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PHONETIC CHARACTERISTICS OF POST-STROKE SPEECH AMONG IGBO SPEAKERS: AN ACOUSTIC ANALYSIS

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Abstract
Post-stroke speech impairment may affect the coordination of the articulatory, phonatory and temporal processes involved in speech production. This study examines the phonetic characteristics of post-stroke speech among Igbo speakers through a comparative acoustic analysis of ten (10) post-stroke and ten (10) neurologically healthy speakers. The post-stroke speakers were recruited from Nnamdi Azikiwe Teaching Hospital, Nnewi and Nwakaibe Wellness Home, Enugwu-ukwu while the control group were purposely selected across Awka axis to match with age and gender. Speech samples were recorded in controlled conditions and analysed using Praat, with attention to formant frequencies, fundamental frequency, intensity, duration, Voice Onset Time (VOT), speech rate and pause patterns. The findings reveal differences between the two groups across articulatory, phonatory and temporal dimensions. The post-stroke participants generally exhibited lower pitch and intensity values, variability in formant characteristics and segmental duration, differences in VOT, and altered speech timing. While speech rate varied considerably across participants, the post-stroke speakers consistently produced more frequent and longer pauses than their control counterparts. The findings suggest that post-stroke speech cannot be adequately characterised as simply slower or less precise; rather, it reflects a multidimensional disruption in the coordination of speech production.

Keywords: Post-stroke speech, Acoustic analysis, Formants, Temporal characteristics, Igbo.

1.0 Introduction

Speech production is a highly coordinated process involving the interaction of respiration, resonance, phonation, articulation and prosody (Peacher, cited in Jayaraman and Das, 2025).. Effective speech requires the precise timing and coordination of these systems, and neurological damage resulting from stroke may disrupt this coordination in ways that become perceptible in the acoustic signal (Duffy, 2013). Depending on the site and extent of neurological damage, stroke may be associated with aphasia, dysarthria, apraxia of speech (AOS), or combinations of these disorders. Although these conditions are clinically distinct, their manifestations may overlap in individual stroke survivors, making post-stroke speech a complex phenomenon that cannot always be adequately described through diagnostic labels alone (Basilakos et al., 2015; Ghoreyshi et al., 2022).

Acoustic analysis provides an important means of examining this complexity because it makes it possible to quantify aspects of speech production that may otherwise be described only impressionistically. Measures such as formant frequencies can provide evidence of articulatory realisation, while fundamental frequency and intensity offer information about phonatory characteristics. Then duration and Voice Onset Time (VOT) provide insight into segmental timing and the coordination of articulatory and laryngeal events (Ladefoged and Johnson, 2015; Frommkin et al., 2018; Anyasi, Babarinde and Iloene, 2020; Onwudiwe, 2020). At the level of connected speech, speech rate and pausing reveal how speakers organise speech temporally (Tjaden and Wilding, 2011; Götz, 2013; Kent, 2022). These measures are most informative when considered together because neurological impairment may affect several components of speech production simultaneously.

Previous research has shown that neurological speech disorders may be associated with reduced articulatory precision, instability in phonation and disruption of speech timing. Research on dysarthric speech, for instance, has identified difficulties in maintaining stable rhythm, energy and articulatory control (Zhang, Dang, and Wei, 2014). However, the acoustic consequences of stroke are not necessarily uniform. Some speakers may produce slower speech and prolonged segments, while others may exhibit irregular timing or increased speech rate. Similarly, changes in vocal intensity and pitch may reflect differences in respiratory and phonatory control, but their acoustic manifestation may vary according to the individual's impairment. These observations suggest that post-stroke speech is better understood as a multidimensional phenomenon than as a single, predictable pattern of deviation.

The linguistic context of post-stroke speech also deserves greater attention. Much of the existing research has focused on English and other extensively studied languages, while African languages remain comparatively underrepresented in clinical phonetic research. This gap is particularly important for tonal languages such as Igbo, in which fundamental frequency contributes not only to the acoustic quality of the voice but also to the realisation of lexical contrasts. Research on Igbo has demonstrated the relevance of F0 to tonal production and has also shown that its realisation may vary according to vowel and consonantal context (Nkamigbo, 2017). Consequently, acoustic changes in the speech of Igbo speakers following stroke require interpretation within the phonetic and phonological structure of the language.

