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Unveiling the Unheard: Acoustic vs. Perceptual Insights into the Occurrence of Intrusive Vowels in Initial Consonant Clusters of Algerian Arabic

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ABSTRACT: *The phonetic nature of consonant clusters is much more intricate than what a human ear may perceive. In this scope, the present research paper aims to experimentally examine biconsonantal complex onsets in Algerian Arabic to unveil the presence of subtle vocalic intervals within these clusters. To this end, both acoustic and perceptual experiments were conducted to investigate the distribution and phonetic properties of intrusive vowels. Results revealed that certain onset clusters exhibited brief, elusive vocoids that do not stem from an epenthesis process but rather serve as transitional elements to coordinate consonantal gestures. These intrusive vowels were observed to surface only in the acoustic record while maintaining audibly intact clusters. Notably, their distribution was constrained by speech rate, degree of voicing, and the sonority profile of the juxtaposed consonants. Besides, they were found to possess a phonetic quality distinct from that of the adjacent lexical vowels.*

KEYWORDS: Intrusive Vowels, Consonant Clusters, Complex Onsets, Algerian Arabic, Acoustic Analysis, Perceptual Test

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1. Introduction

One of the notable phonological features of Algerian Arabic (henceforth AA), similar to other Maghrebi Arabic dialects, is the loss of unstressed vowels in word-initial syllables due to the syncope process (Watson, 2002). As a result, complex onsets in the form of CCV and CCCV are greatly evident in this variety. This phonological feature is believed to have arisen from historical linguistic interaction with Berber, the indigenous language of the region. Crucially, owing to the perplexity that consonant clusters introduce in speech production and perception – stemming primarily from changes such as assimilation, deletion, or insertion – their phonetic and phonological properties have sparked off the interest of a great amount of research cross-linguistically.

A pilot study on consonant clusters in AA has revealed that not all two juxtaposed consonants perceived as consonant clusters are in fact pure clusters. Interestingly, a number of examined words, perceptually judged as containing two-consonant clusters, were found to be contaminated by a short vowel interval in the acoustic record. The present study therefore aims to cast light on the distribution and properties of this interconsonantal vocoid that appears in initial two-consonant clusters based on acoustic and perceptual evidence.

The remainder of this paper is structured as follows: Section 1.1 elucidates the composition of consonant clusters based on the universal sonority sequencing principle. Section 1.2 reviews relevant prior research on the emergence of intrusive vowels in several languages and outlines the objectives of the current study. Section 2 focuses on the acoustic analysis of Algerian biconsonantal onsets. Section 3 is dedicated to the analysis of the perceptual experiment. Section 4 discusses the findings. Finally, Section 5 presents the conclusion, summarizing the main outcomes of this research endeavor.

1.1 Consonant Clusters and Sonority Sequencing Principle

Consonant clustering is said to be guided by the Sonority Sequencing Principle (henceforth SSP). This study is dedicated to exploring initial consonant clusters. In line with SSP, "[u]niversally preferred complex onsets are constructed by selecting a segment lower on the sonority scale and following it with one higher on the scale" (Carlisle, 2001, p. 4). Thus, onset clusters tend to rise in sonority toward the nucleus. According to Clements (1990), the sonority hierarchy posits that consonant clustering is regulated by consonants' manner of articulation as follows (1):

(1) Sonority Scale:
Stops --- Fricatives --- Nasals --- Liquids --- Glides --- Vowels
Least sonorous ______________________ Most sonorous

AA allows consonant combinations that both adhere to and fall foul of the sonority scale. To illustrate, complex onsets in words like /kħal/ 'black', /gmal/ 'lice', /ʃwa/ 'he-grilled', and /dwa/ 'medicine' are formed with different levels of rising sonority: stop-fricative onset /kħ/, stop-nasal onset /gm/, fricative-glide onset /ʃw/, and stop-glide onset /dw/. Contrarily, complex onsets in words like /sˤbaγ/ 'he-colored', /lsæn/ 'tongue', /rged/ 'he-fell asleep', and /wden/ 'an ear' are formed with different levels of falling sonority: fricative-stop onset /sˤb/, liquid-fricative onset /ls/, liquid-stop onset /rg/, and glide-stop onset /wd/. Additionally, this dialect exhibits another type of complex onset that violates the SSP by combining two consonants of the same sonority (i.e., plateaus, Carlisle, 2001). Examples include stop-stop onset in /dbaħ/ 'he-slaughtered', fricative-fricative onset in /ʃħam/ 'fat', and nasal-nasal onset in /nmel/ 'ants'. Consequently, it is reasonable to postulate that the phonotactics of this dialect adds further layers of complexity to the phonetic and phonological properties of consonant clusters' production and perception.

1.2 Intrusive Vowels in Consonant Clusters

The contiguity of two consonants is much more intricate than what the ear may perceive. In effect, though some consonants can be successfully joined together, the gestural features of other consonants may result

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in different coordination patterns as a transition is made from one consonant to another. More importantly, a vocalic interval may surface to enhance a smoother transition.

A spectrographic analysis of consonant clusters and geminates in word-initial position, occurring both in isolated words as well as within sentence context, in Moroccan Arabic has been attempted by Ali et al. (2008). The findings have revealed a vowel material being inserted to break clusters which had previously been thought of as pure consonantal sequences. Ali et al. (2008) thus assumed that this vowel insertion results from an epenthesis process. Despite the fact that epenthesis is one of the most robust processes of vowel insertion in consonant clusters, a growing body of literature has revealed another similar process which was more phonetic than phonological in nature attested across different languages (e.g., Levin, 1987; Davidson & Stone, 2003; Hall, 2003, 2006, 2011; Davidson, 2006; Bradley, 2006; Fougeron & Ridouane, 2008; Ridouane, 2008; Garmann et al, 2021; Crouch, 2023; among others).

