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ARTICLE

Voicing or register in Jarai dialects? Implications for the reconstruction of Proto-Chamic and for registrogenesis

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Abstract

Jarai is a Chamic language of Vietnam and Cambodia that is traditionally described as preserving the original Austronesian voicing contrast in onset obstruents. However, there is anecdotal evidence that it has developed a register contrast, i.e. a binary contrast based on a bundle of spectral properties like pitch, voice quality and vowel quality. We conducted production and perception experiments of the voicing/register contrast in two Jarai varieties spoken in Saom Kaning, Cambodia, and Ea Sup, Vietnam, to determine if they preserve voicing and/or have developed a register contrast. Results show that both dialects have a register contrast primarily based on vowel height modulations (F1) and that onset voicing has become at best an optional secondary property of register. F1 is also the primary cue used for register identification in both dialects. Implications for the diachronic development of the register contrast in Chamic languages and in Mainland Southeast Asia in general are discussed.

Keywords: Jarai; Voicing; Register; Transphonologization; Chamic

1. Introduction

Jarai is a language spoken in Vietnam and Cambodia that belongs to the Chamic branch of the Austronesian family. Until recently, it was described as having a voicing contrast in initial plain stops, like most Chamic languages. However, it has recently been suggested that instead of this expected voicing contrast, Jarai may have a register contrast similar to that of most Austroasiatic languages of the Annamite Cordillera (Williams & Siu 2013; Jensen 2014). This observation seems to coincide with the realization that Chru and Southern Raglai, two other Chamic languages also described as having a voicing contrast, are actually registral (Brunelle et al. 2020; Brunelle, Brown & Hà 2022). This paper aims at determining if two Jarai dialects spoken at the extremes of the Jarai dialectal continuum preserve stop voicing or have developed register, by means of production and perception experiments.

In Section 2, we give an overview of voicing and register in Austroasiatic and Chamic languages. We then provide basic background information about the Jarai language and the two dialects under study in Section 3. In Section 4 and Section 5, we present the acoustic and perceptual experiments that were designed to explore the voicing/register contrasts found in Jarai, with a focus on unaspirated stops. In Section 6, we discuss the implications of the results for models of register development and for the history of Chamic languages.

2. Voicing and register in Mainland Southeast Asia

Scholars of Mon and Khmer, two Austroasiatic languages with well-established Indic scripts, have long observed that the voicing contrast marked in onset obstruents in their classical texts corresponds to vowel modulations in their contemporary spoken varieties (Blagden 1910; Maspero 1915). It is generally accepted that Austroasiatic originally had a voicing contrast in obstruents that was replaced with a ***register*** contrast, i.e., a bundle of phonetic properties including vowel quality, voice quality and pitch, realized on the following vowel. Thus, the Old Khmer minimal pair /ta/ 'grandfather' ~ /da/ 'duck' is now realized as [taː] ~ [ti̤ə] in the conservative Khmer dialects of Eastern Thailand (Wayland 1997; Wayland & Jongman 2001; Maspong 2021).

In typical register systems, high register vowels (< voiceless onset obstruents) have relatively open initial portions, a modal voice and a higher pitch, while low register vowels (< voiced onset obstruents) have relatively close initial portions, a breathy or lax voice and a lower pitch. However, different languages emphasize different cues. For example, Ban Nakhonchum Mon largely realizes the register distinction through voice quality and pitch (Abramson, Tiede & Luangthongkum 2015), but vowel quality is the only remaining reflex of register in Standard Khmer (Huffman 1985; Ferlus 1992). While voicing and register were tacitly treated as mutually exclusive in most research conducted in the past forty years, recent studies suggest that voicing remains an optional secondary cue of register in Chru, Chrau and Mnong (Brunelle et al. 2020; Tạ, Brunelle & Nguyễn 2022; Brunelle, Đinh & Tạ 2023).

The phonetic motivations for the development of register from voicing have been discussed in detail elsewhere (for an overview, cf. Brunelle & Tạ 2021). In a nutshell, they are usually attributed to secondary articulations meant to increase the size of the supraglottal cavity to favor closure voicing by boosting the transglottal airflow (Gregerson 1976; Ferlus 1979), to formant cut-back following the aspiration of former voiced stops (Wayland & Jongman 2002), or to an auditory low-frequency effect (Kingston et al. 1997).