Despite the growing use of acoustic methods in the study of neurological speech disorders, empirical evidence on the phonetic characteristics of post-stroke speech among Igbo speakers remains limited. The present study addresses this gap by comparing the acoustic and temporal characteristics of post-stroke and neurologically healthy Igbo speakers. It examines formant frequencies, pitch, intensity, duration, VOT, speech rate and pause patterns, while excluding Vowel Space Area, which is reserved for a separate study. The study argues that examining these measures together provides a more comprehensive account of post-stroke speech than focusing on any single acoustic parameter. Although acoustic analysis has been widely applied to the investigation of neurological speech disorders, relatively little is known about the acoustic characteristics of post-stroke speech among speakers of Igbo, a tonal language spoken predominantly in southeastern Nigeria.

2.0 Review of Related Literature

Acute brain stroke, also known as cerebrovascular accident (CVA), is a critical medical emergency that occurs when the blood supply to part of the brain is interrupted, leading to oxygen deprivation and potential brain cell death (Al-daffery et al., 2023). It is a medical emergency with serious consequences, requiring immediate intervention to minimize brain damage and improve outcomes. Hope, Seghier, Leff and Price (2013) explain that in the acute stage of stroke, several factors can affect a patient’s communicative abilities, including medical status and level of consciousness. These factors aside, damage to the dominant (typically left) hemisphere of the brain, particularly to regions within the territory of the middle cerebral artery, can be especially detrimental to higher-level linguistic functions (i.e., linguistic-symbolic planning) and lower-level planning, programming, and execution of speech motor movements. They affirm that damage to the brain’s speech and language regions can result in aphasia (a disorder of language), apraxia of speech (AOS; a disorder of speech motor planning/programming), and/or dysarthria (a disorder of speech execution and control) (Hope et al., 2013).

However, the relationship between neurological damage and the resulting speech characteristics is complex because stroke may produce different combinations of motor and linguistic impairments (Kent, 2000; Hickok and Poeppel, 2007).. Aphasia, dysarthria and AOS may occur separately or together, and the speech characteristics observed in an individual may reflect overlapping effects (Duffy, 2005; Basilakos, 2018; Palmer and Pauranik, 2021). Consequently, acoustic analysis has become increasingly relevant because it allows researchers to move beyond broad diagnostic categories and examine measurable changes in the speech signal.
One important area of acoustic investigation concerns articulatory precision. Formant frequencies, particularly F1 and F2, provide acoustic evidence of vowel articulation and may reveal changes in the positioning of the tongue and other articulators. Research on dysarthric speech has associated neurological impairment with reduced articulatory precision and difficulty maintaining stable articulatory targets (Zhang, Dang, and Wei, 2014). Nevertheless, formant variation should not be interpreted as a direct diagnostic marker because it may arise from several interacting factors, including individual anatomy, phonetic context and the nature of the neurological impairment. Its significance is therefore greater when formant differences occur alongside changes in other aspects of speech production.

Phonatory characteristics provide another important dimension of post-stroke speech. Fundamental frequency reflects vocal-fold vibration and is perceived primarily as pitch, while intensity is associated with the acoustic energy of the speech signal (Clark, Yallop and Fletcher, 2007; Crystal, 2008; Roach, 2009; Ladefoged and Johnson, 2014; Onwudiwe, 2020; Yule, 2020). Changes in these measures may indicate altered control of phonation or respiratory support. In Igbo, however, pitch requires particular attention because F0 contributes to the realisation of lexical tone. Nkamigbo (2017) demonstrates that the acoustic realisation of Igbo tone is influenced by F0 and may vary according to vowel and consonantal context. This suggests that changes in pitch following stroke may have implications that extend beyond general voice quality, although acoustic differences alone cannot establish whether tonal contrasts have been compromised.

