Attal (2022) examined the acoustic profiles of pediatric cochlear implant users ($N=4$; aged 11 years) using PRAAT, documenting deviations in intensity, pitch stability, formant dispersion, and high levels of jitter and shimmer relative to normative thresholds³. Similarly, Nakata et al. (2006) investigated vocal performance in deaf children with cochlear implants ($N=3$; aged 9–12 years), observing pitch drift and intervallic variations during sustained vocalizations⁴.

To address the empirical gap concerning acoustic differentiation between neuromotor execution deficits and sensory-auditory deprivation, this study establishes an objective comparative profile across three matched dyads: typically developing children, children with cerebral palsy, and deaf children. Through computerized acoustic extraction via PRAAT, this research identifies quantitative phonetic parameters to support diagnostic baseline profiling and targeted speech-language intervention.

2. Research Questions

2.1. General Research Question

Do measurable acoustic-phonetic differences exist between children diagnosed with cerebral palsy and deaf children when analyzed via PRAAT software?

¹ - Salama, A. (2015). *Voice disorders: Concept, etiology, and intervention* (1st ed.). Dar Amjad for Publishing and Distribution, pp. 10–11.

² - Abar, Z., & Belhouchat, K. (2023). A study of the physical characteristics of voice in children with motor-neurological disabilities. *Algerian Journal of Education and Mental Health*, 17(1), p. 78

³ - Arar, F., & Attal, Y. (2022). Evaluation of voice characteristics in deaf children with cochlear implants. *Al-Rawaiz Journal*, 7(1), p. 489

⁴ - Janba, M., & Feni, S. (2020). Acoustic characteristics of voice in children with cochlear implants using Tajweed technique. *Al-Jami' in Psychological Studies and Educational Sciences*, 5(2), p. 369.

2.2. Subordinate Research Questions

- Do measurable acoustic-phonetic differences exist between children with cerebral palsy and typically developing children?
- Do measurable acoustic-phonetic differences exist between deaf children and typically developing children?
- Do intra-group variations in acoustic-phonetic characteristics exist among children diagnosed with cerebral palsy?
- Do intra-group variations in acoustic-phonetic characteristics exist among deaf children?

3. Hypotheses

3.1. General Hypothesis

Measurable acoustic-phonetic divergences exist between children with cerebral palsy and deaf children when evaluated via PRAAT software.

3.2. Subordinate Hypotheses

- Measurable acoustic-phonetic divergences exist between children with cerebral palsy and typically developing children.
- Measurable acoustic-phonetic divergences exist between deaf children and typically developing children.
- Quantifiable intra-group variations in acoustic-phonetic metrics exist among children diagnosed with cerebral palsy.
- Quantifiable intra-group variations in acoustic-phonetic metrics exist among deaf children.

4. Significance of the Study

This study contributes to the clinical phonetics and speech-language pathology literature through the following dimensions:

- Analyzing the interaction between neuromotor impairment, auditory feedback disruption, and physical acoustic output.
- Documenting objective acoustic markers (fundamental frequency, intensity, jitter, shimmer, resonance formants, and HNR) within pediatric clinical groups.
- Advancing diagnostic protocols in clinical speech-language therapy from perceptual evaluation toward digital acoustic instrumentation.
- Providing baseline empirical data to inform motor-speech training, vocal rehabilitation, and sensory-feedback strategies for children with cerebral palsy and profound hearing loss.

5. Research Objectives

- To evaluate the research questions and test the operational validity of the hypotheses.
- To map acoustic-phonetic profiles of children with cerebral palsy, deaf children, and neurotypical controls using the computational framework of PRAAT.

- To establish acoustic-articulatory correlations by analyzing formant frequencies (\$F_1\$, \$F_2\$, \$F_3\$) alongside perturbation and noise parameters.
- To generate objective clinical data supporting evidenced-based intervention programs and acoustic modeling in clinical phonetics.

6. Conceptual and Operational Definitions

6.1. Acoustic Sound (Voice)

- **Conceptual Definition:** An external physical disturbance propagating through an elastic medium characterized by wave motion wherein mechanical displacement occurs across specific temporal intervals⁵.
- **Operational Definition:** The physical acoustic signal generated via phonation, measured via electroacoustic instruments in decibels (dB) for intensity and Hertz (Hz) for spectral frequency within the human auditory range of 20 Hz to 20,000 Hz.

6.2. Physical Acoustic Characteristics

The quantitative acoustic parameters extracted from sustained vocal emissions, comprising:⁶

- **Pitch / Fundamental Frequency (\$F_0\$):** The psychoacoustic correlate of the physical rate of vocal fold vibration, quantified in Hertz (Hz).
- **Vocal Intensity:** The magnitude of acoustic energy per unit area, measured logarithmically in decibels (dB), corresponding psychoacoustically to perceived loudness.
- **Vocal Timbre and Quality:** The spectral profile of a phonatory source independent of pitch and intensity, determined by harmonic structure and vibratory regularity.
- **Vocal Resonance:** The supraglottal filtering, amplification, and attenuation of the glottal sound source within the pharyngeal, oral, and nasal cavities.

6.3. Cerebral Palsy (CP)

- **Conceptual Definition:** A non-progressive neuromotor disorder caused by an injury or developmental anomaly sustained by the immature brain during fetal or early infancy stages, impairing motor control, tone, posture, and coordination⁷.
- **Operational Definition:** A clinical diagnosis confirmed by neuropsychiatric assessment and motor function classifications, presenting with spasticity, coordination deficits, and dysarthric speech patterns affecting phonatory-respiratory control.

6.4. Deafness / Hearing Impairment

⁵ - Nouani, H. (2018). *Speech-language pathology and the Arabic language: An introduction to speech disorders* (1st ed.). Dar Al-Khaldounia for Publishing, p. 54.

⁶ - Salem, O. F. (2015). *Communication disorders in theory and practice* (2nd ed.). Dar Al-Maseera for Publishing, Distribution, and Printing, p. 193.

⁷ - Safadi, I. H. (2007). *Motor disabilities and cerebral palsy*. Dar Al-Yazouri Scientific for Publishing and Distribution, p. 32

- **Conceptual Definition:** A sensory impairment involving severe attenuation or total loss of hearing function, impeding the processing of acoustic speech signals⁸.
- **Operational Definition:** An audiometrically verified sensorineural hearing loss exceeding 70 dB HL across the conversational frequency spectrum in the better ear, preventing the unassisted acquisition and self-monitoring of speech.

6.5. The Deaf Child

A pediatric subject presenting with profound hearing loss (≥ 70 dB HL) that restricts conversational fluency and oral speech processing through air-conducted sound alone⁹.

6.6. PRAAT Software

An open-source digital signal processing program developed by Paul Boersma and David Weenink at the Institute of Phonetic Sciences, University of Amsterdam (available at www.praat.org), utilized for the spectral, formantic, and perturbation analysis of speech signals¹⁰.

Computationally, PRAAT processes speech signals through robust digital signal algorithms that extract periodicity, formant tracks, and perturbation parameters directly from the acoustic wave structure¹¹.

7. Research Methodology

The present study adopts an exploratory descriptive-comparative multi-case design, suitable for analyzing acoustic phenomena, capturing physical speech variations, and comparing healthy controls with pathological groups¹².

8. Sampling and Subject Profiles

The purposive sample comprises six pediatric participants ($N=6$), organized into three clinical dyads:

- **Control Group (Reference Dyad):** Two neurotypical children (one female, one male), aged 7 to 8 years, displaying age-appropriate speech-language milestones, enrolled in the first and second grades of primary school.
- **Cerebral Palsy Group:** Two children diagnosed with spastic cerebral palsy presenting with dysarthria (one female, one male), aged 7 to 8 years, receiving regular speech therapy, enrolled in primary school (grades 1 and 3).