Register is found in many, if not most Austroasiatic languages. It has been studied experimentally in Mon (Lee 1983; L.Thongkum 1990; Abramson, Tiede & Luangthongkum 2015), Kuy (L.Thongkum 1989; Abramson, Luangthongkum & Nye 2004; Lau-Preechathammarach 2023), Khmer (Wayland 1997; Wayland & Jongman 2001; Maspong 2021), Wa (Watkins 2002), Chrau (Tạ, Brunelle & Nguyễn 2022) and Khmu (Svantesson & House 2006; Abramson, Nye & Luangthongkum 2007; Kirby, Pittayaporn & Brunelle 2023) and has been described in many others. However, it is far less common in Austronesian languages, the phylum to which Jarai belongs. A tense-lax contrast that seems equivalent to register has been extensively studied in Javanese (Fagan 1988; Hayward 1993; Hayward et al. 1994; Hayward 1995; Adisasmito-Smith 2004; Thurgood 2004; Dresser 2005; Brunelle 2010; Kenstowicz 2021) and voicing-conditioned vowel alternations are well-attested in closely related Madurese (Cohn 1993a, 1993b; Cohn & Lockwood 1994; Cohn & Ham 1999; Misnadin, Kirby & Remijsen 2015; Kirby 2020; Misnadin & Kirby 2020), but otherwise, register seems limited to Chamic languages and no reconstruction of Proto-Austronesian or of any branch of Austronesian has to our knowledge ever included a register contrast.

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Within Chamic, register has long been reported in all dialects of Cham (Friberg & Hor 1977; Edmondson & Gregerson 1993; Bùi 1996; Brunelle 2005, 2006, 2009), even if some authors analyze it as a form of tone (Blood 1967; Moussay 1971; Hoàng 1987; Phú, Edmondson & Gregerson 1992; Thurgood 1993, 1996, 1999). A vowel-based register is reported in Haroi (Lee 1977; Mundhenk & Goschnick 1977; Đoàn 2009) and recent phonetic evidence establishes that register is also found in Chru (Brunelle et al. 2020) and in some Raglai dialects (Lee 1998; Tạ 2009; Brunelle, Brown & Hà 2022). While Cham, Chru, Haroi and Raglai are all spoken within 80 km of the coast of Vietnam, Jarai is spoken further afield in the Highlands of the Annamite cordillera and seems to form a distinct branch of Chamic with closely related Rade (Brunelle 2023). Finding register in that language would force us to reconsider reconstructions of Proto-Chamic, as they all assume a voicing contrast in onset obstruents (Lee 1966; Burnham 1976; Thurgood 1999).

3. The Jarai language

Jarai is the largest Chamic language. The geographical distribution of Jarai in Vietnam and Cambodia is given in Figure 1. According to the Vietnamese census, there were 513,930 Jarai in Vietnam in 2019 (General Statistics Office of Vietnam 2020). The Ratanakiri Provincial Planning Department reported 31,359 Jarai in 2021, a figure that probably includes the large majority of Jarai in Cambodia.

As far as we know, there is no systematic assessment of dialectal variation in Jarai, but the phonology, syntax and basic lexicon are fairly similar across varieties, and speakers report mutual intelligibility. In this paper, we report experiments on two Jarai dialects spoken at the periphery of the Jarai dialectal continuum. The first one is the Western Jarai dialect spoken in Ratanakiri province, Cambodia. Despite minor lexical and phonological differences between villages, it is relatively homogenous. The majority of its speakers are fluent in Khmer (with various degrees of competence) and some also speak Kachok, Tampuan and Vietnamese, depending on the proximity of other language communities. We conducted our experiments in the village Saom Kaning, where most of our participants resided.