Temporal characteristics provide a further perspective on post-stroke speech. Duration and VOT capture the timing of individual speech events, while speech rate and pauses reflect the organisation of connected speech (Clark, Yallop and Fletcher, 2007; Roach, 2009; Ladefoged and Johnson, 2014). Previous research suggests that neurological speech impairment may be associated with slower speech and increased pausing, but the available evidence also indicates considerable individual variation (Darley, Aronson, and Brown, 1969a & 1969b ; Crystal, 2014; Lansford and Liss, 2014). Foe instance, a speaker may produce slower speech because of reduced motor efficiency, while another may produce a relatively high speech rate but compensate through frequent pauses. This distinction is important because it challenges the assumption that reduced speech rate alone is a sufficient indicator of temporal disruption.

The existing literature therefore points towards three interconnected dimensions of post-stroke speech: articulatory precision, phonatory control and temporal organisation. Yet these dimensions are often examined separately, and relatively little attention has been paid to their interaction in African tonal languages. In the case of Igbo, this represents a significant gap because the acoustic interpretation of pitch must take account of its linguistic role in tone, while the broader phonetic characteristics of post-stroke speech remain insufficiently documented. The present study responds to this gap by bringing together segmental and suprasegmental acoustic measures and temporal characteristics in a comparative analysis of post-stroke and healthy Igbo speech. Rather than assuming that stroke produces a single acoustic profile, the study examines the extent to which different measures converge or diverge in characterising post-stroke speech.

3.0 Methodology

The study adopted a comparative acoustic design involving ten (10) post-stroke Igbo speakers and ten (10) neurologically healthy control group. The post-stroke participants were medically confirmed stroke survivors with observable speech impairment and were recruited through healthcare settings in Anambra State, including Nnamdi Azikiwe University Teaching Hospital (NAUTH), Nnewi and Nwakaibe Wellness Home, Enugwu-Ukwu. Participants with pre-existing speech impairment or relevant mental health conditions were excluded. Healthy Igbo speakers that constituted the control group were recruited around Awka axis to match with age and gender. Speech samples were elicited through structured tasks involving the production of sounds, words and sentences and were recorded in a quiet environment using a Zoom H1n digital recorder.

The recordings were analysed acoustically using Praat (Boersma and Weenink, 2025). The analysis examined formant frequencies, fundamental frequency, intensity, duration, VOT, speech rate and pause characteristics. Speech rate was calculated in syllables per second, while pause analysis considered pause frequency and average pause duration. The acoustic measures were compared across post-stroke and control productions to identify differences in articulatory, phonatory and temporal characteristics. Ethical principles were observed throughout the research process; informed consent was obtained, confidentiality and anonymity were also maintained.

4.0 Data Presentation and Analysis

This section presents the findings of the acoustic and temporal analysis of speech produced by the post-stroke and control participants. The analysis focuses on formant frequencies, pitch, intensity, duration, Voice Onset Time (VOT), speech rate and pause patterns. The results are presented comparatively to identify differences in the speech characteristics of the post-stroke (ST) group and the control (CT) group.

4.1 Formant Characteristics

The mean formant frequencies for the control and post-stroke groups are presented in Table 1 below:

Table 4.1: Mean F1 and F2 Values of Igbo vowels (Control vs Post-Stroke)

Vowel	Group	F1 (Hz)	F2 (Hz)
a /a/	Control	737.87	1718.30
	Stroke	985.19	1827.16
e /e/	Control	549.71	1999.36
	Stroke	633.20	1832.25
i /i/	Control	364.49	2130.56
	Stroke	425.19	1849.76
ị /ɪ/	Control	492.92	1840.93
	Stroke	492.55	2119.55
o /o/	Control	510.18	1776.74
	Stroke	421.66	1216.41
ọ /ɔ/	Control	429.13	1384.07

	Stroke	581.38	1273.51
u /u/	Control	452.96	1558.52
	Stroke	589.38	1730.46
ụ /ʊ/	Control	515.77	1428.46
	Stroke	515.76	1428.46

The analysis of formant frequencies revealed differences between the post-stroke and control groups in the acoustic realisation of vowels. In the post-stroke productions, some high vowels exhibited relatively higher F1 values, while some front vowels showed lower F2 values compared with the control productions. These patterns indicate differences in the acoustic realisation of vowel articulation between the groups. This suggests that the control speakers generally demonstrated clearer and more stable formant structures, whereas some post-stroke productions showed reduced formant clarity and less stable vowel resonance.