⁸ - Bourdj, M. (2020). *A study of dysgraphia in profoundly deaf children (Field study at the school for hearing-impaired children, Oum El Bouaghi)* [Unpublished master's thesis, Department of Speech-Language Pathology]. University of Larbi Ben M'hidi, Oum El Bouaghi, p. 29

⁹ - Bourdj, M. (2020). Op. Cit, p. 29

¹⁰ - Ben Aissa, K. (2019). *User guide for the PRAAT speech signal analysis and processing software* (Center Notebooks Series No. 9). Scientific and Technical Research Center for the Development of Arabic Language (CRSTDLA), p. 5.

¹¹ - Boersma, P. (2001). Praat, a system for doing phonetics by computer. *Glott International*, 5(9/10), pp. 342–344.

¹² - Zeibari, T. H. (2011). *Research methods in sociology* (1st ed.). Majd University Foundation for Studies and Publishing, p. 23.

- **Deaf Group:** Two profoundly deaf children (one female, one male), aged 7 years, receiving specialized speech-language therapy, enrolled in pre-school preparatory programs.

Table 01: Sociodemographic and Clinical Profile of the Control Group

Case No.	Subject Name	Gender	Chronological Age (DOB)	Academic Level	Clinical Classification
01	Maria	Female	8 Years (08/01/2017)	2nd Grade Primary	Neurotypical Control
02	Abderrahmane	Male	7 Years (29/04/2018)	1st Grade Primary	Neurotypical Control

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Table 02: Sociodemographic and Clinical Profile of the Cerebral Palsy Group

Case No.	Subject Name	Gender	Chronological Age (DOB)	Academic Level	Clinical Classification
03	Nour El-Houda	Female	8 Years (24/03/2017)	3rd Grade Primary	Spastic Cerebral Palsy / Dysarthria
04	Zakaria	Male	7 Years (05/01/2018)	1st Grade Primary	Spastic Cerebral Palsy / Dysarthria

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Table 03: Sociodemographic and Clinical Profile of the Deaf Group

Case No.	Subject Name	Gender	Chronological Age (DOB)	Academic Level	Clinical Classification
05	Imene	Female	7 Years (25/05/2018)	Preschool / Preparatory	Profound Sensorineural Deafness
06	Yacoub	Male	7 Years (19/12/2018)	Preschool / Preparatory	Severe-to-Profound Deafness

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

9. Instrumentation and Data Collection Protocol

Acoustic evaluations were conducted via PRAAT software running on a calibrated workstation under standard recording conditions:

- **Acoustic Environment and Instrumentation:** Recordings were acquired in a quiet clinical setting. A high-fidelity unidirectional condenser microphone was positioned at an angle of 45 degrees, approximately 10 to 15 cm from the participant's mouth, minimizing aerodynamic clipping.

- **Signal Acquisition Parameters:** Signals were digitized via single-channel mono recording at a sampling frequency of 22,050 Hz with 16-bit quantization. Audio input levels were monitored within green-band meters to prevent peak distortion¹³.
- **Phonetic Task Elicitation:** Participants performed sustained vocalizations of the three primary cardinal vowels: open-central [a], close-back rounded [o], and close-front unrounded [i] at a comfortable pitch and volume for at least two seconds per trial.
- **Signal Processing and Acoustic Extraction:** Audio files were segmented to isolate stable mid-vowel portions, excluding onset and offset transients. Spectrographic analysis (effective Gaussian bandwidth: 260 Hz) tracked intensity curves (yellow), F_0 pitch contours (blue), formant tracks (F_1 , F_2 , F_3 ; red dotted lines), alongside perturbation parameters (local jitter%, local shimmer%) and harmonics-to-noise ratio (HNR)¹⁴.

Quantifying harmonic purity alongside spectral perturbation is essential to differentiate true glottal cycle irregularities from ambient recording artifacts¹⁵, while providing standardized thresholds for normative pediatric pitch and perturbation bounds¹⁶.

10. Data Analysis and Findings

This section presents the empirical acoustic data extracted via PRAAT software, delineating the phonetic and resonant parameters across the three clinical groups.

10.1. Analysis of the Control Group (Reference Dyad)

This subsection examines the baseline acoustic profile of typically developing children to establish normative comparative benchmarks for pitch, intensity, perturbation, and resonance formants.

These formantic dispersions (F_1 , F_2 , F_3) in the control dyad confirm regular acoustic filtering, aligning with standard long-term spectral models of supraglottic vocal tract geometry in prepubertal phonation¹⁷.

10.1.1. Case 01: Maria (Female, 8 Years, Neurotypical)

This case analyzes the sustained vowel production of the eight-year-old female neurotypical subject to assess physiological vocal fold periodicity and standard vocal tract configurations.

¹³ - Ben Aissa, Op. Cit, pp. 18–19.

¹⁴ - Ben Aissa, K, Idid, p. 39

¹⁵ - Ryalls, J., & Behrens, S. (2000). *Introduction to speech science: From basic phonetics to the clinic*. Allyn & Bacon, Boston, pp. 78–84.

¹⁶ - Baken, R. J., & Orlikoff, R. F. (2000). *Clinical measurement of speech and voice* (2nd ed.). Singular Publishing Group, San Diego, pp. 175–182.

¹⁷ - Löfqvist, A., & Mandersson, B. (1987). Long-time average spectrum of speech and voice analysis. *The Journal of the Acoustical Society of America*, 82(2), pp. 445–448.

Figure 02: Spectrographic Representation of Vowel [o] for Case 01 (Maria)

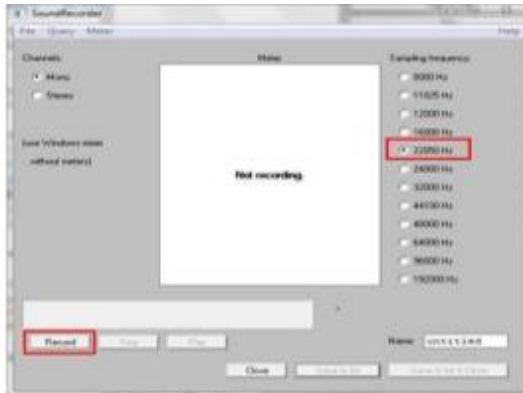
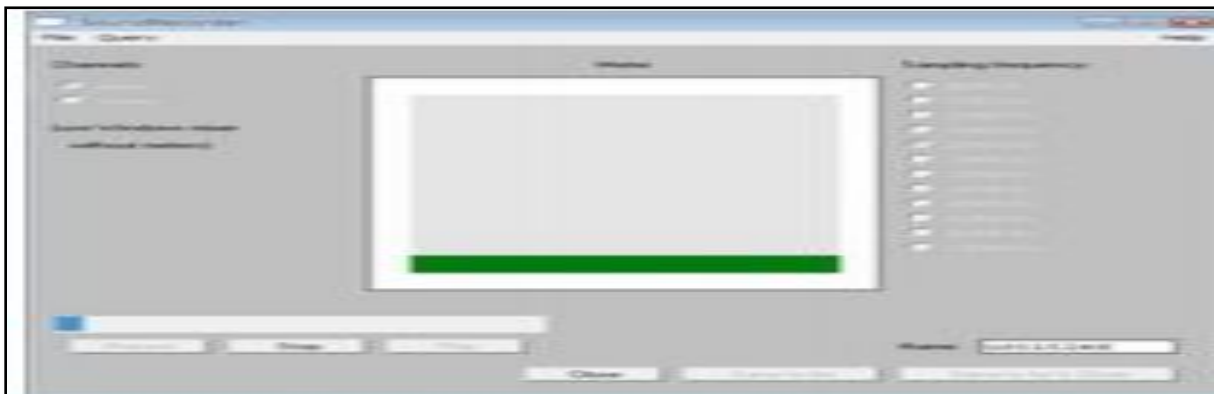


Figure 01: Spectrographic Representation of Vowel [a] for Case 01 (Maria)



Source: Elaborated by the researchers via PRAAT software

Figure 03: Spectrographic Representation of Vowel [i] for Case 01 (Maria)