Arguably, a distinction has been made between the insertion of an epenthetic vowel and another type of vowel insertion, often referred to as '*excrescent*'. Levin (1987, p.192) has pointed out that, unlike epenthetic vowels, excrescent vowels are inserted due to some phonetic default rules, motivated by the need to mediate contiguous articulations though they carry no phonological significance on their own. Likewise, Hall (2003, 2006) has identified two patterns of insertion: (1) the insertion of a vocalic articulatory gesture (i.e. epenthetic vowels) viewed as phonological segments; and (2) the insertion of phonologically invisible vowels (i.e. non-epenthetic vowels) labeled '*intrusive vowels*'. Her argument is like this: unlike epenthetic vowels, these vocalic materials (i.e. intrusive vowels) do not act as syllable nuclei. They typically constitute phonetic transitions between consonants, often in heterorganic clusters (i.e. clusters of consonants with different oral gestures). She has also proposed that they generally bear the quality of a schwa or a copy of a nearby vowel, albeit with a weak quality yet may disappear altogether at fast speech rates. Hall (2011) has further claimed that intrusive vowels are phonetically weaker than epenthetic and lexical vowels, due to their short duration and centralized quality – good causes to make the speaker unaware of their actual presence. However, when Hall (2011) asked Lebanese Arabic speakers to write down the words which they have produced in their vernacular forms using Classical Arabic orthography, they incorporated the epenthetic vowels into their writing. This means that those speakers were fully conscious of the presence of an epenthetic segment in those clusters.

In his phonetic and phonological examination of vowelless syllables in Tashlhiyt Berber, Ridouane (2008) has averred that the schwa-like vowels inserted in consonant sequences are intrusive vowels (rather than phonological epenthetic vowels) with no structural function. His account has been underpinned by acoustic, fibrescopic, and photo-electroglottographic analysis of voiceless words which have been found to surface without any vocalic syllabic elements. Ridouane (2008) has further provided two phonological arguments in disfavor of epenthesis. The first argument has been built upon versification of Tashlhiyt poetry where syllables containing only voiceless obstruents are considered as light syllables, hence the second consonant is said to occupy the nucleus position. The second argument has been founded on the basis of an assibilation phonological process in which the dental /t/ and /d/ are realized as [s] and [z]. However, the adjacency of /t/ and /r/ blocks the assibilation process, unless there was an intervening syllable nucleus /a, i, or u/. Ridouane (2008, p. 353) has contended that if the schwa acts as a syllable peak, it will also maintain assibilation in words like /t-rkz/ 'she dances' vs. [s(ə)rkz] 'a nonsense word'.

An extensive acoustic, electropalatographic, and laryngographic work has been conducted by Shitaw (2014) on the articulatory timing of two-stop clusters in Tripolitanian Libyan Arabic. In addition to an overlap between two consonantal closures, Shitaw (2014) has pinpointed, on the basis of duration, two types of interconsonantal interval: (1) a short delay emanating from the release of the first stop in syllable-initial position seen as an excrescent; and (2) a longer delay between two closures in syllable-final position seen as an epenthetic. He has further observed that both consonantal gestures decreased in duration in faster articulation rates but increased in slow articulation rates.

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Different explanatory accounts have been suggested as regards the occurrence of vocalic elements in consonantal sequences. Gafos (2002) has proposed a gestural coordination model in which he elucidates that when two consonants are heterorganic, the center of the first consonant's gesture is aligned with the onset of the second consonant's gesture, thus generating an open vocal tract (i.e., an open transition) and giving rise to a schwa-like sound. He then argues that unlike the lexical schwa, a schwa-like vowel is inserted in consonant sequences in Moroccan Colloquial Arabic as a transition between consonantal gestures which may fade away in fast speech. In the same vein, Hall (2006) has assumed that intrusive vowels are non-segmental elements that arise as a result of gestural retiming to facilitate the transition between consonant articulations. Similarly, Davidson and Stone's (2003) ultrasound study has revealed that the presence of an excrescent schwa in the acoustic record emanates from gestural mistiming occurring during a brief period of open vocal tract. Likewise, Bradley (2006) has carried out a cross-dialectal analysis of the realization of Spanish obstruent-rhotic clusters. He has argued that intrusive vowels are an acoustic outcome of non-overlapping consonant gestures and are not part of the segmental representation which explains their invisibility to phonological processes.

Fougeron and Ridouane (2008) have investigated the nature of the vocalic elements which have a schwa-like quality in Tashlhiyt Berber. They, first, argue that these vocoids do not arise from epenthesis which requires its own time slot and articulatory gesture, syllable nuclei position, and phonological context-dependency. In much the same way as previous researchers, Fougeron and Ridouane (2008) have contended that these vocalic intervals are transitional elements which occur as a result of the misalignment of consonantal gestures. They have also noticed that the occurrence of these elements is contingent on the amount of voicing in the sequence, i.e. the transitional vocoid appears when one or both adjacent consonant is voiced.

Likewise, Davidson (2006) has argued that intrusive schwa functions as a repair for what she calls '*ill-phonotactically formed clusters*'. Upon holding an acoustic comparison between the transitional schwa and the phonological schwa in terms of duration and formant frequencies, Davidson (2006) has found that the former is characterized by shorter duration, lower F1 and F2 midpoints, and thus has asserted that the transitional schwa surfaces due to gestural mistiming when articulators move from one constriction to another. She has further elucidated that this gestural mistiming can be regarded as "the failure of a speaker to coordinate the consonants of the cluster with sufficient overlap to prevent the production of a transitional schwa" (Davidson, 2006, p. 132).

Another account has been established by Staroverov (2011) in his analysis of word-final stop-liquid and liquid-stop (e.g. /-kl/ and /-lk/, respectively) clusters in Russian. Staroverov (2011) has investigated the acoustic attributes of the vocalic material that appears in the temporal lag between two-consonant constrictions, and has compared it with the lexical schwa vowel that appears in other phonological contexts. He has figured out that this vocalic interval which is characterized by a shorter duration, lower F1 and F2, and higher F3 vis-à-vis the lexical vowel is in fact an extension and vocalization of the liquid gesture rather than a separate independent transitional vowel. However, this liquid extension is realized only in stop-liquid clusters but never detected in the opposite order (i.e., liquid-stop clusters). Staroverov (2011) has argued that this vocalic extension sustains the perceptibility of the liquid /l/.

