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Shigeko Shinohara, Qandeel Hussain. Acoustic Correlates of Word-Initial Obstruents of the Ikema Dialect of Miyako Ryukyuan. *Sophia Linguistica*, In press, 72, pp.1-22. hal-04469221

HAL Id: hal-04469221

<https://hal.science/hal-04469221>

Submitted on 20 Feb 2024

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Acoustic Correlates of Word-Initial Obstruents of the Ikema Dialect of Miyako Ryukyuan

Shigeeko Shinohara

Laboratoire de Phonétique et Phonologie, CNRS & Sorbonne Nouvelle, France

Qandeel Hussain

University of Toronto, Canada; North Carolina State University, Raleigh, USA

Abstract

The Ryukyuan languages spoken in Ryukyu Islands of Japan are known to have typologically rare word-initial geminates. However, the phonetic aspects of Ryukyuan languages are still scarcely documented in the literature. The current study investigates the acoustic correlates of manner, place, voicing, and length in word-initial obstruents of endangered Ikema Miyako Ryukyuan, using a wide range of temporal and non-temporal measures (duration, F0, intensity, F1, and F2). The results showed that duration is the most reliable acoustic correlate for the classification of manner, voicing, and length contrasts of word-initial obstruents. F1 contributed to the classification of manner and voicing whereas intensity additionally distinguished the length contrasts. The overall findings indicated that Ikema speakers can use a combination of temporal and non-temporal acoustic correlates to tease apart the subtle consonantal distinctions. The findings of the current study will help inform the phonetic and phonological typology of Ryukyuan languages and will further contribute to the studies of speech production in endangered languages.

Keywords: obstruents, geminates, word-initial, Miyako Ryukyuan, typology

1. Introduction

The Ryukyuan languages spoken in Ryukyu Islands of Japan share a common protolanguage with Japanese (Karimata 2015, Pellard 2015). The Ikema dialect of Miyako Ryukyuan language is mainly spoken on Ikema Island, in Sarahama on Irabu Island, and in Nishihara on main Miyako Island (Shinohara & Hussain 2020, Figure 1).¹ Ikema was originally spoken only on Ikema Island but during the 18th and 19th centuries, a part of the population migrated to neighboring islands. The estimated number of Ikema speakers in 2022 was around 1300 (Nakama *et al.* 2022). Ikema is no longer learned by the younger generation. As is the case with all the Ryukyuan languages, most of the speakers of Ikema are above 50 years of age (Nakayama & Ono 2013). Thus, the current status of Ikema as a severely endangered language calls for a detailed acoustic-phonetic

¹ The word *Ikema* in Ikema dialect is /ikima/. We use Japanese transliterations of the names of dialects and places following previous literature in English. All the dialects of Miyako Ryukyuan including Ikema are classified as *definitely endangered* by UNESCO (Moseley 2010) and *moribund* by Ethnologue (Simons & Fennig 2017).

study which will help inform phonetic and phonological typology. The current study will be a valuable addition to the ongoing discussions regarding the perception and production of a rare type of speech sounds in the world's languages (Hussain & Mielke 2020, Ladefoged & Maddieson 1996, Tucker & Wright 2020, Whalen *et al.* 2011).

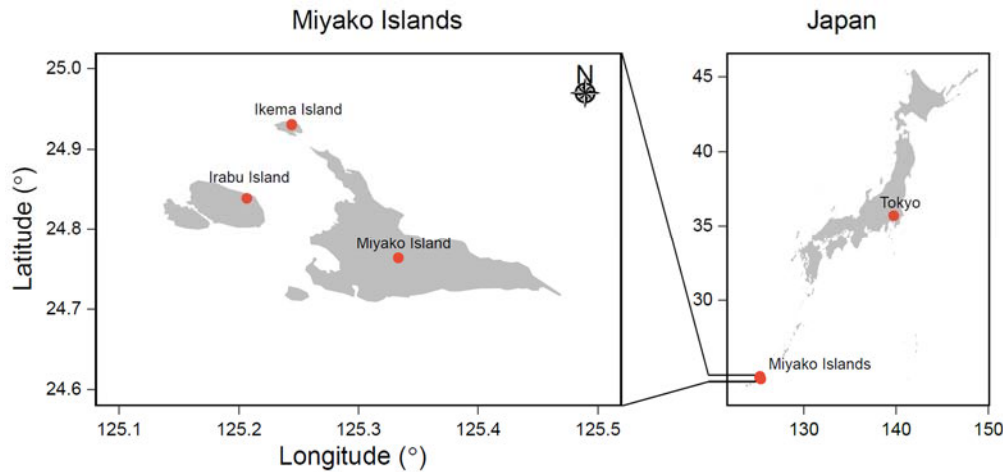


Figure 1: Map of Japan indicating the Miyako Islands (main Miyako Island, Ikema and Irabu Islands).

Ryukyuan languages possess interesting consonantal features but they are scarcely described with modern acoustic-phonetic and classification tools. Phonetic aspects of Japanese dialects are well-documented in the current literature (Gao & Arai 2019, Fujimoto & Shinohara 2018b, Hussain & Shinohara 2019, Kawahara 2005, Takada 2018, among others) but only a handful of studies are available on Ikema. Some recent studies are predominantly based on the data collected from the Ikema speakers of Nishihara (Hayashi 2010, Igarashi *et al.* 2011, Kibe 2019), except Ford *et al.* (2023) and Hayashi (2007) who recorded a few informants originally from Ikema Island. Matsuura (2019) presented acoustic data from four different dialects of Miyako Ryukyuan including Ikema. The data used in Matsuura (2019) are based on Kibe (2019) who compiled data from the speakers of Nishihara (main Miyako Island) and Ikema Island but provided no information as to which speakers were analyzed. Several studies have also investigated the articulatory correlates of vowels and consonants of Nishihara Ikema speakers using real-time Magnetic Resonance Imaging (rt-MRI) (Fujimoto & Shinohara 2016; 2017, Fujimoto *et al.* 2023).

