Representing implosives: Gradient features for ambiguous segments *

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BLS · February 2020

1 Introduction

- **Observation:** Implosives show mixed phonological and phonetic patterning across languages.
  - Implosives pattern phonologically with obstruents in some languages and implosives in others.
  - Implosives are produced variably within and across languages: ingressive airflow, glottal closure, lowering of the larynx, F0 effects, and implosion are all variable.
  - Mielke (2005) shows that laterals and nasals are also phonetically and phonologically variable, and refers to them as *ambiguous*.
- **Question:** What is the phonological featural representation of implosives that matches their phonetic realization and accounts for their phonological patterning?
  - Previous feature theories (with the exception of Clements and Osu (2002)) assume that implosives are obstruents, distinguished from other obstruents by an extra laryngeal feature.
  - Implosives are absent from studies of sound similarity such as the sonority hierarchy (Parker 2002, 2011).
- **Goal:** We examine the cross-linguistic phonological patterns of implosives and propose a representational solution to the mixed patterning of implosives, relying on gradient rather than binary universal feature values.

Roadmap

1 Introduction
2 Phonological patterning of implosives
3 Phonetic properties of implosives
4 A gradient feature analysis
5 Possible alternative analyses
6 Conclusions

*Special thanks to the Guébie community. Thanks also to Christina Bjorndahl and Rachel Walker, as well as audiences at Georgetown University, LabPhon 16, WOCAL 9, and the LSA 2020 for feedback on various aspects of work. This work is partially funded by NSF DEL grant number 1760302.

2 Phonological patterning of implosives

2.1 Background

- Implosives are present in about 14% of the world's languages, based on the sample of 2,155 languages in the Phoible database.

	ɓ	ɗ	ʄ	ɠ
Count	293	241	45	19
Percent of languages	14%	11%	2%	1%

  - The bilabial implosive is more common than the alveolar, which is more common than the palatal or velar.
  - Languages containing implosives in their inventories are primarily concentrated in subsaharan Africa, with some representation in southeast Asia and Central and South America as well (Moran et al. 2014).

- Implosive patterning in six languages or language families is considered here.

2.2 Implosives pattern with obstruents

2.2.1 Hausa

- In Hausa there is a set of glottalized consonants [ɓ, ɗ, 'y, k, kw, ky] that contrast with voiced and voiceless plosives, and sonorant consonants (nasals, liquids, glides) (Newman 2000, p. 392).

- **Distributional facts**

  - Sonorants do not co-occur in a word in Hausa, but implosives (like obstruents) co-occur with sonorants: *dȃri*, 'hundred'

- **Assimilation facts**

  - Similarly, in CC clusters where the first is an obstruent or implosive, the cluster surfaces as a geminate with the features of the second consonant (Newman 2000, 2004).
    - Sonorants do not show this pattern (1c)

(1) **CC asssimilation in Hausa**

	Underlying	*Surface*	*Gloss*
a.	zàaf-zàafáa	zàazzàafáa	'hot'
b.	káɗ-kàɗáa	kákkàɗáa	'keep beating'
c.	fàrkáa	fárkáa, *fákkáa	'paramour'

- There is no evidence that implosives in Hausa ever pattern with sonorants.

2.2.2 Fula

- In Fula, implosives contrast with voiced and voiceless stops, and sonorants (Paradis 1992).

- **Distributional facts**

  - In coronals CC sequences, the first C must be more sonorous than the second. Implosives pattern with obstruents in this distributional requirement.
    - Liquids, glides, and nasals precede stops and implosives.

  - Stops and implosives never precede other stops or implosives.
- A suffix /-dV/ surfaces as [dV] after a sonorant but [-VrV] after an obstruent. Implosives again pattern with obstruents.