The observed differences were not uniform across all vowels or participants. Rather, the post-stroke group showed variability in the degree to which vowel formants differed from those of the control group. This suggests that the acoustic characteristics of vowel production following stroke were heterogeneous across the speakers examined. The findings therefore indicate that post-stroke speech was associated with measurable differences in vowel formant characteristics, particularly in F1 and F2. These differences provide evidence of altered vowel articulation in the post-stroke speech samples, although the specific direction and magnitude of the changes varied across vowel categories.

4.2 Pitch, Intensity and Duration

The mean pitch, intensity and duration measurements for the control and post-stroke groups are presented in Table 2.

Table 2: Mean Pitch, Intensity and Duration of Control and Post-Stroke Groups

Vowel	Group	Pitch (Hz)	Intensity (dB)	Duration (ms)
a /a/	Control	210.25	73.00	627.4
	Stroke	186.57	68.57	619.4
e /e/	Control	212.47	77.45	589.5
	Stroke	194.09	67.57	691.1
i /i/	Control	216.49	75.82	666.8
	Stroke	205.85	72.03	607.7
ị /ɪ/	Control	213.01	74.50	670.3
	Stroke	189.79	69.97	584.1
o /o/	Control	206.63	74.56	547.4
	Stroke	183.94	70.21	559.1
ọ /ɔ/	Control	212.53	75.58	616.3
	Stroke	173.23	69.59	601.9
u /u/	Control	210.51	73.62	686.3
	Stroke	201.90	71.28	641.9
ụ /ʊ/	Control	213.27	77.97	572.1
	Stroke	174.04	71.83	551.6

The pitch measurements show that the post-stroke group recorded lower mean pitch values than the control group across all eight vowel categories. The largest difference occurred for /ɔ/, for which the control group recorded a mean pitch of **212.53 Hz**, compared with **173.23 Hz** for the post-stroke group. A similarly marked difference was observed for /ʊ/, with the control group recording **213.27 Hz** compared with **174.04 Hz** for the post-stroke group. The smallest difference occurred for /i/, where the control group recorded **216.49 Hz** and the post-stroke group **205.85 Hz**.

The intensity measurements likewise show a consistent difference between the two groups. Across all eight vowel categories, the control participants recorded higher mean intensity values than the post-stroke participants. The greatest difference was observed for /e/, where the control group recorded **77.45 dB**, compared with **67.57 dB** for the post-stroke group. The smallest difference occurred for /i/, with mean intensity values of **75.82 dB** for the control group and **72.03 dB** for the post-stroke group.

The duration results, however, reveal a less uniform pattern. The post-stroke group produced longer mean durations for /e/ (**691.1 ms**) than the control group (**589.5 ms**) and for /o/ (**559.1 ms**) than the control group (**547.4 ms**). In contrast, the post-stroke group produced shorter mean durations for /a/ (**619.4 ms** compared with

627.4 ms), /i/ (**607.7 ms** compared with **666.8 ms**), /ɪ/ (**584.1 ms** compared with **670.3 ms**), /ɔ/ (**601.9 ms** compared with **616.3 ms**), /u/ (**641.9 ms** compared with **686.3 ms**) and /ʊ/ (**551.6 ms** compared with **572.1 ms**). The differences in the result may be as a reduced motor coordination or shortnesss of breath.

4.3 Spectrographic Characteristics of Vowel Production

The spectrographic representations provide additional qualitative evidence of differences between the speech productions of the two groups.