Ikema contrasts both word-medial and word-initial geminates with singletons. The acoustic correlates of word-medial geminates have been widely reported in the current literature (Cohn *et al.* 1999, Ham 2001, Kawahara 2015, Ridouane 2010, Rojczyk & Porzuczek 2019, among others). In word-medial position, Ikema is unlikely to be different from other languages of the world where duration is reported to be the main acoustic cue differentiating singletons and geminates. However, word-initial geminates are typologically rare (Dmitrieva 2012, M. H. Hamzah *et al.* 2020, Kraehenmann 2001, Muller 2003, Thurgood 1993). An important question is how listeners discern whether speakers intended a singleton or geminate consonant in phrase-initial position. To better understand the importance of various acoustic correlates, the current study departs from the previous studies of Ikema by investigating both temporal (duration) and non-temporal (F0, intensity, F1, and F2) acoustic correlates of word-initial obstruents of Ikema Miyako Ryukyuan (see 1.2 for an overview of these acoustic correlates). We also explore the ranking and importance

of different acoustic measures in the classification of manner, place, voicing, and length contrasts of word-initial obstruents.

The paper is organized as follows. We first present a sketch of the Ikema obstruent system (Section 1.1). Acoustic correlates of obstruents are presented in Section 1.2. Methods and procedures are outlined in Section 2. The main findings are presented in Section 3. Section 4 summarizes and discusses the results.

1.1. A sketch of Ikema obstruent system

Ikema has a rich set of obstruents (Table 1). There are three manners of articulation (plosive, fricative, and affricate) and four places of articulation (bilabial, alveolar, alveolopalatal, and velar). Voicing and length in word-initial obstruents are fully lexical and contrastive (e.g., /ffa/ ‘child’ vs. /vva/ ‘you’, /ti/ ‘hand’ vs. /tti:/ ‘pipe,’ see more examples in Table A1 in the Appendix). The initial geminates contribute to phonological weight and bimoraic word minimality. A word should have at least two moras in an utterance, a constraint satisfied by words like /zza/ and /tta/ with a short vowel, whereas /ta/ ‘rise field’ and /ti/ are pronounced with a long vowel [ta:] and [ti:], respectively. Based on her fieldwork in Nishihara, Miyako Island, Hayashi (2010) provides the following vowels: /i I u a/,³ and consonants: /p b t d k g f v s z h ts m ŋ n r w j/ (symbols are adapted). Among these, /ts/ is realized as [tɕ] before /i a u/ and [ts] before /I/; /s/ is realized as [ɕ] before /i j/ and [s] elsewhere; /z/ may be palatalized as [z] before /i j/ and [z] or [dz] elsewhere. Since there is a contrast between [zz] and [zz] before /a/, we transcribe the latter as /zzja/ (see discussion below). It should be noted that /s/ and /ts/ are contrastive whereas /z/ does not have a contrastive affricate counterpart. /z/ has been variably transcribed as [z] or [dz] in the previous descriptions. There are also voicing and/or length gaps in word-initial obstruents. Hayashi (2010) mentions that word-initial obstruents which can appear as geminates include /tt tts kk ff ss vv zz/ (/vv/ does not contrast with singleton /v/; Ikema words starting from /kk/ are rare). By contrast, geminate obstruents appearing in the medial position also include /pp kk dd/. We note that word-medial /f/ or /ss/ within a single morpheme word seems harder to find than in the word-initial position. Thus, the segments appearing as initial geminates and those as medial ones do not completely overlap. In the current study, the acoustic correlates of the following word-initial obstruents are investigated: singletons /b t d k g ts zj f s z/ [b t d k g tɕ dz f s z] and geminates /tt ff vv ss zz/ [tt ff vv ss zz].

The consonant inventory of Ikema is contrary to the general cross-linguistic voicing and length gaps. Since voiced geminates require more articulatory effort than voiceless geminates, if a language has a length contrast, it is more likely to be in the voiceless series (Blevins 2004, Kirchner 2001, J. J. Ohala 1983, Thurgood 1993, Westbury & Keating 1986). In the previous studies of Ikema speakers from Nishihara (Fujimoto & Shinohara 2015; 2017), geminate obstruents were characterized by longer duration than singletons and full voicing was found in voiced obstruents during the closure phase. They also noted a longer VOT of /t/ compared to its geminate counterpart /tt/ in the word-initial position. Articulatory studies of geminate obstruents in the same dialect of Ikema (a single speaker analysis in Fujimoto & Shinohara 2016; two speakers in Fujimoto & Shinohara 2017, Fujimoto *et al.* 2023) found expansion of the pharynx which is one of the

³The special symbol /I/ is used for a vowel articulated at the alveolar ridge with more or less frication noise (Fujimoto & Shinohara 2018a).

articulatory correlates generally used to enhance the voicing contrast (Proctor *et al.* 2010).

	Bilabial	Alveolar	Alveolopalatal	Palatal	Velar	Glottal
Plosive	p b	t d			k g	
Fricative	f	s z	(ç) (z)			h
Affricate		ts (dz)	(tç) (dz)			
Nasal	(m) m	ɲ n				
Approximant	w			j		
Liquid		r				

Table 1: Consonant inventory of Ikema (adapted from Hayashi 2010). Segments in parentheses are marginally contrastive and may appear as allophones.