The second dialect under investigation is spoken in Ea Sup, Đăk Lăk province, Vietnam. For convenience, we will refer to it as Eastern Jarai. It is geographically separated from

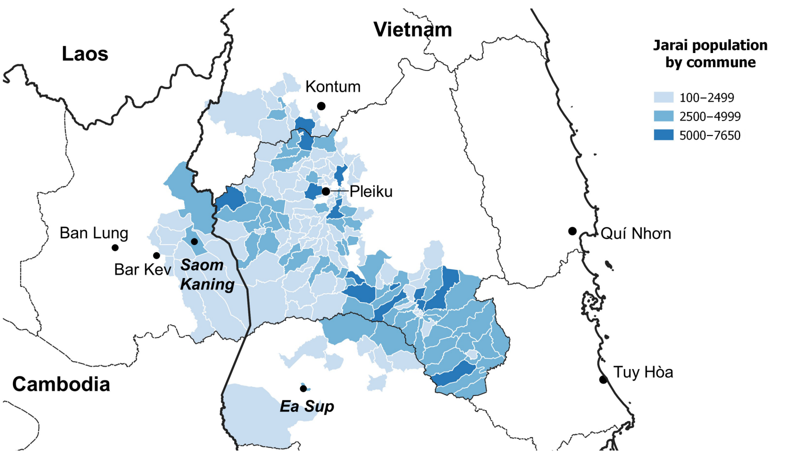

Figure 1. (Colour online) Geographical distribution of ethnic Jarai in Vietnam and Cambodia, by commune.

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Table 1. Jarai onsets (adapted from Dournes 1976)

Voiceless (high register?) stops	p	t	c	k ʔ
Aspirated stops	pʰ	tʰ	cʰ	kʰ
Voiced (low register?) stops	**b**	**d**	**ɟ**	**g**
Implosive stops	ɓ	ɗ	ʄ	
Fricatives	s	h		
Nasals	m	n	ɲ	ŋ
Approximants	w	l,	r	j

other Jarai dialects as its speakers were relocated to Ea Sup from neighbouring areas during and shortly after the Vietnam war, but its speakers do not perceive it to be very different from the varieties spoken in northern Đăk Lăk. Ea Sup Jarai are all fluent in Vietnamese as their village has become surrounded by a Vietnamese town in the past fifty years. Many also speak Rade, a mutually intelligible Chamic language spoken further south, and Lao, which was until recently a lingua franca in the area.

The consonant inventory of Jarai is given in Table 1. It is typical of Chamic languages in that it comprises four series of stops: plain voiceless stops, aspirated voiceless stops, plain voiced stops and implosive stops (described as 'preglottalized' in some sources). The plain voiced stops, bolded in Table 1, are the series that may have conditioned a low register on following vowels (and even have devoiced) if recent reports are accurate.

A few notational decisions with a limited impact on our research questions must be noted. We adopt a phonological analysis and treat /c/ and /ɟ/ as unaspirated stops (following Lafont 1968; Dournes 1976; Siu 1976), even if these consonants are described as affricates in Jensen (2014). We include /cʰ/ because it appears in a handful of lexical entries in two dictionaries (Dournes 1964; Headley 1965). Finally, the complex clusters proposed by Lafont (1968) are excluded because they can for the most part be attributed to the loss of an underlying presyllabic vowel (see Jensen 2014).

As phonological differences between Jarai dialects appear relatively superficial, the inventory in Table 1 is shared by the Jarai varieties spoken in Saom Kaning and Ea Sup.

4. Production experiment

In order to determine if the two Jarai dialects under study preserve a voicing contrast or have a register system, we conducted an acoustic and electroglottographic investigation of their laryngeal contrasts.

4.1 Methodology

4.1.1 Participants

Data collection in Saom Kaning was carried out by the first and second authors and by Kalan Khi, a native speaking assistant, with twenty-one native speakers of Western Jarai (eleven women, ten men) in January 2019. They were all born between 1952 and 2004 and were all natives of Saom Kaning. All had lived their entire lives in the area, except one older man who had spent thirteen years in Bar Kev, one young woman who had spent four years in Ban Lung (two towns also located in the province of Ratanakiri) and one older man who had spent one year in Vietnam. Otherwise, all participants spoke Khmer (but some women only had very basic proficiency) and several could speak Tampuan or Vietnamese at various levels of fluency.

In Ea Sup, data was collected by the first and fourth authors and by Y Tit Kpă, a native-speaking local assistant, with twenty-two speakers of Eastern Jarai (twelve women, ten men) in February and March 2019. They were all born between 1945 and 1993 and were all natives of Ea Sup, except a man born in Bản Đôn, 30 km south, before his family returned to Ea Sup when he was five. Only three participants spent significant time out of Ea Sup: an older women spent ten years in a Jarai village in Cambodia in her childhood, a middle-aged man spent fifteen years in Bản Đôn in his youth and a younger man spent four years in college in Hồ Chí Minh City. All Eastern Jarai participants spoke Vietnamese fluently, most had at least a passive command of Rade, and a few spoke some Mnong, Lao or Khmer.