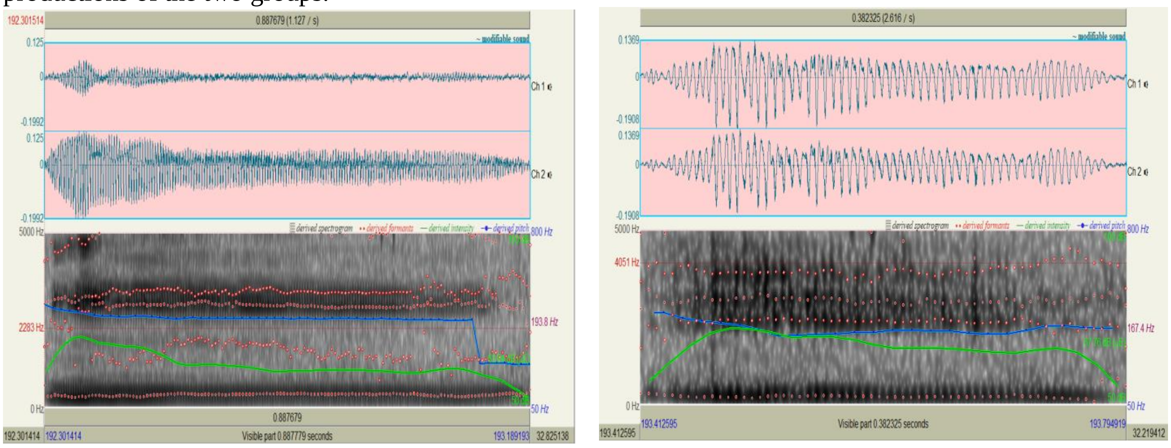

Figure 4.1: Spectrogram of /i/ vowel produced by CT008 (left panel) and ST008 (Right panel).

For /i/, the control participant CT008 produced the vowel with a duration of **888 ms**, whereas the corresponding post-stroke participant ST008 produced the vowel with a duration of **382 ms**. The spectrogram of the control production showed a clearer formant structure and more stable vowel resonance, while the post-stroke production exhibited reduced formant clarity.

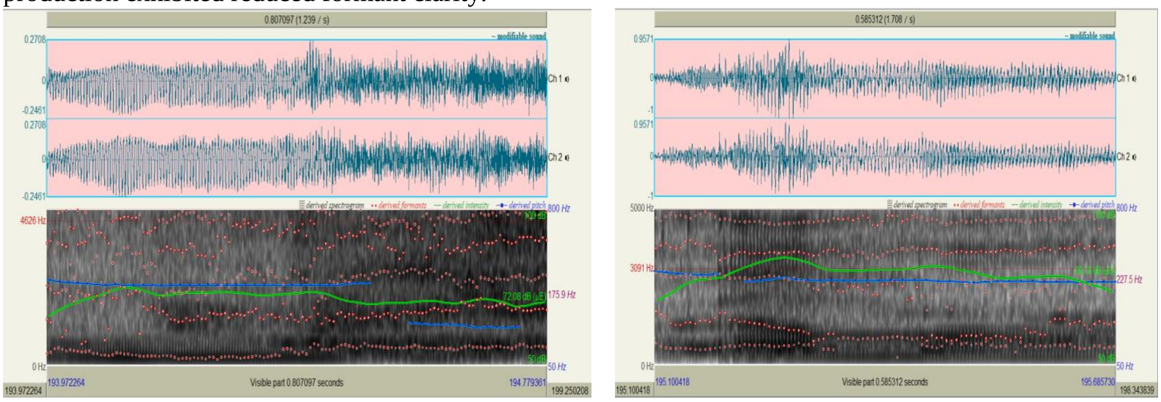

Fig 4.2: Spectrogram of /u/ vowel produced by CT009 (left panel) and ST009 (Right panel).

A similar difference was observed in the production of /u/. The control participant CT009 produced the vowel with a duration of **807 ms**, compared with **585 ms** for the post-stroke participant ST009. The post-stroke production showed reduced temporal extent, weaker harmonic energy and less distinct formant patterns towards the end of the vowel.