1.2. Acoustic correlates of obstruents

A number of acoustic correlates have been proposed to differentiate voicing and length contrasts in the obstruent systems of the world’s languages (Kawahara 2015). In the following paragraphs, we mainly discuss those languages which have both voicing and length contrasts in obstruents. Duration is the most widely known characteristic distinguishing singletons from geminates. Voiceless singleton obstruents are differentiated from the voiced ones in terms of longer duration (closure, frication, and/or aspiration), as noted in Dogri (Ghai 1980), Tokyo Japanese (Hussain & Shinohara 2019, Idemaru & Guion 2008, Kawahara 2005, among others), and Sieneese Italian (Stevens & Hajek, 2004). Similar effects of voicing have been observed in geminate obstruents where the voiceless geminates show slightly longer duration than their voiced geminate counterparts (Hindi: M. Ohala & Ohala 1992, Shrotriya *et al.* 1995; Tokyo Japanese: Hussain & Shinohara 2019, Hirose & Ashby 2007, Idemaru & Guion 2008). Geminates are long consonants, mainly differentiated from singletons by constriction duration (Bengali and Turkish: Lahiri & Hankamer 1988; Tokyo Japanese: Hussain & Shinohara 2019, Kawahara 2005, among others). There remain more issues as to acoustic cues of length difference of word-initial obstruents. In Cypriot Greek, word-initial plosives were characterized by longer VOT (Arvaniti & Tserdanelis, 2000, Muller 2003). In contrast, Kelantan Malay showed shorter VOT in the word-initial geminates than in singletons (H. Hamzah *et al.* 2011).⁴ There are also differences across manners of articulation. Fricatives and affricates, due to their frication noise, are expected to be longer than plosives (cf. Cohn *et al.* 1999, Dmitrieva 2012).

In addition to temporal correlates, fundamental frequency (F0) at the onset of the following vowels has been shown to reliably distinguish both voicing and length contrasts (and, to some extent, manners and place of articulation; Brunelle *et al.* 2020). From a typological perspective, voiced obstruents have a lowering effect on the F0 onsets (Hombert *et al.* 1979, Hussain & Mielke 2020).

⁴Readers are also referred to Lisker & Abramson (1964) and Cho *et al.* (2019) for further discussion of voicing and its effect on VOT.

Higher F0 ratios in word-initial (voiceless and voiced) geminates were observed in Pattani Malay (Abramson 1998). Similar patterns of F0 were found in the word-initial geminates of Kelantan Malay (M. H. Hamzah *et al.* 2020; 2014). Abramson (1998) noted that word-initial singleton and geminate contrast in Pattani Malay is signaled by amplitude (or intensity) at the onsets of the following vowels, which is slightly lower in singletons than in geminates. In Lebanese Arabic, Al-Tamimi & Khattab (2015) did not find clear differences in singletons and geminates in terms of intensity. Minor effects of voicing were indicated where the voiced consonants were characterized by higher intensity than voiceless consonants (*ibid.*). Jessen (2001) attributed the [+tense] feature to both voiceless and geminate obstruents. In general, word-initial consonants are produced with more articulatory strengthening compared to word-medial position (Cho & McQueen 2005). Since geminates are ‘tense’ and singletons are not, the difference between singletons and geminates may be more exaggerated at the word edge. Thus, intensity is expected to be slightly higher in word-initial geminates than in singletons.

The first two formants (F1 and F2) have also been reported to distinguish voicing and length contrasts in obstruents. In Japanese, singletons show a raising effect on F1 onsets, compared to their geminate counterparts (Kawahara 2005). In Lebanese Arabic, Al-Tamimi & Khattab (2015) noted higher F1 in singletons. There were minor differences in F1 across voiceless and voiced obstruents. Overall, voiced obstruents (regardless of their length: singleton or geminate) were characterized by low F1 at the onsets of the following vowels. Al-Tamimi & Khattab (2015) also reported F2 characteristics, but compared to F1, F2 was less reliable in distinguishing voicing and length contrasts in Lebanese Arabic.

All the above-mentioned studies indicate that there is considerable variation in the ways acoustic correlates are exploited by languages for maintaining the voicing and length contrasts in obstruents. Constriction duration appears to be a universal acoustic correlate distinguishing the obstruent manner, place, voicing, and length. However, other acoustic correlates (F0, intensity, F1, and F2) may be language-specific. Studies have shown that in some languages, non-temporal correlates may not have a decisive effect on the perception of geminates in word-medial position (Dmitrieva 2012, M. H. Hamzah *et al.* 2014). Thus, the acoustic correlates other than duration are secondary and may signal manner, place, voicing, and length in Ikema, which has a relatively large inventory of word-initial obstruents.

The current study investigates the acoustic correlates of different manner, place, voicing, and length contrasts in word-initial obstruents of Ikema Miyako Ryukyuan spoken on Ikema Island (Figure 1). We examine the effect of manner, place, voicing, and length on the following acoustic correlates: duration of consonants, F0, intensity, F1, and F2 onsets of the following vowels. We expect that word-initial geminates of Ikema would be characterized by longer duration, higher intensity and F0, and lower F1 and F2 (Al-Tamimi & Khattab 2018). Exceptionally, the VOT of /t/ would be longer than /tt/, as observed in the Nishihara Ikema speakers (Fujimoto & Shinohara 2015; 2017, Fujimoto *et al.* 2023). Voiceless obstruents would be longer in duration than voiced obstruents, one of the universal correlates of voicing (Lisker 1986). In terms of manner and place of articulations, fricatives and affricates would show longer durations compared to plosives. Moreover, we expect that many acoustic cues would occur to the extent that they allow fully lexical contrast in everyday words in Ikema. If one cue is absent (e.g., closure duration in word-initial /t/ and /tt/), the other cues (e.g., VOT, F0, or intensity) may dominate and help maintain or enhance the length contrast.