Crouch et al.'s (2023) analysis of complex onsets in Georgian has demonstrated that intrusive vocoids are articulatory artifacts that appear during the extended lag between consonant constrictions. These vocoids possess a schwa-like quality (F1 around 500 Hz and F2 around 1500 Hz). Besides, the researchers have found that the distribution and duration of these vocalic elements are influenced by the cluster's sonority profile. They were more evident in onsets with rising sonority compared to those with falling sonority and exhibited shorter lags in falls than in rises. In this regard, Hall (2003) in her cross-linguistic survey has claimed that they are more likely to emerge with liquids than with other sonorants, and more frequently with rhotics than laterals, except the alveolar trill. She has further established an implicational hierarchy for the occurrence of the intrusive vowels as follows (Hall, 2003, p. 28):

(2) Vowel intrusion triggers
obstruents, if ever → other approximants, nasals → r → l → ɾ, ʁ → gutturals [such as /ħ, h, ʕ, x, q/]
Among nasals: m→ n

Similarly, Garmann et al. (2021) have discovered that vocalic intrusions in Norwegian clusters are more frequent when the cluster is made up of a voiced stop as the first consonant (C1) and a tap or a flap as the second consonant (C2). Besides, they are more common when the second consonant is a liquid, particularly if it is a rhotic tap or flap rather than a lateral.

To recap, as has been reported above, several studies have sought to scrutinize the emergence of intrusive vocoids between consonants in various languages. Our study posits that this phenomenon is also apparent in Algerian consonant clusters. Yet, as far as we know, no previous research has addressed it, leading to an under-researched area in the phonetic and phonological literature of this dialect. As a corollary, we attempt to conduct an experimental study to analyze the occurrence of this phenomenon in the complex onsets of AA, ergo addressing this gap in the literature. Using the terminology proposed by Hall (2003) in her cross-linguistic study of this phenomenon, we refer to such interconsonantal vocoids as 'intrusive vowels'.

The current research paper aims to explore the distribution and properties of intrusive vowels when appearing in biconsonantal clusters of AA. Specifically, we aim to investigate, drawing on an acoustic experiment, whether the emergence of such vocoids is constrained by the sonority shape of the onset cluster (rising sonority, falling sonority, and plateau), the extent of voicing (when both consonants C1 and C2 are voiced, both C1 and C2 are voiceless, or when one of them is voiced and the other is voiceless), place of articulation (homorganic clusters, i.e., same place, and heterorganic clusters, i.e., different places), speech rate (normal and fast), and context of occurrence (in isolation and within a sentence). We also aim to examine whether the duration of intrusive vowels is affected by the aforementioned variables. Additionally, we attempt to scrutinize the acoustic properties of such vowels in order to determine their quality, focusing particularly on their formant frequencies (F1 and F2) and duration in comparison to those of the adjacent lexical vowels. Alternatively, the study employs a second experiment which is a perceptual test where a group of native speakers with a high level of education and expertise, who are unaware of the study's objectives, will assess whether the target words are perceived to contain consonant clusters (CCs) or not based solely on their perception. Thereby, the present research will unveil both acoustic (or articulatory) and perceptual correlates of the interconsonantal vowel intrusion, offering valuable insights into the phonetics and phonology of AA.

In order to meet these objectives, we will address the following research questions:

1. Do complex onsets in Algerian Arabic exhibit vowel intrusion?
2. Under what conditions do intrusive vowels appear in Algerian Arabic biconsonantal clusters, and how do these conditions affect their duration?
3. Do these intrusive vowels share the same acoustic correlates as the adjacent lexical vowels?
4. Are intrusive vowels heard or unheard by the Algerian Arabic speakers' ears?

In line with these research questions, our hypotheses are as follows:

- We expect that consonant clusters in AA demonstrate vowel intrusion as our pilot study has unveiled.
- We hypothesize that the appearance of intrusive vowels is constrained by the sonority shape, voicing extent, and place of articulation of the combined consonants, in addition to the speaking rate and the context of the utterance. We predict that these vocoids appear significantly when the consonant sequence contains a voiced stop or a trill, yet they may disappear at a fast speech rate.
- We anticipate that intrusive vowels do not share the same acoustic correlates (F1, F2, and duration) as the neighboring lexical vowels.

– Finally, we propose that AA speakers are unaware of the presence of these elements that putatively surface only in the acoustic record, whilst maintaining audible pure clusters.

2. Experiment One: Acoustic Analysis

2.1 Methods

2.1.1 Subjects and Stimuli

Five native (4 males and 1 female) speakers of AA were recruited for the production experiment. All participants were aged between 23 and 27 years and had no background of speaking or hearing impairment. They were provided with a stimulus corpus (see Appendix A) composed of 56 native meaningful words (43 monosyllabic and 13 disyllabic) that start with biconsonantal complex onsets. The participants were recorded while uttering the target words occurring in two contexts: in isolation and within the carrier sentence /gu:lli — zu:ʒ xatˤra:t/ 'Tell me — twice'. The complex onsets consist of voiced or voiceless consonants (e.g., /br/, /tk/, /ns/, /sˤl/), with different sonority shapes: rising sonority (e.g., /ks/, /ml/, /tr/, /dw/), falling sonority (e.g., /ħk/, /wr/, /rb/, /jt/), and plateau (e.g., /db/, /sf/, /mn/, /jw/). These onsets also occur in both homorganic (e.g., /ls/, /zl/) and heterorganic (e.g., /sm/, /nħ/) places of articulation. Furthermore, the corpus was supplemented with 10 extra words that begin with simplex onsets to diversify the stimuli. In total, this resulted in 2640 tokens (2240 target tokens and 400 non-target tokens): 66 words * [4 repetitions at a normal speech rate (twice in isolation and twice within a sentence) + 4 repetitions at a fast speech rate (twice in isolation and twice within a sentence)] * 5 participants. All target clusters were followed by either /a/, /a:/, /e/, /æ/, /u:/, or /i:/ lexical vowels and preceded by the vowel /i/ in the carrier sentence. Table 1 below elucidates the distribution of the stimulus words according to the type and context of the consonant cluster:

Context	Type	Number of words
rising sonority	stop + (fricative/nasal/liquid/glide), fricative + (nasal/liquid), nasal+ liquid, liquid + glide	22
falling sonority	fricative + stop, nasal + (fricative/stop), glide + (liquid/stop), liquid + (fricative/stop)	23
plateau	stop + stop, fricative + fricative, nasal + nasal, glide + glide	11
voicing	+V+V / -V-V / +V-V / -V+V	56 (27/8/11/10)
place of articulation	homorganic / heterorganic	29 (13/16)
extra words	without consonant clusters	10

Table 1. Distribution of stimulus words according to context and type of the consonant cluster

As can be seen, a variety of consonant combinations with different articulatory features (in terms of voicing and place/manner of articulation) was chosen. The goal is to determine the specific contexts in which vowel intrusion is most commonly attested.