(2) *Fula implosives pattern with obstruents in affix selection* (Paradis 1992, p. 121)

a.	fal-dɛ	'bank'
b.	tul-dɛ	'mountain'
c.	ton-du	'lip'
d.	con-di	'flour'
e.	ser-du	'rifle butt'
f.	hiir-dɛ	'evening'
g.	hus-ɛrɛ	'cube'
h.	nad-ɛrɛ	'belt'
i.	sɛɛd-ɛrɛ	'cowrie'
j.	yiit-ɛrɛ	'eye'
k.	fuʃ-ɛrɛ, *fuʃ-dɛ	'pimple'
l.	ɗaaʃ-ɛrɛ, *ɗaaʃ-dɛ	'bulb'

- **Assimilation facts**
  - Obstruents and implosives pattern together again in assimilating to following coronal suffixes, while sonorants do not.

(3) *Implosives pattern with obstruents in assimilation*(Paradis 1992, p. 122)

a.	/mut-n-a/	munna	'to make s.o dive'
b.	/hɔɗ-n-a/	hɔnna	'to make s.o. inhabit'
c.	/fad-t-a/	fatta	'to wait again'
d.	/tiiɗ-t-a/	tiitta	'to harden again'
e.	/yul-n-a/	yulna, *yunna	'to make s.o. pierce'
f.	/ɓir-n-a/	ɓirna, *ɓinna	'to make s.o. milk'
g.	/hɛl-t-a/	hɛlta, *hɛtta	'to break again'
h.	/ɓir-t-a/	ɓirta, *ɓitta	'to milk again'

- According to Paradis (1992, p. 119), 'In Pulaar [...] there are no arguments favoring an analysis of implosives as sonorants. The behavior of these consonants in Pulaar suggests that the should be classified as stops.'

2.3 Implosives pattern with both obstruents and sonorants

2.3.1 Ijo

- Williamson (1978) describes the patterning of implosives in Ijo, spoken in southern Nigeria.
- In Ijo, implosives pattern with sonorants in some respects, but with obstruents in others.
- **Nasalization facts:**
  - In some Ijo varieties, initial sonorants and implosives are produced as nasalized before nasal vowels, while obstruents are not (4) (Williamson 1987).

(4) **Ijo nasalization** (Williamson 1987)[1]

	Kalabari	Nemba	Biseni	Oporoza	Proto-Ijo	
a.	mĩɲɟi	mĩndí	mĩnĩ	bẽnĩ	* ɓẽdĩ́	'water'
b.	mãŋgí	mãŋgí	mɛ̃ɛ̃	bãĩ	*ɓãgĩ́	'run'
c.	pãmba	pãmbá	–	pĩmã	*pãbã́	'wing'

- In this respect, implosives pattern with sonorants, at lest in Kalabari, Nemba, and Biseni.

- **Distributional facts:**

  - Consonants cannot be 'stronger' than a preceding consonant in the word. The strength divisions are provided below (Williamson 1978).

    Strong p, t, k, kp, f, s
    Medium b, d, g, gb, ɓ, ɗ
    Weak m, l, r, w, y, ɣ

  - Note that the two implosives in the inventory, /ɓ, ɗ/, pattern with voiced plosives.
  - This pattern is illustrated by a set of Proto-Ijo forms in (5) (Williamson 1978, 245), though note that the same pattern also holds in the majority of synchronic forms across Ijo.

    (5) **Proto-Ijo consonants decrease in strength throughout a word**

a.	*/o-kosi/	'old (person)'	strong, strong
b.	*/kodmu/	'waist'	strong, medium, weak
c.	*/akalʊ/	'moon'	strong, weak
d.	*/ɗigi/	'rope'	medium, medium
e.	*/ɓeri/	'ear'	medium, weak
f.	*/o-molmi/	'slave'	weak, weak, weak

- Implosives pattern with obstruents with respect to distribution in a word, but sonorants with respect to nasalization in Ijo.

2.3.2 Ikwere

- In Ikwere, implosives (or 'non-explosive stops' as Clements and Osu (2002) call them) pattern with sonorants in some respects and obstruents in others.