2. Methods

2.1. Speakers

Ten speakers of Ikema participated in the study. All the speakers were born and brought up on Ikema Island. Three male participants were born between 1952 and 1959 (mean age 61.7 years) and seven females were born between 1932 and 1952 (mean age 75.6 years). Two of the female speakers and one of the male speakers left Ikema Island at adulthood for study and work in Naha, Okinawa or in Kagoshima, and returned to live on Ikema Island or in Hirara (main Miyako Island) in their 20's. The others spent their whole lives on Ikema Island. All the speakers are bilingual in Japanese.

2.2. Speech material

A corpus of Ikema was compiled for the current study (see Table A1 in the Appendix). The following sources were consulted to find the target words: (a) the word lists for the Miyako Ryukyuan project led by Kibe (2019), (b) an investigation conducted with speakers of Nishihara in 2012 (cf. Fujimoto & Shinohara 2018a), and (c) the word lists in preparation for an Ikema dictionary (p.c. Hiroyuki Nakama, August 2018). When consulting speakers of Ikema Island before the recording, we encountered differences in a few words from the given sources. We found some words containing a singleton /p/ and a sequence of /za/ in written sources, but our speakers did not recognize any words containing singleton /p/, and /za/ sequences were mostly replaced by prepalatal counterpart /zja/ [dza] with the exception of the apparently borrowed word /zaramē/ 'crystal sugar' from Japanese, which was pronounced with [(d)za] by all the speakers, and /za/ 'place' by two speakers.

Somewhat unexpectedly, /z/ and /zz/ were mainly realized as fricatives and occasionally realized as an affricate [dz] and [ddz], respectively, while /zj/ was frequently realized as affricate [dz̥]. Therefore, in our acoustic analyses, we treated /z/ and /zz/ as voiced fricatives, the counterparts of /s/ and /ss/, and /zj/ as voiced affricate, the counterpart of /ts/. As noted in the Introduction (Section 1.1), the consonant inventory of Ikema shows a number of voicing and/or length gaps. We did not find instances of initial geminate /tts/ [tt̥c] in / a/ context or /kk/. The following obstruents were included in the final analyses of the acoustic measurements: word-initial singletons /b t d k g ts zj f s z/ [b t d k g t̥c dz̥ f s z] and word-initial geminates /tt ff vv ss zz/ [tt̥c ff̥c vv̥c ss̥c zz̥c].

2.3. Recording procedure

The recording sessions took place on Ikema Island. Two speakers were recorded at a house of one of the participants, and the others were recorded at a community center on Ikema Island. Before the recordings, speakers were familiarized with the word list and were then asked to produce the target words in citation form. Ikema allows bare forms in phrase-initial position so that the produced forms partly reflect natural language usage. During the recording session, an equivalent of each target word was orally presented in standard Japanese by the experimenter, and the speakers produced the target Ikema word three times. A Sony Linear PCM-M10 digital voice recorder with built-in microphone was used to capture the audio recordings (44.1 kHz, encoded in 16 bit).

2.4. Acoustic and classification analyses

A total of 458 tokens were included in the final analyses (Figure 3). All the acoustic analyses were performed in Praat (Boersma & Weenink 2007). The word-initial voiceless obstruents were segmented from the beginning of release burst or frication intervals to the first glottal pulse of the following vowels (Figure 2). The word-initial voiced obstruents were segmented from the beginning of voiced closure (prevoicing) to the onset of the first glottal pulse of the following vowels. In other words, consonant duration refers to all the audible parts in our analyses, therefore, closure of voiceless plosives is not taken into consideration while prevoicing of voiced ones may overlap with closure interval. Duration of the word-initial obstruents, F0, intensity, F1, and F2 formants at the onset of the following vowels were measured. As our data included three male and seven female speakers, the pitch range for the fundamental frequency was 50-300 Hz for males and 75-500 Hz for females. The formants were extracted using LPC analysis over a sliding 25 ms window (view range: 0-5000 Hz for males and 0-5500 Hz for females). All the acoustic measures were z-score normalized.

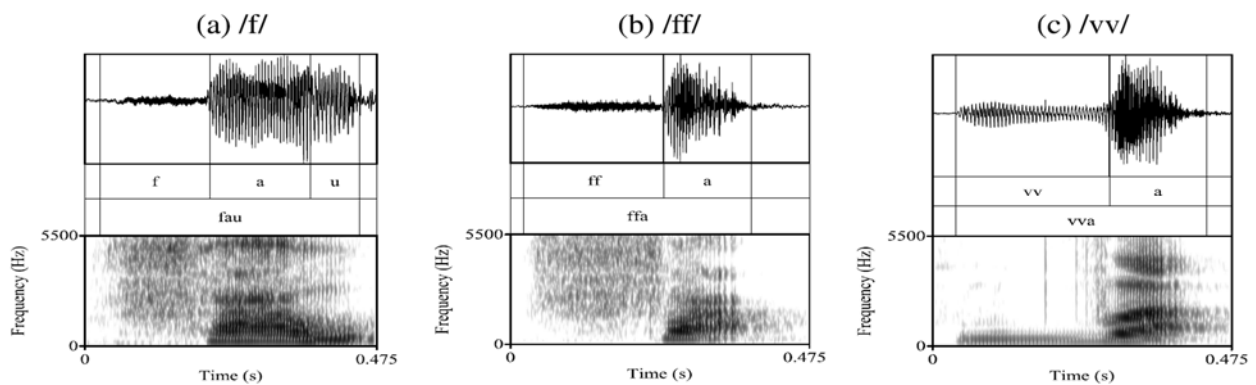


Figure 2: Representative spectrograms and waveforms of word-initial obstruents: (a) /fau/ ‘to eat,’ (b) /ffa/ ‘child,’ and (c) /vva/ ‘you.’