4.1.2 Wordlist and procedure

Because of lexical differences between Western and Eastern Jarai, we designed different wordlists for the two locations (see Appendices I and II), but aimed to find target words containing syllables composed of all possible combinations of onset dentals /t, ɗ, tʰ, ɗ, n/ and velars /k, ɡ, kʰ, ŋ/ followed by the vowels /iː, ɛː, aː, ɔː, uː/. Dental and velar places were selected because they have the largest and smallest numbers of consonants, respectively.

In registral Chamic languages, the register of most onsets is directly predictable from their original laryngeal settings. In some languages, however, sonorants developed a register contrast as they underwent register spreading from the previous consonant or syllable and monosyllabization (Friberg & Hor 1977; Thurgood 1999; Brunelle & Phú 2019). For this reason, a few pairs of nasal-initial syllables (starting with /n-, ŋ-/) suspected to contrast in register were included. Open monosyllables were preferred; when they were not available, monosyllables closed by sonorants or disyllabic words ending with the target syllables were chosen. There was a total of fifty-six words in the Western Jarai wordlist and fifty-seven in the Eastern Jarai wordlist, but only thirty-three words were identical or had close cognates in the two lists. This is in part due to our decision to favor frequent words with specific phonotactic properties over cognates.

Participants read the wordlist four times in a randomized order while four signals were simultaneously recorded through a Steinberg UR44 preamplifier using SpeechRecorder (Draxler & Jänsch 2004). The first signal was a high-quality audio channel recorded though a Shure BETA 53 microphone. The second signal was a glottal waveform recorded through a Glottal Enterprises EG2-PCX EGG. Two additional channels, a larynx height tracker and a low quality back-up audio signal were recorded through the EG2-PCX but will not be reported here.

As few participants could read in Jarai, they were presented with the words by one of the authors in either Khmer (in Saom Kaning) or Vietnamese (in Ea Sup) and were asked to translate them in Jarai and to pronounce them in a frame sentence. A handful of Western Jarai speakers who spoke limited Khmer (mostly older women) were presented with words in Jarai by Kalan Khi, our native-speaking assistant. Participants then had to insert the target words in one of the frame sentences in (1)–(2) before pronouncing them. Variations in the frame sentence were tolerated to facilitate spontaneous productions as long as the segment preceding the target word was a sonorant. The full recording session took between 30 and 60 minutes, depending on the speaker.

(1) Western Jarai frame sentence

/kɔw	hiap	kləːj	___	jwaː	ɲuː	maʔaːk/
1SG	say	word		because	3SG	beautiful

'I say the word ___ because it is beautiful.'

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(2) Eastern Jarai frame sentence

/kɔw	hɛːp	kəlɔːj	___	jwaː	ɲuː	heam/
1SG	say	word		because	3SG	beautiful

'I say the word ___ because it is beautiful.'

All materials recorded during the production experiment can be accessed from the Pangloss collection and raw data can be downloaded from the Nakala repository. (Eastern Jarai: https://pangloss.cnrs.fr/corpus/Eastern_Jarai?lang=fr&mode=pro; https://nakala.fr/10.34847/nkl.61a5z29q; Western Jarai: https://pangloss.cnrs.fr/corpus/Western_Jarai?lang=fr&mode=pro; https://nakala.fr/10.34847/nkl.f71a8dxx).

4.1.3 Data processing and analysis

After removing tokens produced disfluently or sentences in which the target word was disrupted by background noise (from vehicles, loud music and domestic animals), 4464 Western Jarai and 4789 Eastern Jarai words were annotated in Praat Textgrids (Boersma & Weenink 2010). A sample annotation is provided in Figure 2. Stop closures, fricatives and sonorants were labeled based on spectrograms, as well as the open phase of each target syllable, which extends from the consonant release to the end of the vowel. Important voicing landmarks were labeled based on the EGG signal: the onset of voicing was marked in all target syllables, as well as the point of cessation of voicing and the point of resumption of voicing in the case of stops with voicing perturbations (see Section 5.1 for further details).