- **Nasalization facts**

  - Ikwere implosives and sonorants have nasal realizations before nasals, but obstruents do not.
    - [àbã̀], 'jaw', but *[ãɓã̀]
    - There are no cases of a surface implosive followed by a nasal vowel, but there are cases of [m] followed by a nasal vowel. /ɓ/ is analyzed as surfacing as [m] before nasal vowels: the strong subject pronoun /ɓɛ̃/ surfaces as [mɛ̃].

- **Tone depressing facts**

  - Implosives and sonorants do not have a depressing (lowering) effect on surrounding tones.

[1] Additional data to fill out this paradigm is not available, so we rely on the analysis provided by the source of the data, Williamson (1987).

- **Distributional facts:**
  - Obstruents and implosives are more often present in onset than coda position in Ikwere. They may precede liquids in onset clusters, while other sonorants cannot.
    - Similar distributional restrictions are found in other African languages with implosives: Lendu, Hausa, Fula. See (Clements and Osu 2002, 337) for an overview.

2.4 Implosives pattern with sonorants

2.4.1 Ebrié

- In Ebrié (Bole-Richard 1983, 327) (Kwa, Côte d'Ivoire), implosives pattern only with sonorants.
- **Nasalization facts**
  - After a nasal vowel, all vowels, sonorants, and implosives surface as nasal.

(6) *Ebrié nasalization affects implosives* (Bole-Richard 1983, 328)

a. àká ɓà lé ɓá
Aka FUT NEG come
'Aka will not come'

b. ã̀ mã̀ nɛ̃́ mã́
She FUT NEG come
'She will not come'

  - Similarly, the plural morpheme in Ebrié is a nasal prefix, which has a nasalizing effect on vowels, sonorants, and implosives (7).

(7) *Ebrié nasalization in plural contexts* (Bole-Richard 1983, 328)

	Singular	*Plural*	
a.	ájá	ɛ̃́ɲã́	'trees'
b.	áɓɛ́	ɛ̃́mɛ̃́	'ropes'
c.	álɛ́	ã́nɛ̃́	'tongues'
d.	àwɔ́	ã̀ŋwɔ̃́	'cats'

  - Implosives and oral sonorants do not co-occur with nasals. Fricatives and plosives, on the other hand, can co-occur with nasal vowels: ɛ̃̀zɔ̃́, 'shell species'.

2.4.2 Guébie

- There is one implosive sound in Guébie, /ɓ/, which constrasts with other obstruent and sonorant labial(ized) consonants, /p, b, kp, gb, k^w, g^w, w/ (Sande 2017).
- The implosive always patterns with sonorants.
- **Distributional facts**
  - CVCV reduction to CCV is highly likely if the second C is /l/ or /ɓ/, but not otherwise.

(8) **CVCV → CCV**

	CVCV	*CCV*	Gloss
a.	jɪla$^{2.3}$	jla^{23}	'ask'
b.	duɓu$^{3.3}$	dɓu^{3}	'mourn'
c.	bete$^{3.1}$	*bte^{31}	'break'

- Implosives and sonorants fail to co-occur in monomorphemic words containing nasals, while obstruents co-occur freely with nasals.
  - Of the 165 disyllabic words containing an implosive, only 2% of them co-occur with a nasal.
  - Similarly, only 10 of the 686 disyllabic words containing /l/ (1%) also contain a nasal consonant.
  - On the other hand, obstruents regularly co-occur with nasals; between 12 and 30% of the disyllabic words containing each obstruent also contain a nasal. (Since nasals make up 20% of the consonant inventory of Guébie, this is the expected proportion of co-occurrences.)

- **Alternation facts**
  - Vowel hiatus is avoided by inserting /j/, /w/, or /ɓ/.
  - In reciprocal reduplication, /ɓ/ is reduplicated as [l].
    - See Kaye et al. (1981) on a related historical change in Dida and Bete, two neighboring Kru languages.

(9) **[l] ∼ [ɓ] alternation in reduplication**

	(Particle-)Verb	*Reciprocal* (verb-RED-li)	*Gloss*
a.	ɓɔ	ɓɔ-l̲ɔ-lɪ	'finish each other'
b.	ji-ɓe	ji-ɓe-l̲e-li	'know each other'
c.	la	la-la-lɪ	'call each other'
d.	ɟu	ɟu-ɟu-li	'respect each other'

- **Other Kru languages:** Like Guébie, implosives pattern with sonorants to the exclusion of obstruents across Kru languages (Kaye et al. 1981).