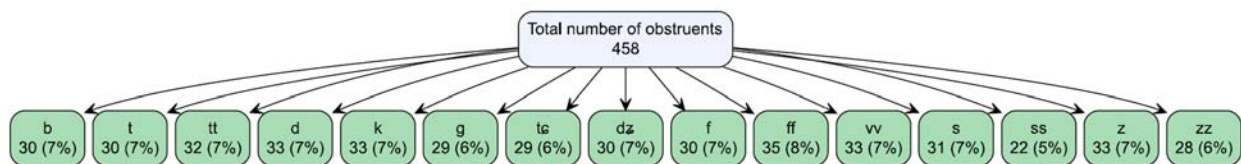


Figure 3: Total number of obstruents included in the analysis.

Classification of all the obstruents of Ikema was performed using the *rpart* package (Therneau & Atkinson 2019) and *predict()* function in R (R Core Team, 2021, *rpart*(Obstruents~ Duration + F0 + Intensity + F1 + F2, data = data, method = "class"); see the *rpart* package for more details). Variable importance was calculated to further investigate the ranking and role of each acoustic measure in the classification of manner, place, voicing, and length contrasts in Ikema (Hussain & Kochetov 2022). Cohen’s *d*’s (standardized difference between means) of the /t/ vs. /tt/ pair was calculated using the *effectsize* package in R (Ben-Shachar *et al.* 2020).

3. Results

3.1. Acoustic correlates

Figure 4 presents boxplots of all the acoustic correlates of word-initial obstruents of Ikema. It can be observed that for the /t-/tt/ pair, mean duration of the word-initial geminate /tt/ was slightly shorter than its singleton counterpart /t/ (only the intervals between release and vowel onset are included). For the /f-/ff/, /s-/ss/, and /z-/zz/ pairs, geminates were consistently longer in duration, compared to singletons. Minor durational differences in voiceless and voiced fricative geminates were also noted. The mean duration of the word-initial geminate /ss/ was slightly longer than voiced geminate /zz/. There appeared to be no clear differences in /ff/ and /vv/ as the boxes show considerable overlap. Overall, fricatives and affricates exhibited longer duration than plosives.

The mean F0 onsets appeared to be higher in geminate obstruents. The /t-/tt/ pair was an exception to this pattern where the mean F0 onset for /t/ was slightly higher than /tt/. Minor voicing effects on F0 onsets can also be observed. For instance, the mean F0 onset of the voiceless fricative /ss/ was higher than /zz/. Similar patterns hold for the singleton /s/ and /z/. In the singleton vs. geminate pairs (/t-/tt/, /f-/ff/, /s-/ss/, and /z-/zz/), the geminate obstruents were characterized by higher intensity onsets than singletons, as indicated by the mean white diamonds. No clear patterns of voicing were observed in intensity. The F1 onsets were consistently higher in singletons (/t f s z/) than in geminates (/tt ff ss zz/), and slightly higher in voiceless than in voiced obstruents. F2 onsets of /b f ff vv/ were slightly lower than all the other obstruents which may be attributed to the lip rounding gesture. It can also be observed that manner and place of articulations showed minor effects on F0, intensity, and F1. F2, on the other hand, appeared to be the lowest in fricatives and affricates.

The word-initial unvoiced stop quantity contrasts are assumed to be difficult to convey from speaker to listener. This raises the following question: In the absence of audible closure duration, how do listeners discern whether it is /t/ or /tt/? To investigate this question, we calculated Cohen's *d*, generally known as a measure of effect size (standardized mean difference between the two variables), to indicate how well listeners might distinguish the length contrast in /t/ vs. /tt/. Higher absolute Cohen's *d* values indicate a larger difference between the means of /t/ vs. /tt/ (acoustically distinct); whereas lower values show small differences in means (acoustically non-distinct). The Cohen's *d* effect size for the /t/ vs. /tt/ duration was -2.23. For other acoustic measures, Cohen's *d* effect size was as follows: -0.05 (F0), 1.23 (intensity), -0.96 (F1), and -0.36 (F2). Cohen's *d* of duration is due to the longer VOT of /t/, not that of geminate /tt/, in contrast to the other pairs of obstruents where geminates exhibit greater duration values. An outstandingly higher absolute Cohen's *d* value suggests that duration still plays a key role in maintaining the length contrast in word-initial /t/ vs. /tt/ (see the next section for variable importance of the all obstruents).⁶

See also Shinohara *et al.* 2023 for the alveolar plosive contrasts in Ikema.