Source: Elaborated by the researchers via PRAAT software

Table 04: Acoustic-Phonetic Characteristics for Case 01 (Maria)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HNR (dB)
[a]	71.25	256.87	1.52	2.90	14.72	866.82	1834.38	3102.69	17.87
[o]	74.02	274.15	1.37	3.05	6.09	824.62	1618.31	3052.58	16.77

[i]	74.82	295.28	1.72	2.44	6.38	674.16	2254.56	3188.8	19.65
								7	

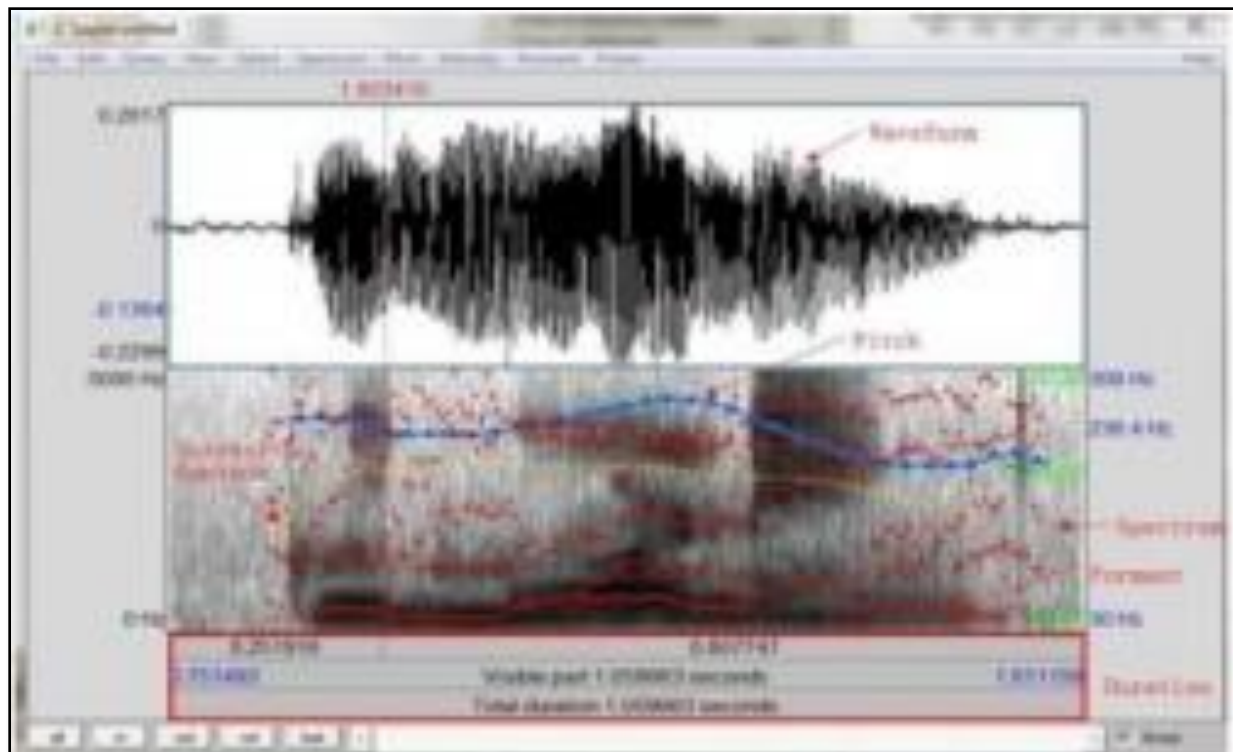
Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

acoustic values for Case 01 reflect normative phonatory control. For vowel [a], an intensity of 71.25 dB and a fundamental frequency of 256.87 Hz fall within standard ranges for pediatric females (250–300 Hz). The first formant ($F_1=866.82\text{ Hz}$) demonstrates appropriate oral opening and vertical tongue positioning, while F_2 (1834.38 Hz) and F_3 (3102.69 Hz) confirm normal vocal tract resonance. Vowel [o] demonstrates typical spectral shifts, including lowered F_2 (1618.31 Hz) signaling tongue retraction and lip rounding, alongside a low shimmer value (6.09%). Vowel [i] exhibits expected high-front vowel acoustic patterns, with a lowered F_1 (674.16 Hz), an elevated F_2 (2254.56 Hz), and an optimal HNR of 19.65 dB. Perturbation metrics reflect stable laryngeal vibration consistent with normal pediatric development.

10.1.2. Case 02: Abderrahmane (Male, 7 Years, Neurotypical)

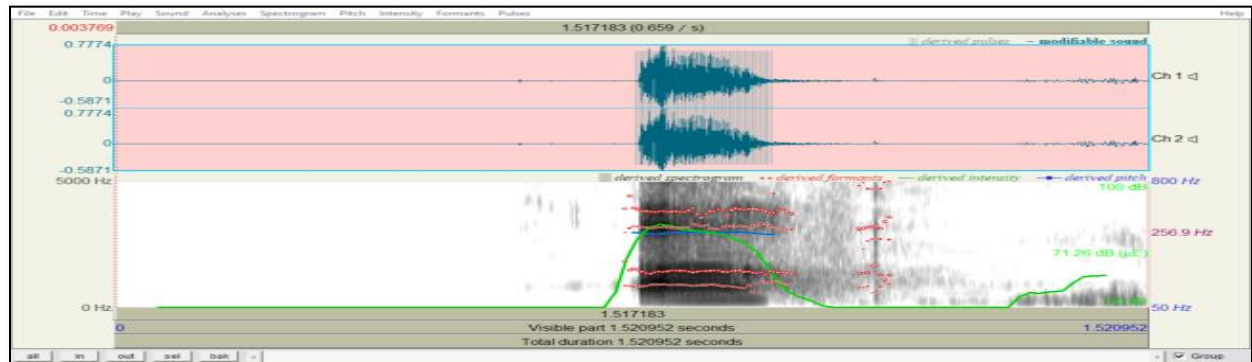
This case evaluates the sustained vowel productions of the seven-year-old male neurotypical control to document normative acoustic stability and formantic configurations in prepubertal male phonation.

Figure 04: Spectrographic Representation of Vowel [a] for Case 02 (Abderrahmane)



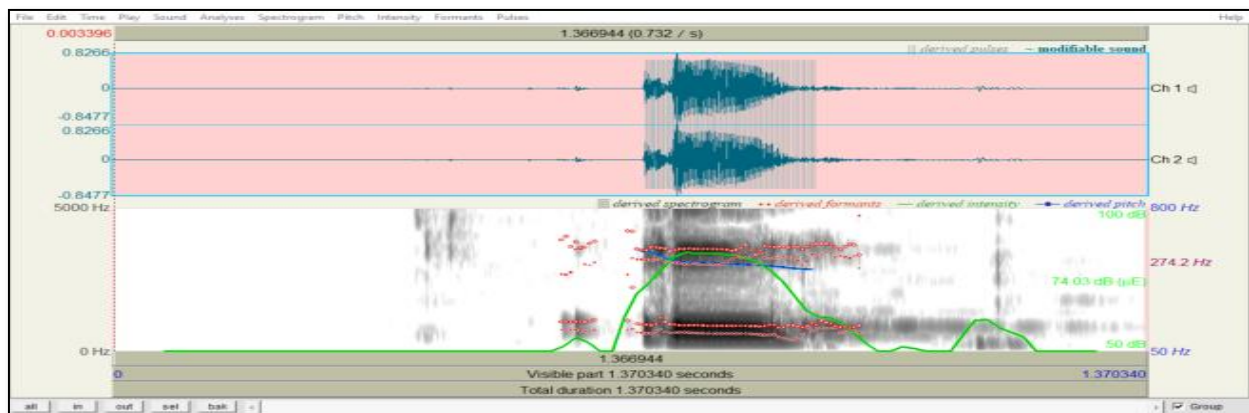
Source: Elaborated by the researchers via PRAAT software

Figure 05: Spectrographic Representation of Vowel [o] for Case 02 (Abderrahmane)