- **Tone facts**
  - Tone spreading rules apply to implosives in the same way as sonorants. Obstruents block tone spreading (10c) while implosives and sonorants do not (10a,b). Tones spread onto following low-toned words. Relevant data from Vata is provided in (10).

(10) **Tone spreading in Vata** (Kaye et al. 1981, 80)

	Underlying	*Surface*	*Gloss*
a.	n^3 li^1	n^3 li^3	'I ate'
b.	n^3 ɓuɓie$^{1.1.2}$	ɓuɓie$^{31.1.2}$	'I pardoned'
c.	n^3 bada$^{1.1}$	n^3 bada$^{1.1}$	'I hung'

- **Distributional facts**
  - As in Guébie, laterals and implosives across Kru fail to co-occur with nasals.
    - Some Kru languages are analyzed as not having contrastive nasal consonants. Instead, surface nasals are derived from underlying sonorants and implosives in words that contain nasal vowels.

2.5 Summary of phonological patterns

- Implosives show mixed behavior, patterning with obstruents in Hausa and Fula, sonorants in Guébie and Ebrié, and with both in Ikwere and Ijo.

	Implosives & Sonorants	**Implosives & Obstruents**
Co-occurrence restrictions	Ijo, Ikwere, Ebrié, Guébie	Hausa
Distribution within a word	Guébie	Fula, Ijo, Ikwere
Alternations	Ebrié, Guébie	Hausa, Fula

3 Phonetic properties of implosives

- Catford (1939) describes implosives in Nama as ingressive stops with a glottal closure, a lowering of the larynx, and implosion when the glottal closure is released.
  - However, not all implosives are produced with glottal closure or ingressive airflow (Ladefoged 1968; Ladefoged and Maddieson 1996).
  - Not all implosives are produced with larynx lowering or negative oral air pressure (Clements and Osu 2002).
  - Similarly, effects of implosives on F0 of the following vowel differ across speakers and languages (Wright and Shryock 1993; Nagano-Madsen and Thornell 2018)
- Clements and Osu (2002) determine that the most reliable feature to differentiate an implosive is the lack of an increase in oral air pressure during production.
  - Our acoustic findings for Guébie (Sande and Oakley 2020) are consistent with those of Clements and Osu (2002):
    - Implosives lack an increase in oral air pressure during production.
  - However, we also found the following:
    - Implosives have an average intensity between that of sonorants and obstruents (and statistically significantly different from both groups)
    - Implosives and sonorants are statistically significantly longer in duration than obstruents.
  - Intensity and duration are possible acoustic correlates of *resonance* in the vocal tract, or *sonority*.

4 A gradient feature analysis

- Distinctive feature theories make predictions about the sounds that we expect to see patterning together phonologically across languages.
  - Sounds that share features, such as vowels with a [-back] feature (front vowels), for example, form a natural class.
  - These natural classes can be the targets or triggers of phonological alternations.
- The majority of the literature on the features of implosives assumes that they are obstruents, and focuses on the laryngeal features which distinguish implosives from plosives and ejectives.
  - Chomsky and Halle (1968); Greenberg (1970); Halle and Stevens (1971); Keating (1984); Lombardi (1995); Hall (2007)
  - An exception: (Clements and Osu 2002) propose that implosives in Ikwere are both [-obstruent] and [-sonorant], based on language-specific articulatory, acoustic, and phonological properties.
  - With the exception of Clements and Osu (2002), all prior work on features of implosives predicts that implosives are obstruents and should pattern with obstruents to the exclusion of sonorants.

We propose that features are universal but gradient.

- The sonority hierarchy is built into the grammar as a universal gradient feature [sonorant].
- Implosives (and other ambiguous segments) fall in between obstruents and sonorants on the universal sonority scale. We adopt a modified version of Gradient Symbolic Representations.