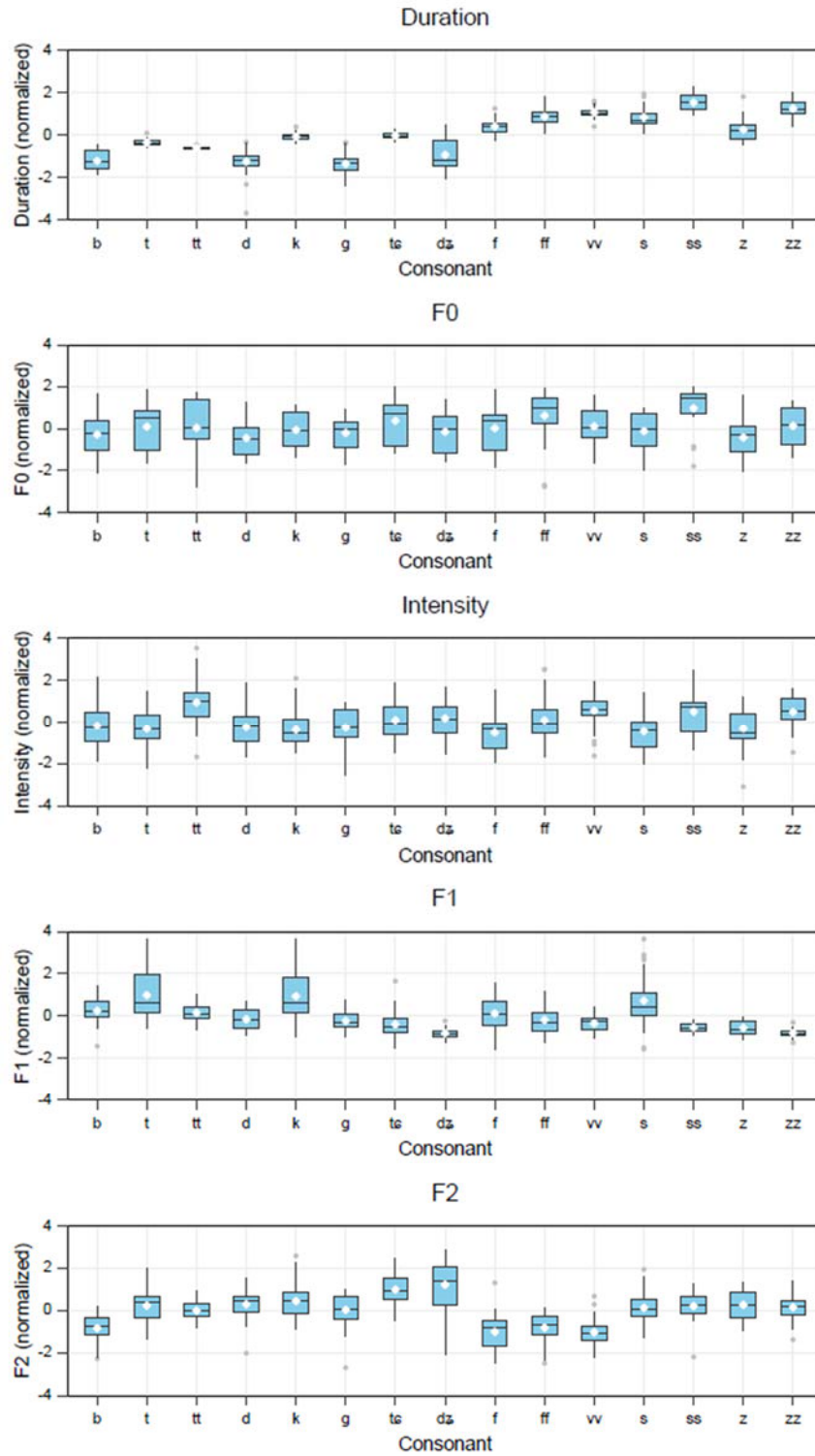


Figure 4: Duration, F0, intensity, F1, and F2 of the word-initial obstruents of Ikema. All the acoustic measures were z -score normalized. White diamonds indicate the means.

3.2. Classification and relative importance of features

Figure 5 presents the classification matrix. The highest correct classification rate can be observed in /zz/ (93%), /tt/ (84%), and /s/ (84%). It was surprising to see that all the /g/ tokens were either classified as /d/, /b/, or /t/. A large number of /z/ tokens were misclassified as /tʃ/ or /t/. /f/ was frequently classified as /s/. The alveolar plosive triplet /t tt d/ was more correctly classified than the fricative triplet /f ff vʋ/.

Classification Matrix

		Predicted														
		b	t	tt	d	k	g	tʃ	dʒ	f	ff	vʋ	s	ss	z	zz
Actual	b	60	10	17	13	0	0	0	0	0	0	0	0	0	0	0
	t	0	77	0	0	23	0	0	0	0	0	0	0	0	0	0
	tt	0	16	84	0	0	0	0	0	0	0	0	0	0	0	0
	d	3	15	3	78	0	0	0	3	0	0	0	0	0	0	0
	k	0	6	0	0	79	0	12	0	0	0	0	3	0	0	0
	g	10	10	0	78	0	0	0	3	0	0	0	0	0	0	0
	tʃ	0	3	0	0	17	0	79	0	0	0	0	0	0	0	0
	dʒ	3	17	0	7	0	0	17	50	0	0	0	0	0	7	0
	f	0	0	0	0	20	0	3	0	20	10	13	27	0	3	3
	ff	0	0	0	0	0	0	0	0	9	28	31	6	9	9	11
	vʋ	0	0	0	0	0	0	0	0	0	9	64	9	0	0	18
	s	0	0	0	0	0	0	6	0	0	0	0	84	0	3	6
	ss	0	0	0	0	0	0	0	0	0	0	5	0	77	0	18
	z	0	12	0	0	0	0	45	0	3	0	3	0	0	27	9
	zz	0	0	0	0	0	0	0	0	0	0	7	0	0	0	93

Figure 5: Classification matrix of all the obstruents of Ikema.

Figure 6 displays the relative rankings of various acoustic measures for each phonological contrast category. The higher the importance values, the more vital the acoustic features (such as Duration and F2) were in the classificatory models for distinguishing manner, place, voicing, and length. Figure 6 shows that duration is the most important acoustic feature for distinguishing the manner of articulation in word-initial obstruents of Ikema, followed by F1, F2, F0, and intensity. Place is best differentiated by F2 and duration. Voicing and length are distinguished by duration. Interestingly, intensity is the second most important acoustic feature in the classification of Ikema length contrasts. Overall, duration was ranked as the most important acoustic feature in the classification of manner, voicing, and length in the word-initial obstruents of Ikema.