Source: Elaborated by the researchers via PRAAT software

Figure 06: Spectrographic Representation of Vowel [i] for Case 02 (Abderrahmane)



Source: Elaborated by the researchers via PRAAT software

Table 05: Acoustic-Phonetic Characteristics for Case 02 (Abderrahmane)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HNR (dB)
[a]	72.76	283.36	1.85	1.24	8.40	856.49	1715.55	3003.59	19.21
[o]	74.67	281.63	1.68	1.83	5.79	793.97	1681.07	3070.63	16.87
[i]	77.29	295.13	0.46	3.22	8.76	548.79	1945.57	3460.39	13.88

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Case 02 presents stable acoustic patterns across all vowel targets. Fundamental frequency (\$F_0\$) ranges from 281.63 Hz to 295.13 Hz, aligning with normative pediatric male data. Jitter remains low for [a] (1.24%) and [o] (1.83%), indicating stable vocal fold oscillation. Formant positions conform to standard articulatory configurations: elevated \$F_1\$ (856.49 Hz) for the open vowel [a], and depressed \$F_1\$ (548.79 Hz) alongside elevated \$F_3\$ (3460.39 Hz) for the close-front [i]. An HNR ranging between 13.88 dB and 19.21 dB indicates glottal closure free of breathiness or acoustic turbulence.

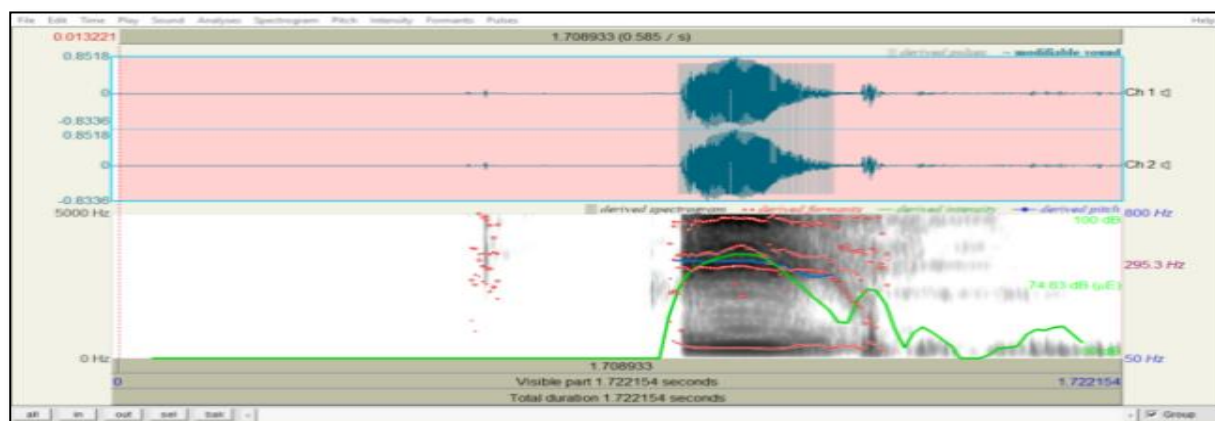
10.2. Analysis of the Cerebral Palsy Group

This subsection delineates the acoustic-phonetic data of children diagnosed with spastic cerebral palsy to identify the empirical markers of dysarthric phonation and neuromotor speech impairment.

10.2.1. Case 03: Nour El-Houda (Female, 8 Years, Cerebral Palsy)

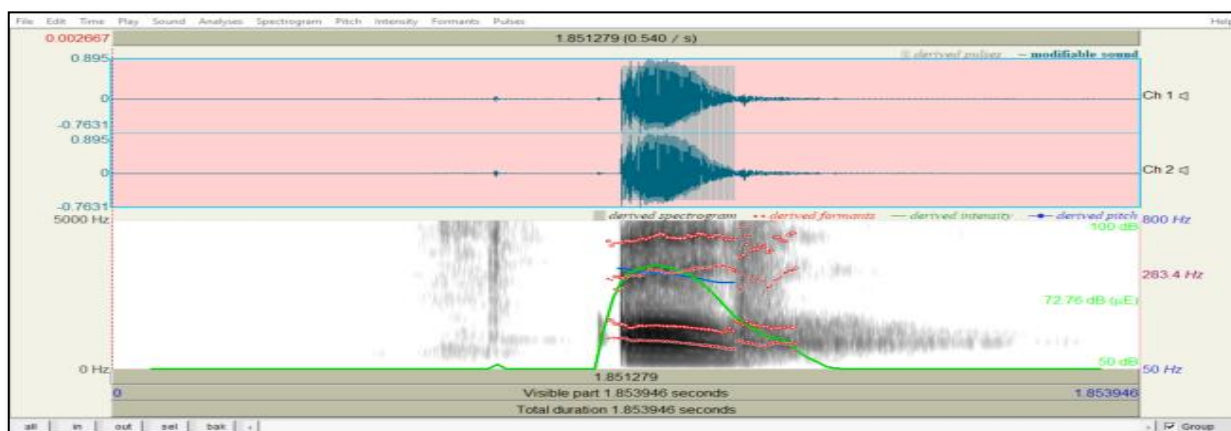
This case examines the acoustic parameters of sustained cardinal vowels produced by the eight-year-old female subject to identify phonatory disruptions and formantic variations resulting from spastic motor dysregulation.

Figure07: Spectrographic Representation of Vowel [a] for Case 03 (Nour El-Houda)



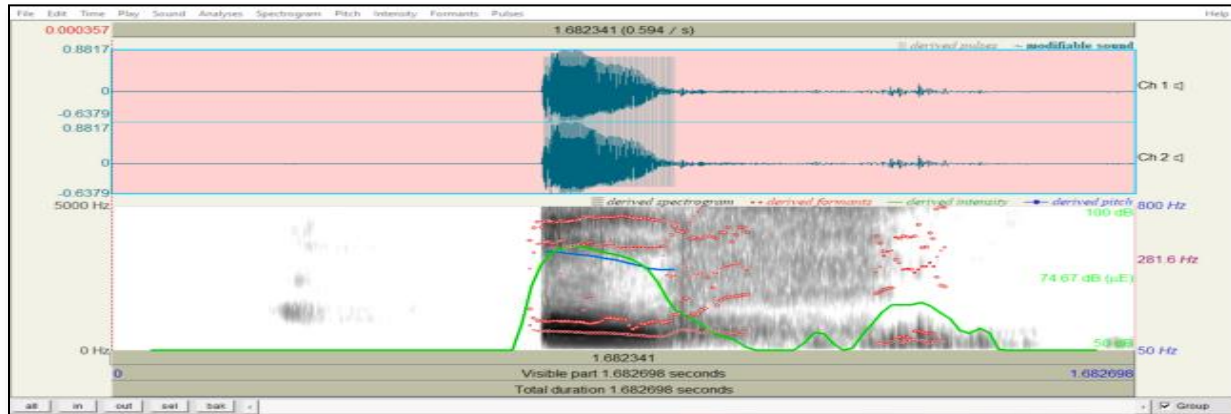
Source: Elaborated by the researchers via PRAAT software

Figure 08: Spectrographic Representation of Vowel [o] for Case 03 (Nour El-Houda)



Source: Elaborated by the researchers via PRAAT software

Figure 09: Spectrographic Representation of Vowel [i] for Case 03 (Nour El-Houda)



Source: Elaborated by the researchers via PRAAT software

Table 06: Acoustic-Phonetic Characteristics for Case 03 (Nour El-Houda)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HNR (dB)
[a]	77.93	419.96	2.00	1.79	5.92	1095.22	1838.29	2646.69	16.31
[o]	76.92	387.36	1.51	0.59	3.27	888.95	1541.58	3105.78	21.34
[i]	66.58	391.63	1.73	1.32	5.79	793.62	2003.16	2999.10	15.77