Acoustic and durational measurements were obtained at every millisecond of the audio recordings using PraatSauce (Kirby 2018). Since a 25-ms window was used for acoustic measures, the first and last 12 ms of each vowel will not be reported as their measurement windows span adjacent segments or silence. The acoustic measures reported here include f0, F1, F2, CPP and two spectral tilt measures, H1*–H2* and H1*–A1*. These two spectral tilt measures were chosen as they are the most significant in distinguishing the two voicing series/registers in the Jarai dialects under study (H2*–H4*, H1*–A2* and H1*–A3* were also measured, but are not presented here). They were corrected for formant frequencies (Iseli & Alwan 2004).

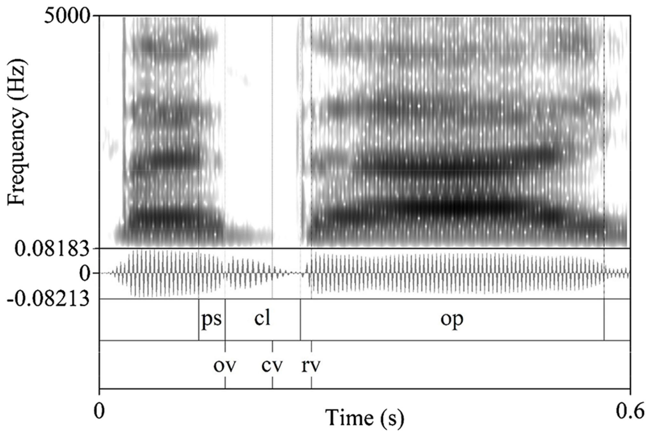

Figure 2. Annotation of Western Jarai target word /daː/ 'duck'. *Top*: spectrogram; *Middle*: EGG signal; *Bottom*: acoustic landmarks (ps: previous sonorant, cl: closure, op: open phase, ov: onset of voicing, cv: cessation of voicing, rv: resumption of voicing).

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Table 2. Proportion of excluded measures

	f0	F1	F2	H1*–H2*	H1*–A1*
W. Jarai	4.1%	3.8%	4.2%	4.1%	7.2%
E. Jarai	3.7%	3.9%	4.0%	3.7%	6.6%

Outliers were removed following a two-step process. Local tracking errors were first detected by converting f0, F1 and F2 into z-scores, by speaker. Derivatives were then obtained for each of these z-normalized measures. Any measure whose derivative was not between -.5 and .5 z was excluded, as it corresponds to a dramatic jump likely associated with a tracking error. These excluded measures were left blank. Global tracking errors and outliers were then excluded by obtaining mean f0, F1, F2 for each combination of speaker, vowel and voicing/register (after the exclusion of local errors) and excluding any measure distant from the mean by more than three standard deviations. All H1*–H2* and H1*–A1* measures calculated from excluded f0, F1 or F2 measures were also excluded. The proportion of excluded measures, per dialect, is reported in Table 2.

Since there is significant variation in acoustic ranges across speakers, all non-durational measures were z-normalized by speaker before conducting statistical analyses and plotting data. In order to ease visualization of the data, these z-normalized measures were converted back into familiar scales in the figures by using the means and standard deviations of all speakers (mean of all speakers + z-score * mean standard deviation of all speakers).

4.1.4 Statistical modeling

The significance of differences between key indicators was assessed by fitting linear mixed models on the data with the *lmerTest* package in R (Kuznetsova, Brockhoff & Christensen 2017). Models were fitted on plain stop VOT and on the means of f0, H1*–H2*, H1*–A1*, CPP, F1 and F2 over the first ten sampling points (10 ms) of vowels after plain stops, which, as we will see shortly, is systematically the area of greatest difference between voicing series/registers (the depth of voicing/register effects in vowels are roughly time-locked rather than proportional to vowel duration). Fixed main effects included voicing/register, vowel quality and place of onsets, and all two-way interactions of these fixed factors were included (three-way interactions were excluded as they resulted in overfitting). Random slopes by-subject and by-word were also included. Models were simplified top-down by iteratively dropping the interaction with the lowest F-value in the ANOVA of the model. Interactions were dropped one by one as long as the resulting models had a lower Akaike information criterion (AIC) score than the previous model or a higher or equal, but not significant different AIC. Note that no attempts were made to run statistical models on the acoustic properties of other consonants, either because they do not contrast in voicing/register or, in the case of sonorants, because we do not have enough target words containing them to fit robust models.