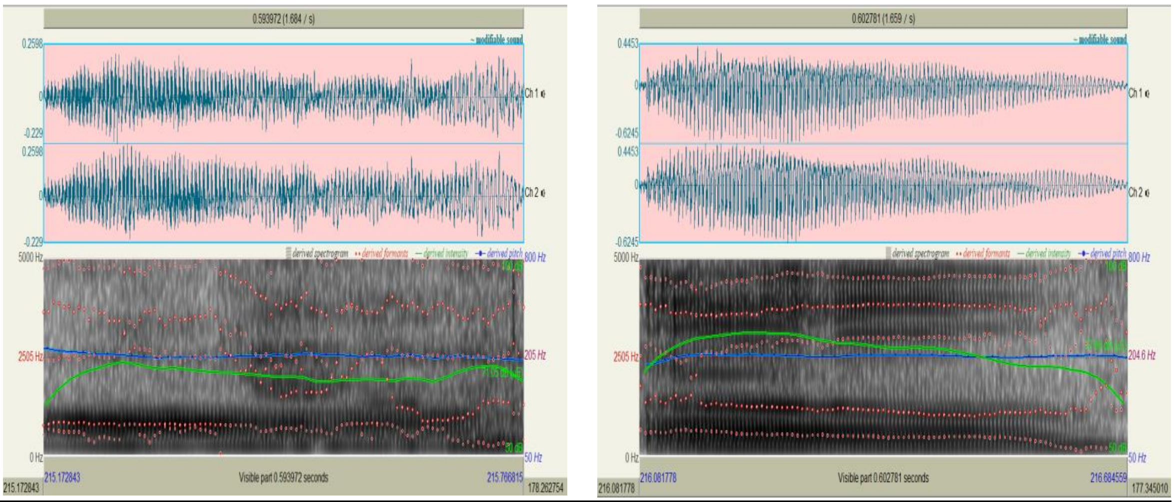

Fig 4.3: Spectrogram of /ɔ/ vowel produced by CT005 (left panel) and ST005 (Right panel).

The production of /ɔ/ presented a contrasting pattern. The control participant CT005 produced the vowel with a duration of **593 ms**, while the post-stroke participant ST005 produced it for **602 ms**. Although the difference in duration was relatively small, the post-stroke spectrogram displayed broader and less sharply defined formant bands with slight fluctuations across the vowel's duration.

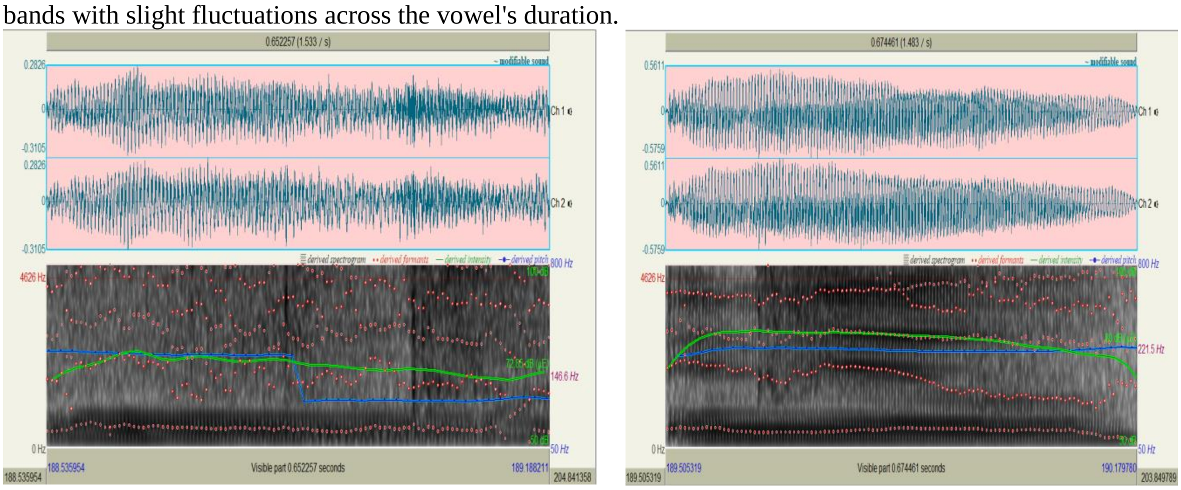

Fig 4.4: Spectrogram of /o/ vowel produced by CT008 (left panel) and ST008 (Right panel).