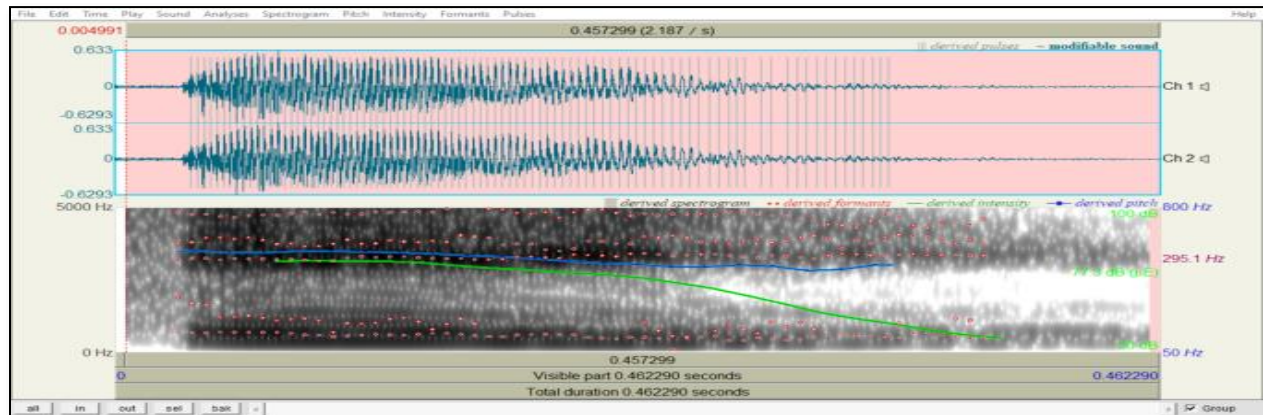
Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Data for Case 03 reveal clear acoustic signs of neuromotor dysregulation. The fundamental frequency is elevated across all vowel productions ($F_0=419.96\text{ Hz}$ for [a], 387.36 Hz for [o], and 391.63 Hz for [i]), indicating hyperfunctional laryngeal tension and excessive subglottic pressure associated with spasticity. For vowel [a], an elevated F_1 (1095.22 Hz) indicates impaired mandibular control and exaggerated vertical jaw opening. Conversely, vowel [i] displays reduced intensity (66.58 dB) and elevated F_1 (793.62 Hz), indicating muscular fatigue and incomplete lingual elevation. Despite motor impairment, perturbation metrics for [o] remain within acceptable limits (jitter 0.59%, shimmer 3.27%, HNR 21.34 dB), indicating that back rounded configurations are biomechanically more stable for this participant.

10.2.2. Case 04: Zakaria (Male, 7 Years, Cerebral Palsy)

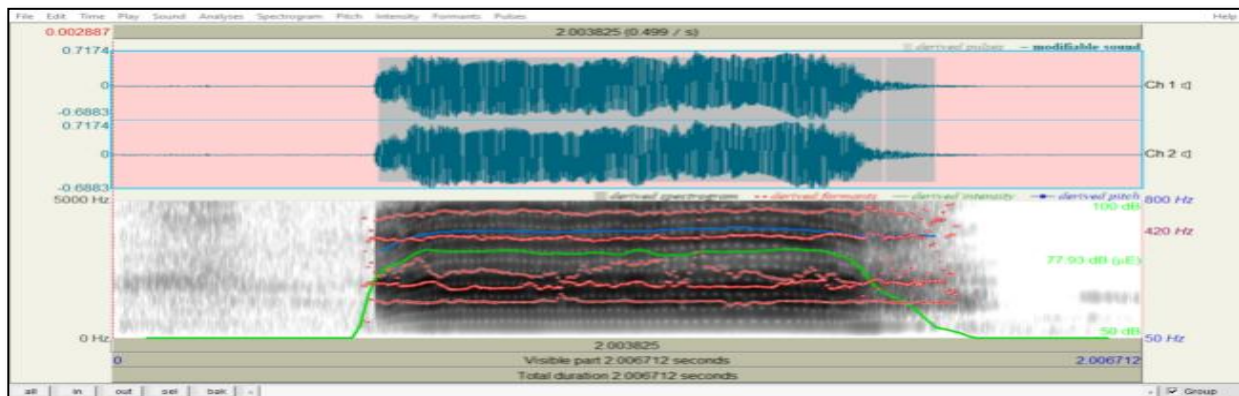
This case examines the acoustic parameters of sustained vowel vocalizations produced by the seven-year-old male subject to evaluate articulatory range, perturbation patterns, and respiratory-phonatory stability associated with spastic dysarthria.

Figure 10: Spectrographic Representation of Vowel [a] for Case 04 (Zakaria)



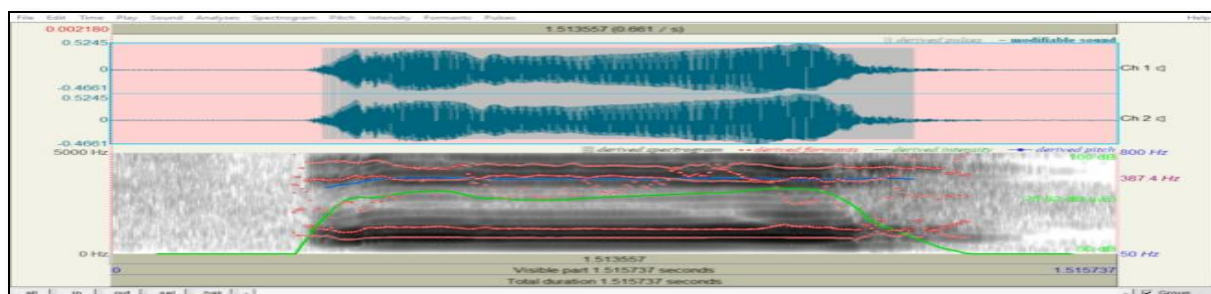
Source: Elaborated by the researchers via PRAAT software

Figure 11: Spectrographic Representation of Vowel [o] for Case 04 (Zakaria)



Source: Elaborated by the researchers via PRAAT software

Figure 12: Spectrographic Representation of Vowel [i] for Case 04 (Zakaria)



Source: Elaborated by the researchers via PRAAT software

Table 07: Acoustic-Phonetic Characteristics for Case 04 (Zakaria)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HNR (dB)
[a]	82.35	303.72	1.21	1.13	12.71	1161.89	1516.14	2142.63	19.97
[o]	69.88	311.01	2.39	0.36	2.84	929.93	1472.44	2626.47	24.41
[i]	61.21	370.08	2.29	0.42	9.19	876.55	2301.28	2977.11	24.34

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Case 04 presents acoustic evidence of dysarthric phonatory instability. Vowel [a] demonstrates an elevated intensity of 82.35 dB paired with high shimmer (12.71%), indicating compensatory phonatory effort and impaired respiratory-phonatory control. Formant tracking reveals an elevated \$F_1\$ (1161.89 Hz) and compressed \$F_2\$ (1516.14 Hz) and \$F_3\$ (2142.63 Hz), reflecting centralized vowel undershoot and restricted articulatory range of motion. Conversely, vowels [o] and [i] exhibit low jitter values (0.36% and 0.42%) and high HNR values (>24 dB), contrasting with reduced vocal intensity during [i] (61.21 dB), which demonstrates respiratory decrescendo during fine anterior articulatory posturing.

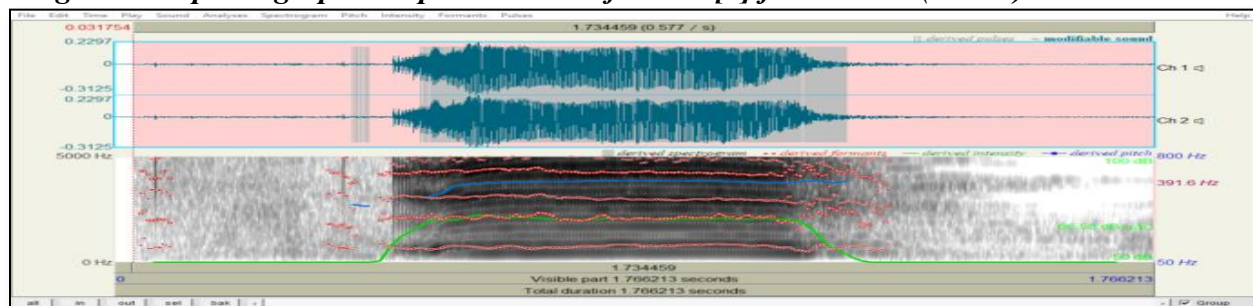
10.3. Analysis of the Deaf Group

This subsection analyzes the acoustic profiles of profoundly deaf children to evaluate the phonetic, resonant, and phonatory destabilizations induced by the absence of real-time auditory biofeedback.