Cohen's d's were used to assess the weight of each acoustic property in the voicing/register contrast (Cohen 1988; Clayards 2008; Brunelle et al. 2020; Brunelle, Brown & Hà 2022; Tạ, Brunelle & Nguyễn 2022). They were calculated by dividing the difference between the vowel-weighted and subject-weighted means of each property for each voicing/register category by its standard deviation. A large absolute Cohen's d (> 0.8) indicates that the two distributions under investigation have a large difference and that they could play a role in contrast maintenance.

4.2 Production results

We will present results from the two dialects in parallel to facilitate comparison. We will start with a description of the onsets (Section 4.2.1), go over the acoustic properties of the following vowels (Section 4.2.2) and then report results on the relative relevance and magnitude of each acoustic property in the voicing/register contrast (Section 4.2.3).

4.2.1 Onsets

A simple look at the VOT distribution in the two Jarai dialects is sufficient to see that onset voicing is no longer the cue that distinguishes the reflexes of Proto-Chamic voiced and voiceless plain onset stops (Figure 3, top row). High register stops (< *plain voiceless stops) systematically have a moderate positive VOT, as expected, but only a small minority of low register stops (< *plain voiced stops) have a negative VOT, the large majority patterning with voiceless stops. For this reason, we will henceforth refer to plain stops as *high/low register stops* rather than as *voiceless/voiced stops*. Other stops behave as expected in both dialects: aspirated stops systematically have a long positive VOT and the implosive stop /ɗ/ preserves a strong negative VOT.

Mixed models run on plain stops with a positive VOT reveal that in Western Jarai, coronal stops have a slightly longer VOT in the high than the low register before the vowels /aː, ɛː, uː/, but not before /iː, ɔː/. Moreover, this effect is not found in velar stops (RegisterHigh (/ɔː/ as the reference level) $\beta = 4.5$ ms, $t = 1.5$, $p = .136$, RegisterHigh:Vowel uː: $\beta = 9.3$ ms, $t = 2.1$, $p = .035$, RegisterHigh:PlaceVelar $\beta = -7.6$ ms, $t = -2.8$, $p = .005$ – Table W1, App. 3). In Eastern Jarai, there is a slightly shorter VOT in high register than in low register velar stops but no similar difference is found in coronal stops (RegisterHigh $\beta = -1.4$ ms, $t = -0.8$, $p = .504$, RegisterHigh:PlaceVelar $\beta = -6.8$ ms, $t = -4.2$, $p = .025$ – Table E1, App. 3). As significant VOT differences between registers are all under 10 ms, it is unlikely that they are under speaker control.

Voice onset time, however, is not always a sufficient indicator of voicing. In voiced obstruents, vocal fold duration often ceases before the end of the consonant because of the aerodynamic voicing constraint (Ohala 1983, 2011), a build-up in supraglottal air pressure that hinders transglottal airflow. An instance of this interruption of voicing in a voiced

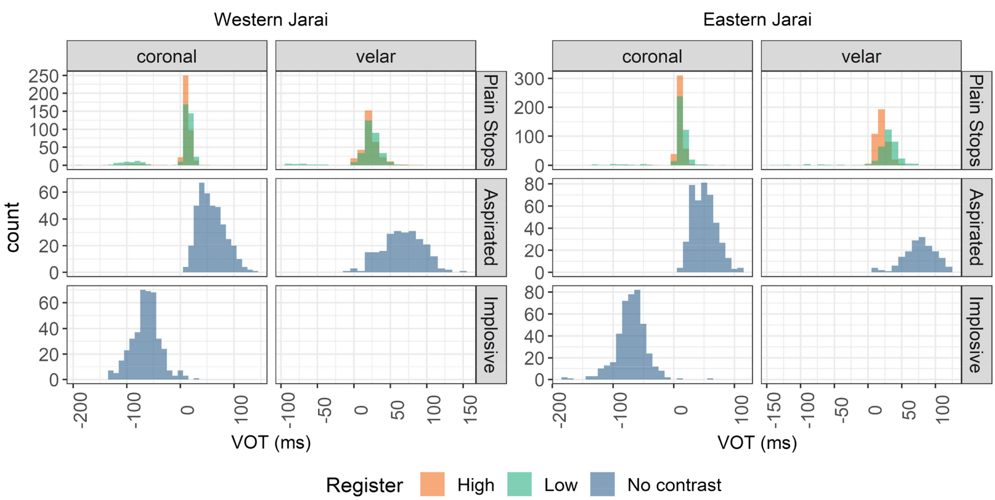

Figure 3. (Colour online) VOT distribution in stops in Western Jarai (left) and Eastern Jarai (right).