2.1.2 Procedures and Measurements

The participants were recorded in a quiet and anechoic room. They were instructed to utter the stimulus words, presented randomly on laptop screens, first in isolation then embedded in the carrier sentence at both normal/habitual and fast speech rates. If any hesitations or errors occurred, the researcher requested them to reiterate the utterance. The stimuli were displayed in Arabic script, with a diacritic 'Es-suku:n' (a circle-shaped symbol °) used to indicate consonant clusters. The recordings were made using a Dictopro digital voice recorder, which features highly sensitive dual microphones and advanced noise reduction capabilities, and saved as WAV audio files.

Sound segmentation was manually assessed using PRAAT speech analysis software, version 6.2.10 (Boersma & Weenink, 2022), relying on waveforms, spectrograms, as well as auditory judgment. Following previous research, intrusive vowels were phonetically transcribed as a superscript schwa [^{ə}]. Vowel duration (both intrusive and lexical vowels) in milliseconds (ms) —when intrusive vowels were present— was measured from the onset of the first formant (F1) to the offset of the second formant (F2) through visual and auditory inspection. F1 and F2 frequencies in Hertz (Hz) were gauged at the midpoint position of the vowels.

2.2 Results of the Acoustic Experiment

2.2.1 Occurrence of Intrusive Vowels

As expected, the acoustic scrutinization demonstrated that vowel intrusion is evident in the AA dialect. Certain onset clusters exhibited either long or short interconsonantal vocalic material, while other clusters remained intact i.e., no vocalic interval was detected. Figure 1 below illustrates the three patterns:

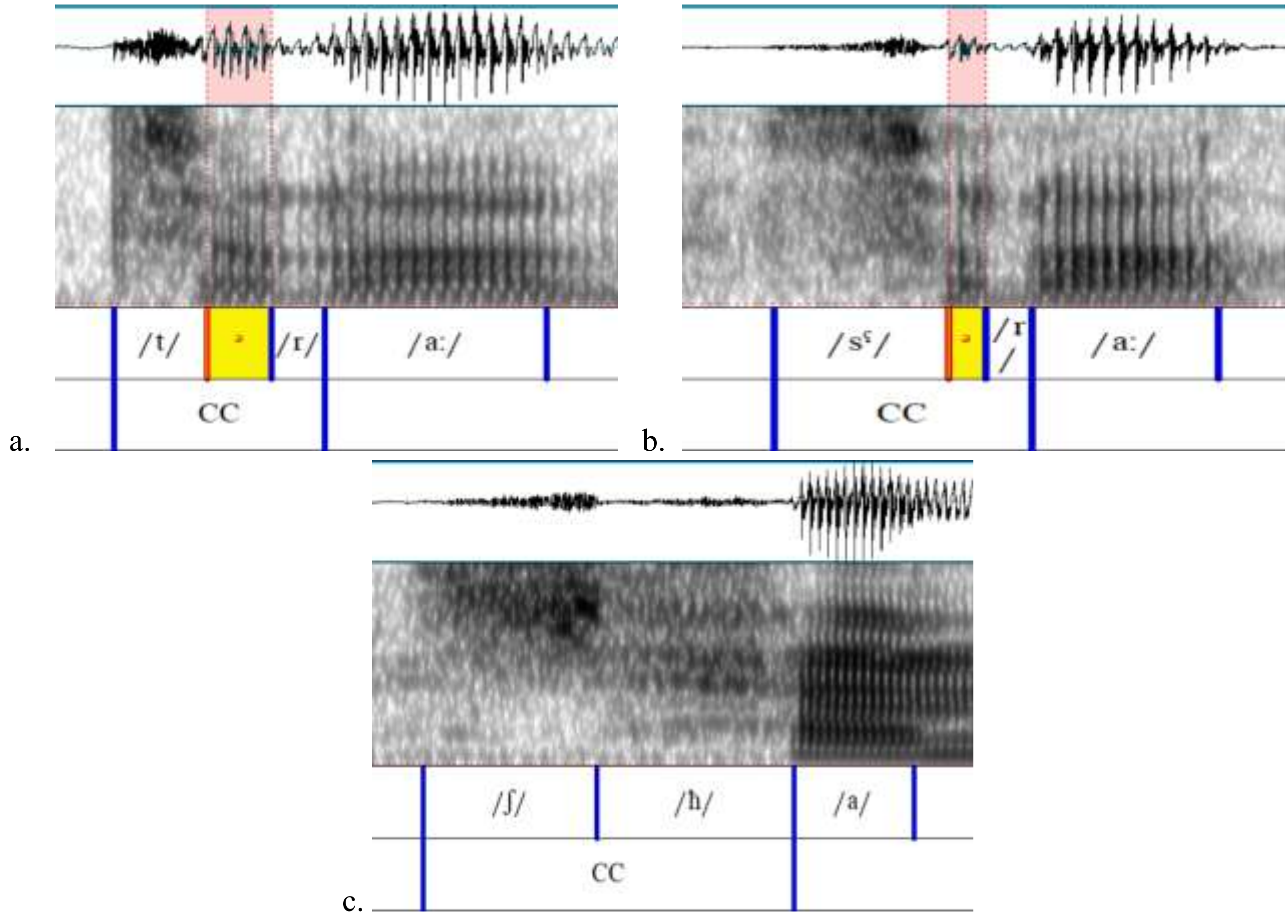

Figure 1. Illustrations of waveform and spectrogram for the realization of onset clusters: (a.) long intrusive vowel in [t^{ə}ra:b] 'soil', (b.) short intrusive vowel in [s^{ə}ra:t] 'happened', and (c.) no appearance of vowel intrusion in [ʃħam] 'fat'

The initial statistical analysis showed that intrusive vowels occurred in 423 out of 2240 tokens throughout the whole dataset. What is also worth noting is that these elements were not consistently attested among all repetitions of the same speaker. This indicates that the occurrence of vowel intrusion seems both restricted and elusive.