- Gradient Symbolic Representations traditionally assume that input segments can be gradiently activated (Smolensky and Goldrick 2016).
- We follow an emerging line of work proposing that *features* can be gradiently activated (Rosen 2016; McCollum 2019; Walker 2019).

Previous versions of the sonority hierarchy do not include implosives:

(11) **The 'complete' sonority hierarchy** (Parker 2011)
vowels[2] ≫ glides ≫ rhotic approx. ≫ flaps ≫ laterals ≫ trills ≫ nasals ≫ voiced fricatives ≫ voiced affricates ≫ voiced stops ≫ voiceless fricatives ≫ voiced affricates ≫ voiced stops

We propose two adjustments to the sonority hierarchy:

- Implosives should be added between nasals and (voiced) fricatives.
- Each step on the hierarchy is associated with an activity value for the feature sonorant.

(12) **Proposed gradient sonority hierarchy** vowels: $[\text{Son}]_1$ ≫ glides: $[\text{Son}]_{.9}$ ≫ rhotic approx.: $[\text{Son}]_{.8}$ ≫ flaps: $[\text{Son}]_{.75}$ ≫ laterals: $[\text{Son}]_{.7}$ ≫ trills: $[\text{Son}]_{.65}$ ≫ nasals: $[\text{Son}]_{.6}$ ≫ **implosives**: $[\text{Son}]_{.5}$ ≫ voiced fricatives: $[\text{Son}]_{.35}$ ≫ voiced affricates: $[\text{Son}]_{.3}$ ≫ voiced stops: $[\text{Son}]_{.25}$ ≫ voiceless fricatives: $[\text{Son}]_{.15}$ ≫ voiceless affricates: $[\text{Son}]_{.1}$ ≫ voiceless stops: $[\text{Son}]_{.0}$

- The proposed gradient sonority feature is related to phonetics in that segments with longer duration, more sustained voicing, and higher intensity (more resonance) are more sonorant.
  - In a MaxEnt-Harmonic Grammar model (Goldwater and Johnson 2003; Hayes and Wilson 2008), language-specific constraint weights interact with this universal sonority activity scale to result in mixed patterning of implosives within and across languages.
- In **Ebrié nasalization** sonorants and vowels nasalize when immediately adjacent to another nasal sound.
- **Relevant constraints**
  - IDENT-SONORANT: For each segment, assign violations according to the difference in the value of the feature [sonorant] in the output as compared to the input.
  - *NASAL-NONNASALSON: For non-nasal each segment adjacent to a nasal segment in the output, assign violations according to the sonority value of the non-nasal segment.
  - IDENT-FEATURE: For each output segment with at least one feature that differs from the corresponding input segment, assign one violation.
- Using the MaxEnt Grammar Tool, the weights in (13) were determined to predict the output distribution of candidates that most closely matches the observed facts.

(13) **Ebrié nasal harmony**

ɛ̃jã	ID-SON 37.6	*NAS-NONNASALSON 33.4	ID-F 7.6	**H**	**Obj**	**Pred**
a. ☞ɛ̃ɲã	.3		1	18.88	1	1
b. ɛ̃jã		.9		30.06	0	0
c. ɛ̃tã	.9		1	41.44	0	0

[2]Parker breaks down vowel sonority into 5 parts, which we've simplified here.

ɛ̃ɓã	ID-Son 37.6	*Nas-NonNasalSon 33.4	ID-F 7.6	**H**	**Obj**	**Pred**
a. ☞ɛ̃mã	.1		1	11.36	1	1
b. ɛ̃ɓã		.5		16.7	0	0
c. ɛ̃bã	.25	.25	1	25.35	0	0

ɛ̃zã	ID-Son 37.6	*Nas-NonNasalSon 33.4	ID-F 7.6	**H**	**Obj**	**Pred**
a. ɛ̃nã	.25		1	17	0	0
b. ɛ̃ɓã	.15	.5	1	29.94	0	0
c. ☞ɛ̃zã		.35		11.69	1	1

- In **Hausa full assimilation**, when an obstruent or implosive is followed by another consonant, it assimilates to the features of that following consonant, resulting in gemination.
- **Relevant constraints:**
  - Ident-Sonorant: For each segment, assign violations according to the difference in the value of the feature [sonorant] in the output as compared to the input.
  - CodaCond: For every coda consonant segment x in the output, if its features are not licensed by a following consonant y, assign 1-a violations, where a is the sonority value of x.
  - Dep-feature: Assign one violation for every feature in the output that lacks a corresponding feature in the input.