10.3.1. Case 05: Imene (Female, 7 Years, Profound Sensorineural Deafness)

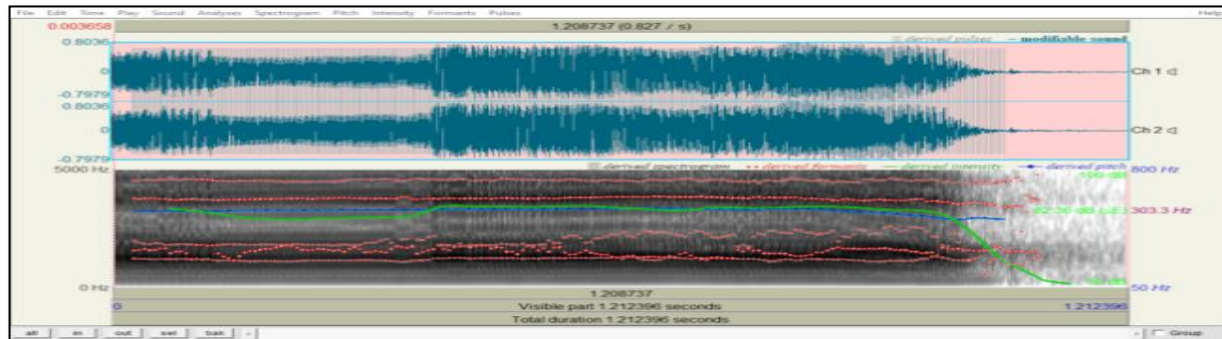
This case evaluates the acoustic parameters of sustained cardinal vowels produced by the seven-year-old female subject to identify vocal perturbation metrics, pitch drift, and articulatory overshooting resulting from profound auditory deprivation.

Figure 13: Spectrographic Representation of Vowel [a] for Case 05 (Imene)



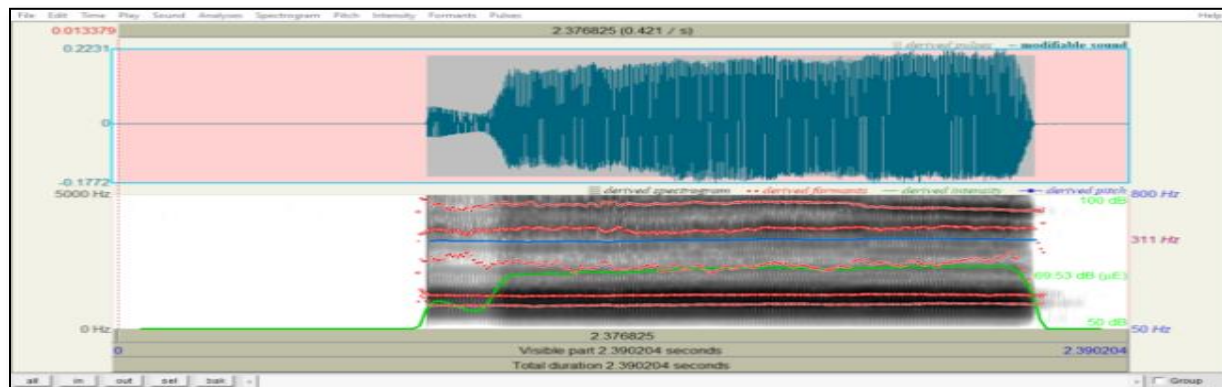
Source: Elaborated by the researchers via PRAAT software

Figure 14: Spectrographic Representation of Vowel [o] for Case 05 (Imene)



Source: Elaborated by the researchers via PRAAT software

Figure 15: Spectrographic Representation of Vowel [i] for Case 05 (Imene)



Source: Elaborated by the researchers via PRAAT software

Table 08: Acoustic-Phonetic Characteristics for Case 05 (Imene)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HN R (dB)
[a]	69.74	291.03	1.76	2.95	14.05	1136.48	1971.76	3333.24	17.21
[o]	72.54	196.74	1.13	1.00	6.00	771.31	1583.61	3115.91	14.63
[i]	67.76	341.68	1.08	5.09	17.60	560.22	2276.70	3216.68	12.87

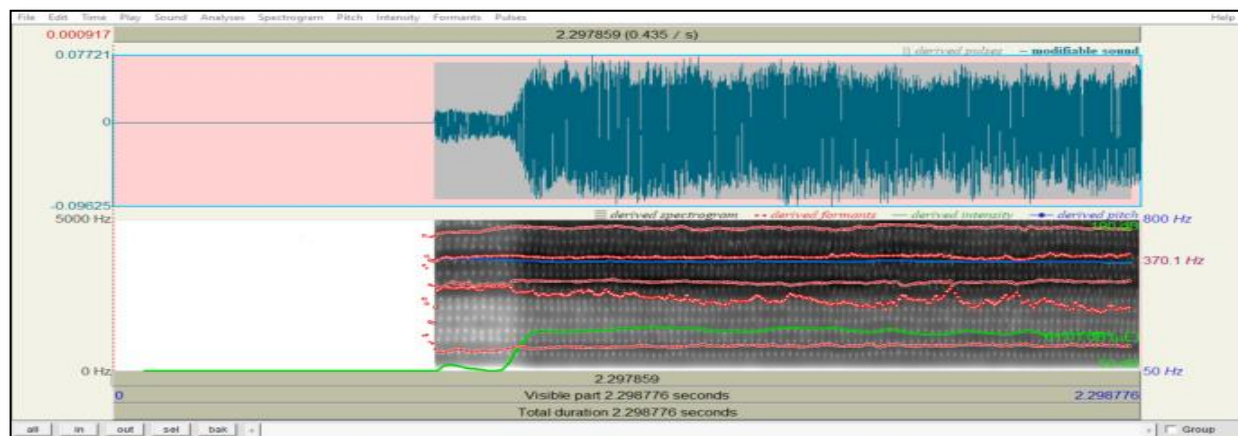
Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Case 05 displays acoustic destabilization resulting from the absence of auditory feedback. Fundamental frequency fluctuates across a 145 Hz range across vowel targets ($F_0=196.74$ Hz for [o] versus 341.68 Hz for [i]). Severe perturbation is present during vowel [i], with jitter reaching 5.09% and shimmer reaching 17.60%, accompanied by a depressed HNR of 12.87 dB, indicating laryngeal tremor and glottal air leakage. For vowel [a], F_1 is elevated (1136.48 Hz), reflecting compensatory visual-kinesthetic overextension of the jaw. These data indicate that while gross vocal tract posturing is maintained via tactile-kinesthetic proprioception, laryngeal stability is compromised without real-time auditory monitoring.