2.2.2 Distribution of Intrusive Vowels

This section reports the results of the statistical analysis on how the occurrence of intrusive vowels was distributed in the entire dataset across the following independent variables: the context of occurrence (isolation vs. within sentence), speech rate (normal vs. fast), sonority shape (rising, falling, or plateau), place of articulation (homorganic vs. heterorganic), and extent of voicing (+V+V, -V-V, +V-V, -V+V)[1]. Results are encapsulated in Table 2 below:

Context of occurrence		isolation	Within sentence		
	-IV	903 (80.6%)	914 (81.6%)		
	+IV	217 (19.4%)	206 (18.4%)		
	total	1120 (100%)	1120 (100%)		
Speech rate		normal	fast		
	-IV	885 (79%)	932 (83.2%)		
	+IV	235 (21%)	188 (16.8%)		
	total	1120 (100%)	1120 (100%)		
Sonority shape		rising	falling	plateau	
	-IV	620 (70.5%)	853 (92.7%)	344 (78.2%)	
	+IV	260 (29.5%)	87 (7.3%)	96 (21.8%)	
	total	880 (100%)	920 (100%)	440 (100%)	
Place of articulation		homorganic	heterorganic		
	-IV	400 (76.9%)	1417 (82.4%)		
	+IV	120 (23.1%)	303 (17.6%)		
	total	520 (100%)	1720 (100%)		
Extent of voicing		+V+V	-V-V	+V-V	-V+V
	-IV	786 (72.8%)	320 (100%)	440 (100%)	271 (67.8%)
	+IV	294 (27.2%)	0	0	129 (32.3%)
	total	1080 (100%)	320 (100%)	440 (100%)	400 (100%)

Note. IV: intrusive vowel

Table 2. Frequency distribution of intrusive vowels across context of occurrence, rate, sonority, place of articulation, and voicing extent

As can be seen, the distribution of the occurring intrusive vowels varied notably across the examined independent variables. Starting with the context of occurrence, the appearance of intrusive vowels was not significantly different between those produced in isolation (19.4%) and those within sentences (18.4%). Regarding speech rate, vowel intrusion was found to be more common in normal speech (21%) than in fast speech (16.8%), suggesting that a faster rate tends to suppress their emergence. Results also revealed that sonority shape played a significant role in the occurrence of such vocoids in that they were most frequently evident in rising sonority (29.5%), followed by plateau (21.8%), and least often in falling sonority (7.3%).

[1] +V refers to a [+voiced] consonant, while -V refers to a [-voiced] or voiceless consonant.

Additionally, the presence of intrusive vowels seems to be influenced by the place of articulation of the combined consonants, with a higher frequency in homorganic clusters (23.1%) compared to heterorganic clusters (17.6%). This indicates that consonants sharing similar places of articulation may trigger this phenomenon more than those with distinct articulatory positions. Finally, voicing combinations showed an intriguing effect on the distribution of vowel intrusion. The latter was only present in +V+V (27.2%) and -V+V (32.3%) clusters but was entirely absent in -V-V and +V-V environments.

In light of these findings, it is vital to filter our data in order to make crucial headway in identifying the complex onsets that significantly instigate the occurrence of intrusive vowels. Accordingly, the target clusters most susceptible to vowel intrusion were identified in the following stimulus words: (1) occurring more frequently in [dˤᵊrab] 'hit', [tᵊra:b] 'soil', [mᵊra] 'woman', [sˤᵊra:t] 'happened', [bᵊri:t] 'recovered', [rᵊbi:ʕ] 'spring', [rᵊged] 'slept', [bᵊna] 'built', [tˤᵊbag] 'plate', and [dᵊbaħ] 'slaughtered'; and (2) occurring less frequently in [qᵊdi:m] 'ancient', [gᵊmal] 'lice', [ɣᵊmel] 'rotted', and [nᵊmal] 'ants'.

A closer look at the articulatory features of the target onset clusters in these words suggests that intrusive vowels are more likely to emerge in sequences involving a liquid plus another consonant sound, namely a stop, or in sequences of two-stop consonants. Besides, these vocalic elements may also appear in clusters consisting of a nasal consonant. However, at least two qualifying remarks are in order here. First, while most of the contaminated clusters appear to contain a liquid consonant, only the trill segment /r/ was found to trigger an intrusive vowel, whether it is assigned as C1 (as in /rb/ and /rg/) or C2 (as in /tr/ and /br/). Alternatively, no instances of this phenomenon were attested in the presence of the lateral /l/ sound. Second, after the trill and stop consonants, vowel intrusion was notably stimulated in the presence of the nasal /m/ consonant rather than its counterpart /n/ sound.

Moreover, certain consonant combinations maintained acoustically pure clusters. Specifically, intrusive vowels did not emerge at all in clusters composed of fricative-fricative, glide-glide, stop-fricative/fricative-stop, stop-glide/glide-stop, and liquid-glide consonants.

2.2.3 Properties of Intrusive Vowels

In an attempt to pinpoint the phonetic nature of intrusive vowels observed in the present experiment, a series of ANOVA tests were carried out. In this regard, an additional independent variable named 'vowel type' was created to distinguish intrusive vowels from lexical vowels. The statistical analysis aimed to examine the effect of the aforementioned independent variables on the duration of these vocoids as well as to identify whether they share the same acoustic properties (duration, F1, and F2) as the adjacent lexical vowels.