The production of /o/ similarly showed variation in duration. The control speaker produced the vowel with a duration of **652 ms**, compared with **674 ms** for the post-stroke speaker. The post-stroke production therefore showed a slightly longer duration alongside differences in formant stability.
Taken together, the spectrographic observations demonstrate that the post-stroke speech samples varied in both duration and formant stability. Some productions were substantially shorter than their control counterparts, while others were slightly prolonged. The visual evidence therefore supports the quantitative duration findings presented in Table 1, which indicate that post-stroke vowel duration was variable rather than uniformly increased or decreased.

4.4 Voice Onset Time (VOT)

VOT was analysed for one control participant, CT005, and one post-stroke participant, ST005. The measurements are presented in Table 3.

Table 3: VOT Measurements for Control and Post-Stroke Speakers

Target Word	**Stop**	**CT005 VOT (ms)**	**ST005 VOT (ms)**
Pa	/p/	51	38
Ta	/t/	68	50
Ka	/k/	74	55
Bà	/b/	8	30

Dà	/d/	12	45
Ga	/g/	16	23

The results show a difference in VOT patterns between the control and post-stroke speakers. For the voiceless stops /p/, /t/ and /k/, the control speaker recorded VOT values of **51 ms, 68 ms and 74 ms**, respectively, whereas the post-stroke speaker recorded shorter values of **38 ms, 50 ms and 55 ms**. The reverse pattern was observed for the voiced stops. The control speaker recorded VOT values of **8 ms** for /b/, **12 ms** for /d/ and **16 ms** for /g/. The corresponding post-stroke values were higher, at **30 ms, 45 ms and 23 ms**, respectively.
Thus, the post-stroke speaker showed a reduced separation between the VOT patterns of the voiceless and voiced stops. The difference was particularly evident for /d/, where the post-stroke speaker's VOT was **45 ms**, compared with **12 ms** for the control speaker. The findings therefore indicate differences in the timing relationship between stop release and the onset of voicing in the post-stroke production. It is important to note, however, that the VOT analysis was based on one participant from each group. The results should therefore be treated as an illustrative comparison rather than as a generalisation about the entire post-stroke group.

4.5 Speech Rate

Speech rate was measured in syllables per second using the sentence *O sìrì nri* ('S/he cooked food'), which contains five syllables. The calculations were based on the total duration of each speaker's production.

Table 4: Speech Rate of Control and Post-Stroke Participants

Participant	Total Duration (s)	Speech Rate (syllables/sec)
CT013	0.902	5.54
ST013	1.025	4.88
CT018	1.121	4.46
ST018	1.126	4.44
CT022	1.001	5.00
ST022	0.785	6.37
CT023	0.824	6.07
ST023	0.607	8.24
CT025	0.783	6.39
ST025	0.847	5.90

The results reveal considerable variation in speech rate among the post-stroke participants. ST013 recorded a lower speech rate than CT013, at **4.88** compared with **5.54 syllables per second**. ST018 and CT018 recorded almost identical rates, at **4.44** and **4.46 syllables per second**, respectively. ST025 also recorded a lower rate than the corresponding control participant, with **5.90** compared with **6.39 syllables per second**. In contrast, ST022 and ST023 recorded higher speech rates than their control counterparts. ST022 produced **6.37 syllables per second**, compared with **5.00 syllables per second** for CT022, while ST023 produced **8.24 syllables per second**, compared with **6.07 syllables per second** for CT023.
The results therefore do not demonstrate a consistent reduction in speech rate across the post-stroke participants. Instead, the data reveal substantial individual variation, with some participants producing slower speech and others producing faster speech than their control counterparts.