10.3.2. Case 06: Yacoub (Male, 7 Years, Severe-to-Profound Deafness)

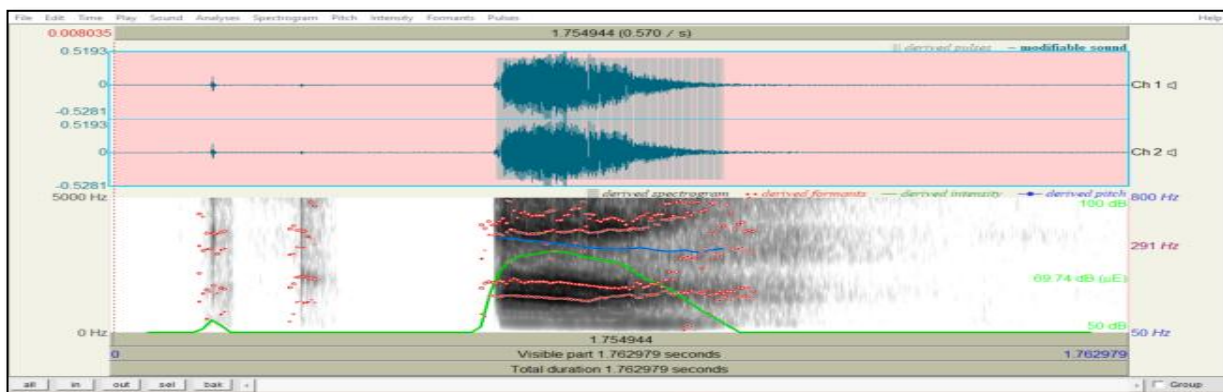
This case investigates the acoustic-phonetic characteristics of sustained vowel productions in the seven-year-old male subject to examine the interaction between auditory sensory deprivation, vocal hyperfunction, and compensatory articulatory patterns.

Figure 16: Spectrographic Representation of Vowel [a] for Case 06 (Yacoub)



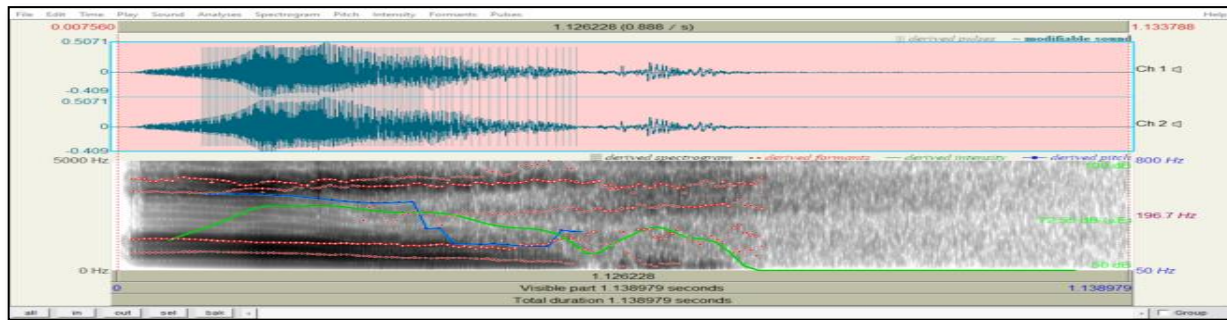
Source: Elaborated by the researchers via PRAAT software

Figure 17: Spectrographic Representation of Vowel [o] for Case 06 (Yacoub)



Source: Elaborated by the researchers via PRAAT software

Figure 18: Spectrographic Representation of Vowel [i] for Case 06 (Yacoub)



Source: Elaborated by the researchers via PRAAT software

Table 09: Acoustic-Phonetic Characteristics for Case 06 (Yacoub)

Vowel Target	Intensity (dB)	Pitch (F0) (Hz)	Duration (s)	Jitter (%)	Shimmer (%)	Formant F1 (Hz)	Formant F2 (Hz)	Formant F3 (Hz)	HNR (dB)
[a]	73.28	288.24	2.21	2.92	5.25	1118.05	1956.49	3035.45	17.10
[o]	82.19	285.98	1.33	0.86	5.06	666.50	1268.77	3441.32	20.82
[i]	72.01	300.48	2.00	2.10	6.74	906.88	2247.86	3196.98	12.86

Source: Prepared by the researchers based on acoustic extraction data via PRAAT software.

Case 06 demonstrates acoustic patterns characteristic of auditory deprivation, alongside adaptations derived from speech therapy. Vowel [o] shows elevated vocal intensity (82.19 dB), controlled jitter (0.86%), and an HNR of 20.82 dB, corresponding to typical \$F_1\$ (666.50 Hz) and \$F_2\$ (1268.77 Hz) formant values. In contrast, vowels [a] and [i] exhibit acoustic instability: [a] displays an elevated \$F_1\$ (1118.05 Hz) and high jitter (2.92%), while [i] exhibits an elevated \$F_1\$ (906.88 Hz), elevated jitter (2.10%), and a depressed HNR (12.86 dB). These patterns indicate inconsistent articulatory positioning and breathiness during high-front vocal tract postures.

11. Discussion of Findings in Light of Hypotheses

This section contextualizes the empirical acoustic measurements within the study's conceptual framework, systematically testing each operational hypothesis against established literature in speech-language pathology and acoustic phonetics.

11.1. First Subordinate Hypothesis: Cerebral Palsy vs. Neurotypical Children

This subsection evaluates the acoustic divergence between children with spastic cerebral palsy and their typically developing peers, focusing on the physiological impact of neuromotor spasticity and dyssynergia on vocal stability and formant architecture. Hypothesis Statement: Measurable acoustic-phonetic divergences exist between children with cerebral palsy and typically developing children.

- **Empirical Validation:** Confirmed. Control participants (Maria and Abderrahmane) maintained pitch stability, balanced vocal intensity, and perturbation parameters within normative developmental ranges. Conversely, children with cerebral palsy (Nour El-Houda and Zakaria) exhibited fundamental frequencies ranging from 303.72 Hz up to 419.96 Hz, consistently elevated above normative male and female baselines, alongside marked intensity dysregulation (spanning from 82.35 dB in Case 04 down to 61.21 dB in Case 03), and elevated shimmer and jitter during open-vowel phonation. These acoustic variations reflect motor execution deficits, excessive laryngeal adductor tension, and reduced subglottic breath support characteristic of dysarthric speech pathology. These findings align with observations by Abar and Belhouchat (2023), who documented vocal instability, reduced respiratory control, and spastic dysprosody in motor-impaired children evaluated via PRAAT¹⁸.

Furthermore, the observed laryngeal strain, hyperfunctional fundamental frequency, and aerodynamic collapse mirror the classic acoustic signatures of pediatric dysarthria documented by Kent, Vorperian, and Duffy (1999). Similar subglottic air wastage and elevated shimmer during sustained vowel phonation were evidenced by Chen (2007),²⁰ confirming that neuromotor spasticity directly impedes steady vocal fold adduction.

11.2. Second Subordinate Hypothesis: Deaf Children vs. Neurotypical Children

This subsection analyzes the acoustic divergences between profoundly deaf children and neurotypical controls, examining how the interruption of auditory self-monitoring impairs pitch control, phonatory periodicity, and glottal harmonic richness.

- **Hypothesis Statement:** Measurable acoustic-phonetic divergences exist between deaf children and typically developing children.
- **Empirical Validation:** Confirmed. Deaf participants (Imene and Yacoub) demonstrated phonatory destabilization, elevated jitter (reaching 5.09% in Case 05), elevated shimmer (up to 17.60%), reduced HNR (falling to 12.86 dB), and marked \$F_0\$ drift. These acoustic deviations reflect the absence of real-time auditory feedback, forcing reliance on tactile and proprioceptive mechanisms. Control children produced regular, harmonic acoustic profiles. These findings confirm the observations of Col and Kuhn-Mounier (1967) regarding fundamental frequency dysregulation in hearing-impaired children, and corroborate Arar and Attal (2022), who reported elevated jitter, shimmer, and formant-tracking irregularities in deaf children using PRAAT²¹.

¹⁸ - Abar & Belhouchat, Op. Cit, p. 78

¹⁹ - Kent, R. D., Vorperian, H. K., & Duffy, J. R. (1999). Dysarthria in children: Acoustic and perceptual features of motor speech disorders. *Seminars in Speech and Language*, 20(2), pp. 132–136.

²⁰ - Chen, Y. (2007). Acoustic analysis of sustained vowels in children with spastic cerebral palsy. *Perceptual and Motor Skills*, 105(3), pp. 1058–1061.