2.2.3.1 Duration of Intrusive Vowels

The acoustic analysis demonstrated that intrusive vowels' duration ranged from 7 to 71 ms, with a mean duration of 27 ms. This variation was found to emanate from the impact of the independent variables. Particularly, the context of occurrence had a statistically significant impact on vowel duration [$F(1, 421) = 16.38$, $p<.001$]. In fact, intrusive vowels were observed to be longer when produced in isolation (29 ms) compared to when produced within sentences (24 ms). Speech rate also significantly influenced duration [$F(1, 421) = 15.09$, $p<.001$], in that it was longer in normal speech (28 ms) than in fast speech (24 ms). Besides, sonority shape had a significant effect on the duration of intrusive vowels [$F(2, 420) = 37.29$, $p<.001$]. At this juncture, a Tukey post hoc was performed to compare the effect between sonority types. Results indicated significant differences in duration between rising sonority and plateau as well as between falling sonority and plateau ($p<.001$ for both), but no significant difference between rising and falling sonority shapes ($p=.551$). Indeed, the mean values of duration were 29 ms for rising sonority, 28 ms for falling sonority, and 19 ms for plateau. This suggests that intrusive vowels were shorter in plateau sequences compared to those with rising or falling sonority shapes. On the other hand, no significant effect was observed for place of articulation (p=.120). Intrusive vowels displayed closely similar durations in homorganic clusters (28 ms) and heterorganic clusters (26 ms). However, voicing did reveal a statistically significant impact on duration [$F(1, 421) = 19.61$, p<.001], with intrusive vowels being longer in +V+V clusters (28 ms) than in -V+V clusters (23 ms).

2.2.3.2 Intrusive Vowels vs. Lexical Vowels

Initially, the statistical results displayed significant differences between intrusive vowels and adjacent lexical vowels, as analyzed throughout the entire data (846 tokens), in terms of duration and F1 (p<.001 for both). However, no significant difference was detected in terms of F2 (p =.422). Figure 2 below shows that lexical vowels were longer in duration and realized with higher F1 in comparison to intrusive vowels, whereas F2 remains identical for both.

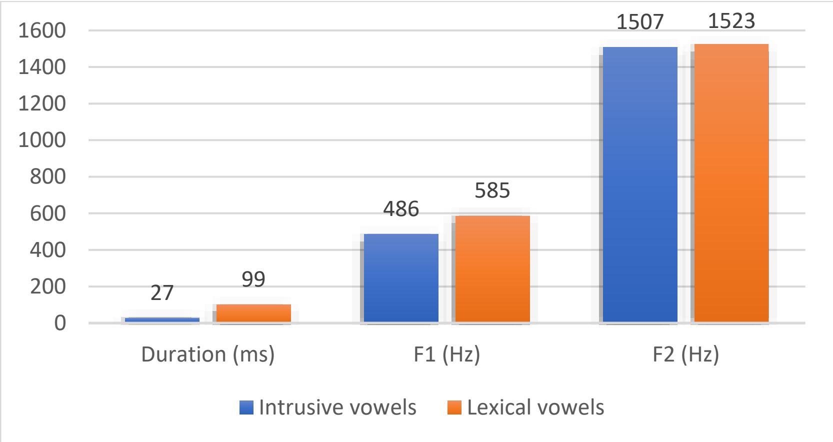

Figure 2. Comparison of mean duration, F1, and F2 values between intrusive vowels and lexical vowels

Moreover, these acoustic measures were assessed using a number of two-way ANOVA tests to compare the phonetic behavior of both types of vowels across the independent variables (context of occurrence, speech rate, sonority shape, place of articulation, and voicing). Accordingly, it was observed that vowel duration remained significantly different when interacting with most independent variables, with lexical vowels consistently being longer than intrusive vowels. Yet, an exception was noted for place of articulation, where no significant difference in duration was found between homorganic and heterorganic clusters for either vowel type. F1, on the other hand, did not exhibit any difference, except for a slight interaction effect between vowel type * sonority shape (p=.032). The F1 for intrusive vowels indicated the following pattern: rising sonority > falling sonority > plateau, while the F1 for lexical vowels exhibited the following order: rising sonority > plateau > falling sonority. As for F2 measurement, results showed no significant difference between the two types of vowels, except for place of articulation. Unlike intrusive vowels, where F2 values did not vary significantly, lexical vowels had higher F2 values in heterorganic clusters than those in homorganic clusters.

3. Experiment Two: *Perceptual Test*

3.1 Methods

Eight native speakers of AA, aged between 30 and 50 years, all with advanced expertise in linguistics (either as PhD students or holders of a PhD degree) and unaware of the study's objectives, participated in the perceptual experiment. The goal was to achieve experts' insights on the perceptibility of the vocalic interval. Each participant received a link to a Google Form that included sound files of the stimulus words. They were requested to listen to the recordings and then select one of the three options: "Yes" (indicating the word begins with an initial CC), "No" (indicating it does not), or "Other" (for any further comment). The sound recordings were chosen from the first experiment (acoustic/production test) and involved stimulus words with acoustically scrutinized CCs, both those involving intrusive vowels and those with pure onset clusters, in addition to some intervening extra words with simplex onsets. In total, the stimuli consisted of 20 sound files, representing in random order 20 recorded stimulus words, as shown in the table below:

Stimuli	Words and Gloss
Target words with CCs having intrusive vowels	[dˤᵊrab] 'hit', [tᵊra:b] 'soil', [mᵊra] 'woman', [sˤᵊra:t] 'happened', [bᵊna] 'built', [tˤᵊbag] 'plate', [dᵊbaħ] 'slaughtered' [rᵊbi:ʕ] 'spring', [nᵊmal] 'ants', [rᵊged] 'slept', [bᵊri:t] 'recovered', [gᵊmal] 'lice', [qᵊdi:m] 'ancient'
Words with pure CCs	/kħal/ 'black', /ʃħam/ 'fat'
Extra words with simplex onsets	/sa:ʕa/ 'watch', /xa:təm/ 'ring', /fi:l/ 'elephant', /kæs/ 'cup', /ħu:t/ 'fish'

Table 3. Stimuli of the perceptual test

3.2 Results of the Perceptual Test

Expectedly, the results of the perceptual experiment confirmed that intrusive vowels are audibly elusive and imperceptible to the human ear. All participants, regardless of the acoustic classification of the stimulus words as containing either pure or non-pure clusters, consistently perceived them as words having biconsonantal onsets. For instance, words like [tᵊra:b] 'soil' and /kħal/ 'black' were similarly viewed as starting with a consonant cluster, unlike /xa:təm/ 'ring' which was identified as a word starting with a single consonant. Consequently, these findings suggest that intrusive vowels remain inaudible even to native experts, emphasizing that only an acoustic analysis can accurately detect their presence.