(14) **Hausa gemination**

zafzaafaa	CodaCond 28	ID-Son 15.2	Dep-F .9	**H**	**Obj**	**Pred**
a. zafzaafaa	.85			23.8	0	0
b. ☞zazzaafaa		.1		1.52	1	1
c. zarzaafaa	.2	.6	1	15.62	0	0

kaƈkaƈaa	CodaCond 28	ID-Son 15.2	Dep-F .9	**H**	**Obj**	**Pred**
a. kaƈkaƈaa	.5			14	0	0
b.☞kakkaƈaa		.5		7.6	1	1
c. karkaƈaa	.2	.8	1	18.66	0	0

farkaa	CodaCond 28	ID-Son 15.2	Dep-F .9	**H**	**Obj**	**Pred**
a.☞farkaa	.2			5.6	1	1
b. fakkaa		.8		12.16	0	0
c. faƈkaa	.5	.3	1	19.46	0	0

- The proposed gradient representations account not just for the patterning of implosives, but other sonority-related patterns across languages.
- Other segments that fall in the middle of the proposed hierarchy are also seen to be phonologically and phonetically mixed across languages:
  - Nasals and laterals (Mielke 2005)
  - Voiced fricatives (Bjorndahl 2018)
  - Fricative vowels (Matt Faytak, p.c.)
  - Others?

5 Possible alternative analyses

1. Implosives universally have features in common with both obstruents and sonorants (cf. Clements and Osu (2002)).

   (15) **Possible universal features of obstruents, implosives, and sonorants**

	+obstruent	*-obstruent*
[+sonorant]	–	Sonorants
[-sonorant]	Obstruents	Implosives

   – *Potential problems*:
   * Over-predicts that we should find a set of sounds that is both [+obstruent] and [+sonorant]. (Though see Bjorndahl (2018) on voiced fricatives as a potential [+obs, +son] class.)
   * Requires binary [obstruent] and [sonorant] features, which is different than what most extant universal feature theories assume.
   * In languages like Guébie and Ebrié, there is no phonological evidence for a [-sonorant] feature of implosives.
   * In languages like Hausa and Fula there is no phonological evidence for a [-obstruent] feature of implosives.

2. Features are not universal, but emergent, and learners of different languages will learn a different set of features for implosive sounds based on language-specific phonetics and phonology (Pierrehumbert 2001; Johnson 2007).

   – Instances of production and perception (exemplars) experienced by the speaker/hearer are stored (in clusters) as they occur, not necessarily associated with an abstract feature set.
   – There are a number of benefits of adopting an emergent feature approach, in particular for segments who pattern with different classes of sounds in different languages.
   – *Potential problem:* An emergent feature approach does not make clear predictions about possible natural classes. What sounds sounds do we expect implosives to pattern with across languages?
   – Though perhaps for cognitive or other functional reasons there are explanations for why some segments/exemplars are clustered together.
   * Within emergent feature theory, phonetically natural classes are the result of common sound changes, while phonetically unnatural classes are the result of less likely sequences of events (Mielke 2008, 87-88). Further historical investigation is needed to determine the sequence of events most likely to have resulted in the current Guébie system (and other cross-linguistic systems with contrastive implosives).

6 Conclusions

- Implosives pattern with obstruents in some languages, sonorants in some languages, and with obstruents and sonorants in different alternations in other languages.
- Allowing phonological features to be gradient is consistent with the phonetic reality and accounts for the mixed behavior of implosives and other ambiguous sounds within and across languages.

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