²¹ - Arar, F., & Attal, Y. Op. Cit, pp. 479–489

This pitch destabilization and elevated perturbation reinforce the findings of Higgins et al. (2005),²² who demonstrated that the deprivation of auditory biofeedback severely hinders the speaker's ability to maintain stable transglottal pressure and targeted vocal frequency.

11.3. Third Subordinate Hypothesis: Intra-Group Variance in Cerebral Palsy

This subsection examines the phenotypic heterogeneity in speech acoustics among subjects with cerebral palsy, analyzing how individual neuromotor distributions and compensatory motor strategies induce distinct phonatory and articulatory profiles within the same clinical diagnostic category.

- **Hypothesis Statement:** Quantifiable intra-group variations in acoustic-phonetic metrics exist among children diagnosed with cerebral palsy.
- **Empirical Validation:** Confirmed. Within the cerebral palsy dyad, Case 03 (Nour El-Houda) maintained relatively stable perturbation metrics and exhibited higher stability during back-vowel production ([o]), whereas Case 04 (Zakaria) exhibited marked intensity variations (82.35 dB for [a] down to 61.21 dB for [i]) and formant centralization (\$F_1\$ exceeding 1161 Hz). These intra-group disparities reflect individual differences in spasticity distribution, orofacial coordination, and compensatory motor strategies, corroborating the findings of Abar and Belhouchat (2023).

Such intra-syndromic variations corroborate Workinger and Kent (1991),²³ who observed that dysarthric manifestations in cerebral palsy vary extensively according to individual postural control, respiratory support, and muscle tone distribution.

11.4. Fourth Subordinate Hypothesis: Intra-Group Variance in Deafness

This subsection examines the acoustic disparities within the deaf group to determine how differences in residual hearing and rehabilitation impact phonatory stability under auditory deprivation.

- **Hypothesis Statement:** Quantifiable intra-group variations in acoustic-phonetic metrics exist among deaf children.
- **Empirical Validation:** Confirmed. Case 05 (Imene) presented phonatory instability across all vowels, characterized by pitch drift (\$F_0\$ range: 196.74–341.68 Hz) and high perturbation values (jitter 5.09%, shimmer 17.60%). In contrast, Case 06 (Yacoub) displayed stronger phonatory control during vowel [o] (\$F_0=285.98\$ Hz, jitter 0.86%, HNR 20.82 dB), accompanied by elevated vocal intensity (82.19 dB) indicative of vocal hyperfunction. These

²² - Higgins, M. B., McCleary, E. A., Ide-Helvie, D. L., & Carney, A. E. (2005). Speech and voice characteristics of children with cochlear implants and children with normal hearing. *Journal of Speech, Language, and Hearing Research*, 48(4), pp. 911–915.

²³ - Workinger, M. S., & Kent, R. D. (1991). Perceptual analysis of speech in children with dysarthria associated with cerebral palsy. In *Clinical dysarthria*. College-Hill Press, Boston, pp. 253–257.

intra-group variations reflect differences in residual hearing, the timing of speech-language rehabilitation, and reliance on visual-orthographic modeling²⁴.

11.5. General Hypothesis: Cerebral Palsy vs. Deafness

This subsection contrasts the acoustic-phonetic profiles of children with cerebral palsy and deaf children to differentiate neuromotor execution deficits from sensory auditory deprivation.

- **Hypothesis Statement:** Measurable acoustic-phonetic divergences exist between children with cerebral palsy and deaf children when evaluated via PRAAT software.
- **Empirical Validation:** Confirmed. While both clinical groups diverged from normative reference values, their pathophysiological mechanisms produced distinct acoustic patterns:
 - **Cerebral Palsy:** Acoustic deviations stem from neuromotor execution failure, characterized by elevated mean \$F_0\$ (hyperfunctional laryngeal spasticity), amplitude fluctuations (respiratory dyscoordination), and restricted formant dispersion (articulatory dysmetria).
 - **Deafness:** Acoustic deviations stem from sensory-auditory deprivation, characterized by elevated perturbation metrics (jitter and shimmer), spectral noise contamination (depressed HNR), pitch instability, and visual-articulatory overshooting (\$F_1\$ elevation).

The acoustic data generated via PRAAT confirm the general hypothesis and validate the capacity of digital acoustic analysis to differentiate neuromotor dysarthric profiles from sensory-based deaf speech patterns.

These individualized articulatory postures, characterized by formant overshooting (\$F_1\$), reflect compensatory visual-kinesthetic reliance in the absence of auditory feedback, consistent with patterns described by Ertmer, Strong, and Sadagopan (2003).²⁵

12. Limitations of the Study

The empirical scope of this investigation is primarily constrained by its small, purposive sample size (\$N=6\$), structured as a comparative multi-case series across three matched dyads. Consequently, while the computerized acoustic measurements yield objective, high-precision descriptive profiles, the findings cannot be generalized across the broader population of children with cerebral palsy or severe hearing loss without caution. Furthermore, variations in individual therapeutic histories, exact neuromotor distribution (diplegic versus quadriplegic configurations), and specific residual audiometric thresholds introduce individual compensatory factors. This study should therefore be interpreted as an exploratory baseline providing qualitative and quantitative acoustic indicators that warrant replication across larger, multi-center pediatric cohorts.

13. Conclusion

Acoustic-phonetic analysis provides an objective method for evaluating speech production in pediatric populations with complex communication disorders. By evaluating acoustic parameters across the cardinal vowels [a], [o], and [i], this study documented distinct speech

²⁴ - Janba, M., & Feni, S. Op. Cit, p. 369.

²⁵ - Ertmer, D. J., Strong, L. M., & Sadagopan, N. (2003). Beginning to talk at 20 months: Early vocal development in a young cochlear implant recipient. *Journal of Speech, Language, and Hearing Research*, 46(2), pp. 331–334.

profiles in children with cerebral palsy and profound hearing loss relative to neurotypical baselines.

The findings confirm that both clinical groups present compromised speech acoustics, but through divergent etiological pathways: children with cerebral palsy exhibit neuromotor coordination deficits, spastic vocal strain, and articulatory restrictions, whereas deaf children show phonatory instability and spectral noise attributable to the disruption of auditory feedback. Significant intra-group variability further highlights the individualized nature of speech motor adaptations in both conditions.

Based on these empirical findings, the following clinical and academic recommendations are proposed:

- **Targeted Speech-Language Intervention:** Implement individualized therapeutic programs targeting respiratory-phonatory-articulatory coordination for children with cerebral palsy, while prioritizing multisensory biofeedback (tactile, visual, and kinesthetic cues) for deaf children.
- **Clinical Integration of Acoustic Software:** Incorporate objective acoustic tools such as PRAAT into routine clinical practice to support standardized diagnostic baseline profiling and quantitative progress tracking.
- **Multisensory Feedback Paradigms:** Deploy real-time visual pitch and intensity displays (such as PRAAT real-time spectrograms, computerized visual targets, and mirror feedback) during therapy to assist deaf children in regulating fundamental frequency and preventing vocal strain.
- **Individualized Remediation Frameworks:** Structure clinical rehabilitation programs around individual acoustic-phonetic profiles rather than generalized diagnostic categories, addressing documented intra-group variations.
- **Multidisciplinary Collaborative Care:** Maintain structured coordination among speech-language pathologists, pediatric neurologists, audiologists, and educators to deliver integrated motor, sensory, and educational interventions.
- **Future Empirical Directions:** Expand future research through longitudinal designs, larger cohorts, and multivariate analyses examining the effects of chronological age, motor severity classifications (GMFCS), audiometric thresholds, and assistive technologies (such as cochlear implants) on speech acoustics.

Research Prospects:

Future empirical inquiries should expand to larger pediatric cohorts to validate these acoustic markers across standardized clinical classifications, particularly the Gross Motor Function Classification System (GMFCS) in cerebral palsy and audiometric hearing thresholds. Additionally, longitudinal studies are warranted to evaluate speech motor adaptation following cochlear implantation versus digital amplification, specifically assessing the clinical efficacy of real-time biofeedback software (such as PRAAT) in enhancing vocal stability and articulatory precision during speech rehabilitation.

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