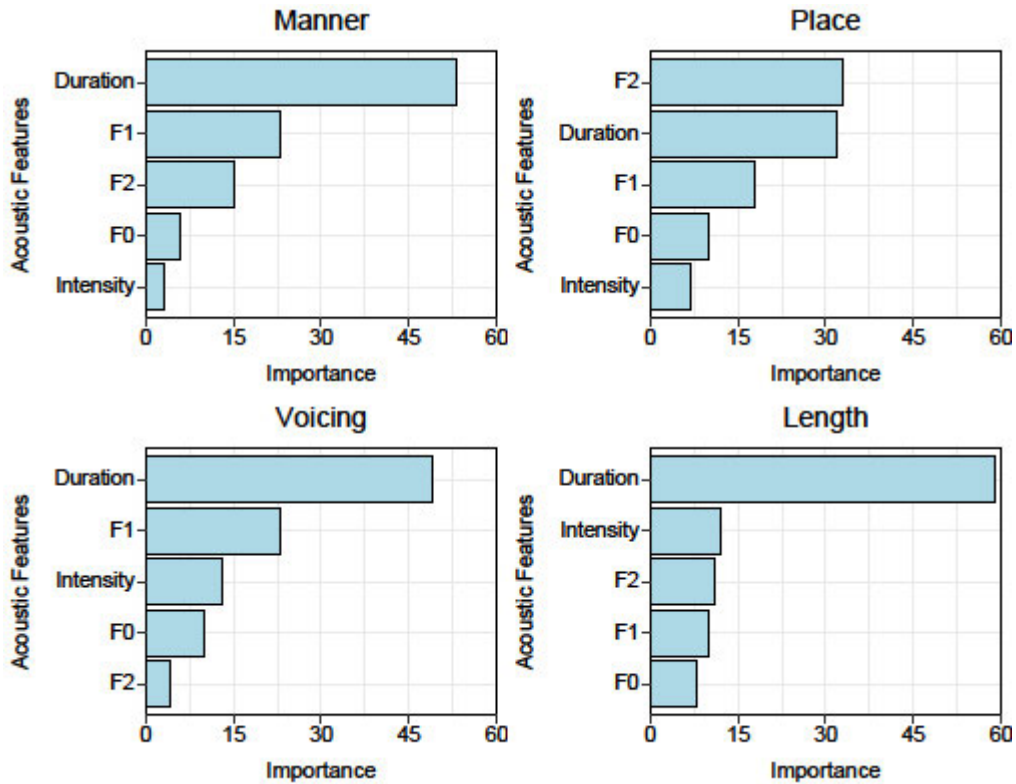


Figure 6: Variable importance by manner, place, voicing, and length. Importance values are unitless.

4. Discussion

The present study investigated the acoustic correlates of manner, place, voicing, and length contrasts of word-initial obstruents of Ikema, an endangered Miyako Ryukyuan language. Geminate consonants (particularly fricatives and affricates) were longer than their singleton counterparts, as has been noted in many languages of the world (Bengali and Turkish: [Lahiri & Hankamer 1988](#); Dogri: [Ghai 1980](#); Hindi: [M. Ohala 2007](#); Italian: [Esposito & Di Benedetto 1999](#); Madurese: [Ham 2001](#); Tashlihyt Berber: [Ridouane 2007](#); Tokyo Japanese: [Hussain & Shinohara 2019](#), [Kawahara 2005](#)). Voiceless obstruents showed longer duration than voiced obstruents, a general trend found in a wide range of languages with a voicing contrast (Hindi: [M. Ohala & Ohala 1992](#), [Shrotriya et al. 1995](#); Tokyo Japanese: [Hussain & Shinohara 2019](#), [Hirose & Ashby 2007](#), [Idemaru & Guion 2008](#)).

Overall, duration was ranked as the most important acoustic feature in the classification of manner, voicing, and length in the word-initial obstruents of Ikema. Place appears to be mainly distinguished by F2. These results are in line with [Hussain & Kochetov \(2022\)](#) who noted that laryngeal/voicing contrasts are reliably differentiated by duration whereas place contrasts are best distinguished by spectral correlates (F1 and F2). Finally, in the classification matrix, the geminates were overall well classified. Unexpectedly, in the view of durational cues as the key acoustic correlate of the length difference, the alveolar plosive triplet /t tt d/, without closure intervals, was more correctly classified than the fricative triplet /f ff vv/. These results suggest that multiple cues

may be involved in the perception of word-initial obstruents.

Previous studies of Ikema speakers from Nishihara had reported longer VOT in word-initial /t/ compared to geminate /tt/ (Fujimoto & Shinohara 2013; 2017, Shinohara & Fujimoto 2018). We replicated this result with our participants of Ikema Island. VOT of the word-initial geminates has been reported to be longer than singletons in Cypriot Greek as expected from the longer geminate interval proportionally affecting each of its parts (Muller 2003). In Ikema, along with Kelantan Malay (H. Hamzah *et al.* 2011), there is a consistent duration difference that goes in the opposite direction to Cypriot Greek. This might be due to the abrupt release or probably articulatory strengthening in the production of voiceless plosive geminates occurring on a language-specific basis. An articulatory (rt-MRI) study of Ikema suggested faster transitions from the geminate plosives toward the following vowel target, compared to their singleton counterparts (Fujimoto & Shinohara 2015). This might also explain why Ikema geminates had short VOTs. The articulatory strengthening of geminates has been discussed in several studies. Jessen (2001) attributed [+tense] feature to voiceless and geminate obstruents. Among several acoustic correlates, [+tense] is associated with longer aspiration in plosives and longer closure durations in geminate plosives (*ibid.*). However, Kim & Clements (2015) argue that aspiration is an enhancement of the feature [+tense] in a language-specific fashion. Germanic languages show more aspiration in the voiceless series as being [+tense] while [+tense] segments in other languages can be enhanced by their closure duration, without additional intervals of aspiration. The Ikema data support the latter view in that geminates are articulated with a stronger release (see below for other acoustic characteristics suggesting it) but relatively less aspiration as compared to singletons. In an electropalatographic study, a greater amount of contact along with longer closure was found in the production of Japanese alveolar geminates (Kochetov & Kang, 2017). One of the Ikema speakers in a rt-MRI study showed significant differences in linguopalatal contact in the midsagittal dimension of word-initial /t/-/tt/ ([ta:] ‘rice field’ vs. [tta] ‘tongue’) (Fujimoto *et al.* 2023). Hence, articulatory enhancement of the geminates seems to be achieved by a tighter constriction. It could also be postulated that the word-initial voiceless singleton-geminate contrast of Ikema is merely a quality difference rather than the phonological length difference. This is in fact a classical view often taken for the initial geminate plosives in Ryukyuan including Ikema. They were often treated as ‘glottalized’ singleton consonants in some older literature (Hirayama 1983). However, the articulatory duration of closure seems to reflect moraic timing in Ikema. In Fujimoto *et al.* (2023), the frame count of the rt-MRI indicated longer closure duration in word-initial geminate /tt/ than in singleton /t/. Thus, length differences are still reflected in the production of the plosives.