4. Discussion

As anticipated, not all pairs of juxtaposed consonants perceived as clusters are in fact phonetically true clusters. The findings of the current research have unveiled that certain complex onsets in Algerian Arabic may reveal acoustically emerging, yet often barely audible, intervening vocalic elements. This asymmetry between acoustic evidence and perceptual judgment lends further weight to the assumption in favor of the intricate nature of clustered consonantal gestures.

On the basis of the results obtained, it is reasonable to postulate that such vocalic intervals do not stem from the epenthesis process. Recall from earlier sections, epenthetic vowels are claimed to have a longer duration, unrestricted distribution and occurrence, and speakers' perception and recognition (Hall 2003, 2006, 2011). However, the interconsonantal vocoids of the present experiment are characterized by shorter duration, lower F1, optional occurrence, and speakers' unconsciousness of their presence all endorse the already-established claim that they are intrusive vowels, or excrescent vowels, which may have surfaced in open transition between consonantal gestures (Gafos, 2002; Hall, 2003, 2006; Bradley, 2006; Davidson, 2006; among others).

Gafos' (2002) gestural coordination framework suggests that a schwa-like vowel is inserted in consonant clusters in Moroccan Arabic due to an open transition between the first and second consonantal gestures. Nonetheless, given that both Moroccan and Algerian Arabic are mutually intelligible dialects, it is feasible to compare Gafos's (2002) illustrative codas that consist of a transitional schwa-like sound (e.g. [sˤna:dˤᵊl] 'sandals', [ħwa:nᵊt] 'shops', see Gafos, 2002 for more examples) to the consonantal sequences in the present study. Apparently, although these transitional schwa-like sounds in Moroccan Arabic seem to have a small yet perceptible amount of time, they are more prominent than those found in the clusters of the present study, which are only faintly noticeable through a spectrographic diagnosis. The relatively short mean duration (27 ms) of these intrusive vowels indicates that the vocal tract remains insufficiently open between the constrictions of the two juxtaposed consonants, rendering these intervening vocoids barely audible.

Furthermore, the acoustic scrutiny has disclosed that the appearance of intrusive vowels is not prevalent across AA consonant clusters. Instead, they tend to intervene in complex onsets, most commonly consisting of a trill /r/ in either the C1 or C2 positions. In contrast, clusters containing a lateral /l/ remain completely intact. This pattern partially aligns with observations in several languages such as Spanish and Norwegian, as reported in previous studies (such as Bradley, 2006, 2007; Gibson et al., 2019; Garmann et al., 2021). Unlike AA, both liquids in these languages have been found to prompt intrusive vowels, yet with a higher occurrence in clusters with a tap than with a lateral. In this scope, Bradley (2007) argued that the extra-short constriction of /r/ triggers the emergence of an intrusive vowel cross-linguistically within consonant clusters because it creates an optimal acoustic backdrop, allowing the listener to clearly distinguish this extra-short constriction from the constriction of the neighboring consonant.

Additionally, intrusive vowels were also found to be more likely triggered in adjacency to a voiced stop or when intervening between pairs of stop consonants. This phenomenon can be attributed to the articulatory dynamics of stop consonants, whose perceptibility highly relies on their release burst, unlike other consonants that are audible during their constriction phase. Besides, AA lacks aspiration – a feature common in stop consonants of several languages like Germanic languages – which also contributes to the perceptibility of these sounds. All these factors make the presence of an intrusive vowel more necessary to ensure a smoother articulatory transition between consonants, thereby aiding in clearer speech perception.

As for the distribution of the intrusive vowels, results showed that their emergence is affected by several factors including speech rate, sonority shape, place of articulation, and voicing extent. However, no significant effect was identified for the context in which they occur. Strictly speaking, whether occurring in isolation or within sentences, intrusive vowels did not exhibit any notable difference. In this regard, it can be merely suggested that speakers may struggle to coordinate consonantal gestures, resulting in gestural misparsing in both careful speech (when producing words in isolation) and non-careful or connected speech (when producing words within sentences). On the other hand, intrusive vowels were observed to emerge in normal (or habitual) speech rate and tended to diminish in fast speech. This finding matches that obtained in previous studies (e.g., Gafos, 2002; Hall, 2003; Shitaw, 2014), underpinning the assumption that faster articulation reduces the transitional space between adjacent consonants, thereby minimizing the production of these transitional vocoids. Moreover, the distribution of intrusive vowels was also contingent upon the sonority shape of the cluster, demonstrating an agreement with Crouch et al.'s (2023) findings for Georgian complex onsets. Specifically, more intrusive vowels occurred in rising sonority clusters, followed by plateau clusters, and a fewer in falling sonority clusters. This result suggests that the higher the sonority scale of the cluster, the wider the transitional opening is, ergo the more likely intrusive vowels are to be triggered. Additionally, the place of articulation of the clustered consonants seems also impactful on the

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distribution of these vowels, which were more evident in homorganic clusters than in heterorganic ones. However, this finding should be interpreted cautiously, as the present experiment's stimuli employed a considerable number of words with heterorganic clusters compared to homorganic ones. Therefore, this result cannot stand robustly enough to contradict Hall's (2003) cross-linguistic survey, where she averred that intrusive vowels failed to occur in homorganic clusters. Finally, in accord with previous studies, the present study posits that a high amount of voicing tends to stimulate a greater occurrence of vowel intrusion. Indeed, this phenomenon was most commonly attested in harmonically voiced clusters or when at least the second consonant in is voiced in mixed-voicing clusters.