4.6 Pause Frequency and Duration

The speech-rate and pause analysis of five speakers from the stroke group and control group are presented in Table 5.

Table 5: Speech Rate, Pause Frequency and Average Pause Duration

Participant ID	**Speech Rate (syll/sec)**	**Pause Count**	**Avg Pause Duration (ms)**
CT013	5.54	5	109.94
ST013	4.88	8	111.35
CT018	4.46	6	132.28
ST018	4.44	8	135.36
CT022	5.0	4	190.85
ST022	6.37	7	192.33
CT023	6.07	5	116.24

ST023	8.24	6	120.33
CT025	6.39	4	148.22
ST025	5.90	6	156.34

The results show a consistent difference in pause frequency between the two groups. Each post-stroke participant produced more pauses than the corresponding control participant. ST013 produced **8 pauses**, compared with **5** for CT013; ST018 produced **8**, compared with **6** for CT018; ST022 produced **7**, compared with **4** for CT022; ST023 produced **6**, compared with **5** for CT023; and ST025 produced **6**, compared with **4** for CT025.

The post-stroke group also recorded longer average pause durations in all five comparisons. ST013 recorded an average pause duration of **111.35 ms**, compared with **109.94 ms** for CT013. Similarly, ST018 recorded **135.36 ms**, compared with **132.28 ms**; ST022 recorded **192.33 ms**, compared with **190.85 ms**; ST023 recorded **120.33 ms**, compared with **116.24 ms**; and ST025 recorded **156.34 ms**, compared with **148.22 ms**.

An important feature of the results is that increased pause frequency and duration occurred irrespective of speech rate. The two post-stroke participants who recorded higher speech rates than their controls—ST022 and ST023—also produced more frequent and longer pauses. This indicates that the relationship between speech rate and pausing is not straightforward in the present data.

4.7 Summary of Findings

The acoustic and temporal analysis reveals several differences between the post-stroke and control groups. The formant results indicate differences in the acoustic realisation of vowels, while the pitch measurements show that the post-stroke group recorded lower mean pitch values across all eight vowel categories examined. Intensity was also consistently lower in the post-stroke group across all vowel categories.

Unlike pitch and intensity, vowel duration did not show a uniform pattern. The post-stroke group produced longer mean durations for /e/ and /o/ but shorter mean durations for /a/, /i/, /ɪ/, /ɔ/, /u/ and /ʊ/. The spectrographic comparisons similarly revealed both shortened and prolonged vowel productions, together with differences in formant clarity and harmonic energy. The VOT analysis, based on one participant from each group, showed shorter VOT values for the post-stroke speaker's voiceless stops and longer VOT values for the voiced stops. This pattern indicates differences in the timing of voicing onset between the two speakers.

The speech-rate results also revealed considerable individual variation. Three of the five post-stroke participants recorded lower speech rates than their controls, while two recorded higher rates. In contrast, the pause findings showed a more consistent pattern: all five post-stroke participants produced more pauses and longer average pause durations than their corresponding control speakers. Therefore, the findings demonstrate differences between post-stroke and healthy speech in articulatory realisation, phonatory characteristics and temporal organisation.

5.0 Conclusion

This study examined the phonetic characteristics of post-stroke speech among Igbo speakers through acoustic and temporal analysis. The post-stroke group consistently recorded lower pitch and intensity values, while duration, VOT and speech rate showed considerable individual variation. The most consistent temporal difference was the greater frequency and duration of pauses among post-stroke speakers.

The findings therefore suggest that post-stroke speech among the Igbo speakers examined is best understood as a multidimensional disruption of speech coordination. The interaction of altered formant patterns, unstable pitch, reduced intensity, variable duration, VOT differences, irregular speech rate and disrupted pausing points towards difficulties that extend across articulation, phonation and temporal organisation. This integrated pattern is consistent with the broader literature on neurological speech disorders but also highlights the need for language-sensitive research. In Igbo, where pitch is linguistically meaningful, acoustic changes cannot simply be interpreted through frameworks developed exclusively from non-tonal languages.

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