Fundamental frequency (F0) onsets were overall higher in geminates than in singletons. The general pattern is consistent with Abramson (1998) who noted higher F0 ratios in the word-initial geminates of Pattani Malay. Similar patterns of F0 were observed in the word-initial geminates of Kelantan Malay (M. H. Hamzah *et al.* 2014). The /t/-/tt/ pair was an exception to this pattern where the mean F0 onset for /t/ was slightly higher than /tt/. Minor voicing effects on F0 onsets were also observed. For instance, the mean F0 onset of the voiceless fricative /ss/ was higher than /zz/. Similar patterns hold for the singleton /s/ and /z/. These findings suggest that F0 signals both voicing and length in the word-initial obstruents of Ikema. There were no consistent F0 patterns across the manner and place of articulations.

The effect of consonant length was also observed on intensity. The geminate obstruents were characterized by higher intensity onsets than singletons. Intensity was the second most important

acoustic feature for the classification of length (Figure 6). Higher intensity can be attributed to the strengthening of the word-initial geminates of Ikema. Abramson (1998) noted a similar type of effect on the word-initial singletons and geminates of Pattani Malay. As word-initial geminates occur at the edges of a domain where closure duration is not perceptible, speakers probably produce initial geminates with more articulatory force than singletons. It is also plausible that there is a larger build-up of intra-oral pressure after geminates than singletons which leads to higher intensity in the former.

The F1 onset was higher in singletons (/t f s z/) than in their geminate counterparts (/tt ff ss zz/), which is consistent with other studies on Lebanese Arabic (Al-Tamimi & Khattab 2015) and Japanese (Kawahara 2005). Higher F1 onset in singletons is probably due to the constriction location or differences in the tongue height. F1 generally correlates with the tongue height, it appears that Ikema geminates had slightly higher tongue blade or body. F1 was the second most important acoustic feature for the classification of manner and voicing (Figure 6). F2 differentiated the length contrast but there was no difference in voiceless and voiced obstruents. F2 was a key contributor for the classification of place. F2 could be affected by a number of articulatory gestures: lip rounding, larger tongue mass contact with the hard palate, forward tongue movement, retracted tongue root, and point of constriction location (Pennington 2011, Ying *et al.* 2012). In order to lengthen the consonant, speakers may expand the tongue constriction, resulting in a larger mass of tongue contact with the hard palate (see Fujimoto *et al.* 2023 for more discussion). Ikema word-initial fricatives exhibited lower F2 onsets compared to affricates and plosives, indicating the effect of manner on F2. As alveolopalatal affricates [tʃ dʒ] cover a large tongue contact area, higher F2 onsets were observed in these two obstruents.

The findings of this study indicated that the manner, place, voicing, and length contrasts in word-initial obstruents of Ikema are achieved by a combination of both temporal and non-temporal correlates. Duration dominates as the key acoustic feature in the classification of word-initial obstruents of Ikema. The perceptual distinction must be required by full lexical contrast in everyday words in Ikema, which may be achieved by as many redundant acoustic cues as there could be. Among them, higher intensity may correspond to ‘stronger’ articulation of geminate obstruents. Due to the absence of cues related to preceding vowel, word-initial obstruents can use intensity, F0, F1, and F2 onsets as additional or secondary correlates to enhance the consonantal contrasts. Our results will contribute to the wider literature on cue enhancement, geminate typology, and phonetic documentation of endangered Ryukyuan languages which are very likely to disappear in the next couple of decades. Future articulatory (ultrasound-imaging and/or electropalatography) and perception studies may also complement the findings of the current study.

*We thank Ikema speakers for their participation and Hiromi Maedomari and staff at the NPO Kyuunu Hukarasha for providing assistance during the recording sessions. The paper benefited from constructive feedback from two anonymous reviewers. This project was funded by Labex EFL to the first author and by a Postdoctoral Travel Award (Graduate School and Office of Postdoctoral Affairs, North Carolina State University, Raleigh) to the second author.

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Appendix

Consonant	Word
/b/	/bata/ ‘stomach’
/t/	/ta/ [ta:] ‘rice field’
/tt/	/tta/ ‘tongue’
/d/	/dariru/ [dari ru(i)] ‘being tired’
/k/	/kazan/ [kadzaŋ] ‘mosquito’
/g/	/gai/ ‘harm’
/ts/ [tʃ]	/tsa/ [tʃa:] ‘tea’
/zj/ [dʒ]	/zjaa/ [dʒa:] ‘place’
/f/	/fau/ ‘to eat’
/ff/	/ffa/ ‘child’
/vv/	/vva/ ‘you’
/s/	/saba/ ‘shark’
/ss/	/ssa/ ‘rumor’
/z/	/zarami/ ‘white sugar’
/zz/	/zza/ ‘father’

Table A1: Word list of word-initial obstruents of Ikema. Phonetic representations are omitted where phonemic representation can replace them.