Regarding the phonetic characteristics of these emerging vocoids, it was found that their temporal lag is notably brief (27 ms), particularly when surrounded by voiced consonants and uttered within sentences and at a fast speech rate. They are also significantly shorter than that of the neighboring lexical vowels. This admittedly accounts for being phonologically invisible and unheard by listeners. Besides, the acoustic experiment revealed an asymmetrical phonetic quality between the intrusive vowels and lexical vowels, ensuring that these vocalic intervals do not arise from an extension of the adjacent lexical vowels. Rather, they are transitional elements that appear as a result of the misalignment of consonantal gestures, as has been vouched for in previous studies (e.g., Gafos, 2002; Davidson, 2006; Fougeron & Ridouane, 2008; and Staroverov, 2011). In the same vein, the acoustic correlates of the intrusive vowels in the current work corroborate earlier research (Gafos, 2002; Davidson, 2006; Ridouane, 2008; Staroverov, 2011; and Crouch et al., 2023; among others) by establishing that they bear a schwa-like quality by virtue of the shorter duration, lower F1 and F2 values. Parallel to Crouch et al.'s (2023) findings, these vocalic intervals were found to possess F1 values around 500 Hz and F2 values around 1500 Hz, further supporting their schwa-like nature.

To bring this discussion to a close, it is pertinent to relate our findings back to the preliminary established hypotheses. As predicted, the results obtained largely conform to these hypotheses. First, the acoustic scrutiny confirmed that vowel intrusion is an inevitable phenomenon in the phonetics of certain consonant clusters in Algerian Arabic. Second, the emergence of intrusive vowels was observed to be constrained by speech rate, voicing degree, and the sonority profile of the juxtaposed consonants. Third, these vocalic intervals are distinct from neighboring lexical vowels; they exhibit a schwa-like quality, which results from the speakers' failure to perfectly coordinate consonantal gestures. Last, as expected, these transitional vocoids are typically imperceptible and challenging for speakers to discern auditorily.

5. Conclusion

Drawing on both acoustic evidence and perceptual judgment, the present research paper uncovered that a set of consonant clusters in Algerian Arabic warrant cautious consideration due to their tendency to feature brief, elusive, and imperceptible intrusive vowels as a result of the misalignment of consonantal gestures. These vowels are argued to surface only in the acoustic record while the clusters themselves are perceived as audibly pure. In this scope, future research could extend the analysis to tri-consonantal clusters – a particularly intriguing and challenging area in the phonology of this dialect.

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Appendix

Sonority Shape

Rising sonority	Stimulus words	Falling sonority	Stimulus words	Plateau	Stimulus words
stop + fricative	/ksa/, /tsˤu:m/, /kħal/	fricative + stop	/zˤdam/, /sˤbaɣ/, /ħki:t/	stop + stop	/qdi:m/, /dbaħ/, /kteb/, /tkæka/, /tˤbag/
fricative + nasal	/smen/, /ɣmel/, /sna:dəl/	nasal+fricative	/mħa:ʒeb/, /nħal/, /nsæl/, /mʒa:ri/	fricative +fricative	/ʃħam/, /ʒhæz/, /sfenʒ/
nasal + liquid	/mra/, /mli:ħ/	glide + liquid	/wlæd/, /jru:ħ/, /wræqi/	nasal + nasal	/nmel/, /mnægi:ʃ/
liquid + glide	/rwa/, /lwa/	nasal + stop	/mqa:li/, /ntˤajjeb/ /mbasˤsˤla/	glide + glide	/jwæsi/
stop + nasal	/tmu:t/, /bna/, /gmal/, /dnu:b/	liquid+fricative	/lsæn/, /lħæf/, /rfi:s/		
fricative + liquid	/sˤla:tˤa/, /sˤra:t/, /zla:fa/	liquid + stop	/lben/, /rbi:ʕ/, /lqi:t/, /rged/		
stop + liquid	/bri:t/, /klæb/, /dˤrab/, /tra:b/	glide + stop	/wden/, /jbæt/, /jtu:b/		
stop + glide	/dwa/				

Voicing

+Voiced /+Voiced	-Voiced / -Voiced	+Voiced / -Voiced	-Voiced / +Voiced
/rwa/,/ɣmel/, /mra/, /lwa/, /bri:t/, /mli:ħ/,/bna/,/gmal/, /dnu:b/, /nmel/,/lben/, /dwa/, /mnægi:ʃ/ /zla:fa/,/mʒa:ri/, /wlæd/,/zˤdam/, /rged/,/wden/,/jru:ħ/, /rbi:ʕ/, /dˤrab/,/wræqi/,/mbasˤsˤla/, /dbaħ/,/jbæt/,/jwæsi/	/ksa/, /tsˤu:m/, /kħal/, /ʃħam/, /sfenʒ/, /ħki:t/, /tkæka/, /kteb/	/mħa:ʒeb/, /nħal/, /nsæl/, /lsæn/, /ʒhæz/, /mqa:li/, /rfi:s/, /lqi:t/, /ntˤajjeb/, /lħæf/, /jtu:b/	/tmu:t/, /sˤla:tˤa/, /sˤra:t/, /klæb/, /sˤbaɣ/, /qdi:m/, /tˤbag/, /smen/, /tra:b/, /sna:dəl/

Place of Articulation

Homorganic clusters	Heterorganic Clusters
/mbasˤsˤla/, /sˤla:tˤa/, /tsˤu:m/, /lsæn/, /nsæl/, /dˤrab/, /zˤdam/, /ntˤajjeb/, /sna:dəl/, /dnu:b/, /tra:b/, /sˤra:t/, /zla:fa/	/sˤbaɣ/, /kħal/, /ksa/, /mli:ħ/, /ɣmel/, /mra/,/lben/, /tmu:t/, /qdi:m/, /bri:t/, /smen/, /nħal/, /lqi:t/, /kteb/, /ʃħam/, /rwa/, /gmal/, /wlæd/, /mʒa:ri/, /rbi:ʕ/, /dbaħ/, /lwa/, /bna/, /klæb/, /dwa/, /ħki:t/, /mħa:ʒeb/, /jru:ħ/, /rfi:s/, /lħæf/, /rged/, /wden/, /mqa:li/, /jtu:b/, /jbæt/,/ʒhæz/, /jwæsi/, /tkæka/, /mnægi:ʃ/, /nmel/, /tˤbag/, /sfenʒ/, /wræqi/

Extra words

Extra words	/sa:ʕa/, /ħumma:n/, /maqla/, /xa:təm/, /gatˤtˤ/, /fi:l/, /ħu:t/, /ʃi:r/, /bi:du/, /kæs/

Table 4. Stimuli of the acoustic experiment (Due to page restrictions, the English glosses are omitted)