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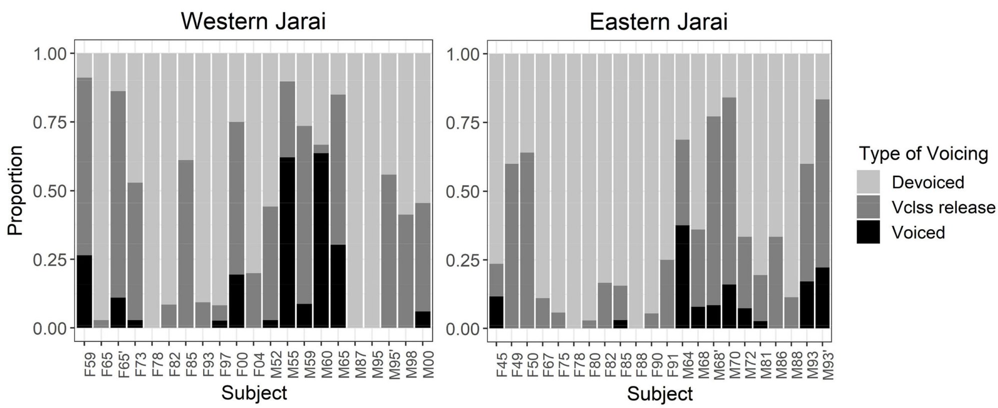

Figure 4. Proportion of low register stops which are fully devoiced, have a voiceless release or are fully voiced, by dialect and speaker. Speakers are organized by sex (F/M) and year of birth.

stop can be seen in Figure 2. Following previous work, we will refer to such cases as *closure voicing with a voiceless release* (Brunelle, Brown and Hà 2022).

In Figure 4, we report the proportion of low register stops by type of voicing. *Voiced* stops have vocal fold vibrations over their entire closure. Voiced stops with a *voiceless release* are similar to the former, but their voicing ceases before stop release. Finally, *devoiced* stops do not have vocal fold vibrations, except for possible carry-over voicing stemming from a previous sonorant (termed 'bleeding' by Davidson 2016). As bleeding can reach up to 30% of the closure even in high register stops (< voiceless stops), only low register stops with voicing over more than the first 30% of their closure were counted as voiced stops with a voiceless release, while voiced stops with a shorter voicing were treated as devoiced.

The breakdown in Figure 4 suggests that even when looking at nuances in closure voicing, low register stops are devoiced most of the time in Eastern Jarai. Full voicing and voicing with voiceless release are a little more prevalent in Western Jarai, but still make up less than half of low register stops. While some lexical items show more devoicing than others, this does not seem to obey any obvious pattern of phonological conditioning. Three words have devoiced closures more than 85% of the time: Western Jarai /giː/ 'to be blocked' and Eastern Jarai /dɛːl/ 'k.o. bird' and /dɔːŋ/ 'to hit a gong'. However, other words pattern less categorically: their rates of devoicing range between 40% and 65% in Western Jarai and between 35% and 70% in Eastern Jarai. In both dialects, men tend to maintain more full voicing or voicing with voiceless release than women, a pattern also encountered in another Chamic language, Raglai (Brunelle, Brown & Hà 2022) and in genetically unrelated languages (Smith 1978; Jessen & Ringen 2003; van Alphen & Smits 2004; Helgason & Ringen 2008; José 2010; Bayley & Holland 2014; MacKenzie 2018; Michnowicz & Planchón 2020).

To summarize this section, the modern reflexes of Proto-Chamic voiced stops /d, ɡ/ in Jarai are no longer systematically voiced, even if they preserve some optional closure voicing in many speakers. Our auditory impressions and observation of spectrograms elicited in non-controlled conditions suggest that the other members of the series, /b, ɟ/, are also normally voiceless. In the next section, we establish that the original Chamic voicing contrast has evolved into a register system in Jarai.

4.2.2 Vowels

Now that we have shown that neither dialect preserves a robust voicing contrast, let us look at Jarai vowels to see if they exhibit the type of acoustic modulations expected in a

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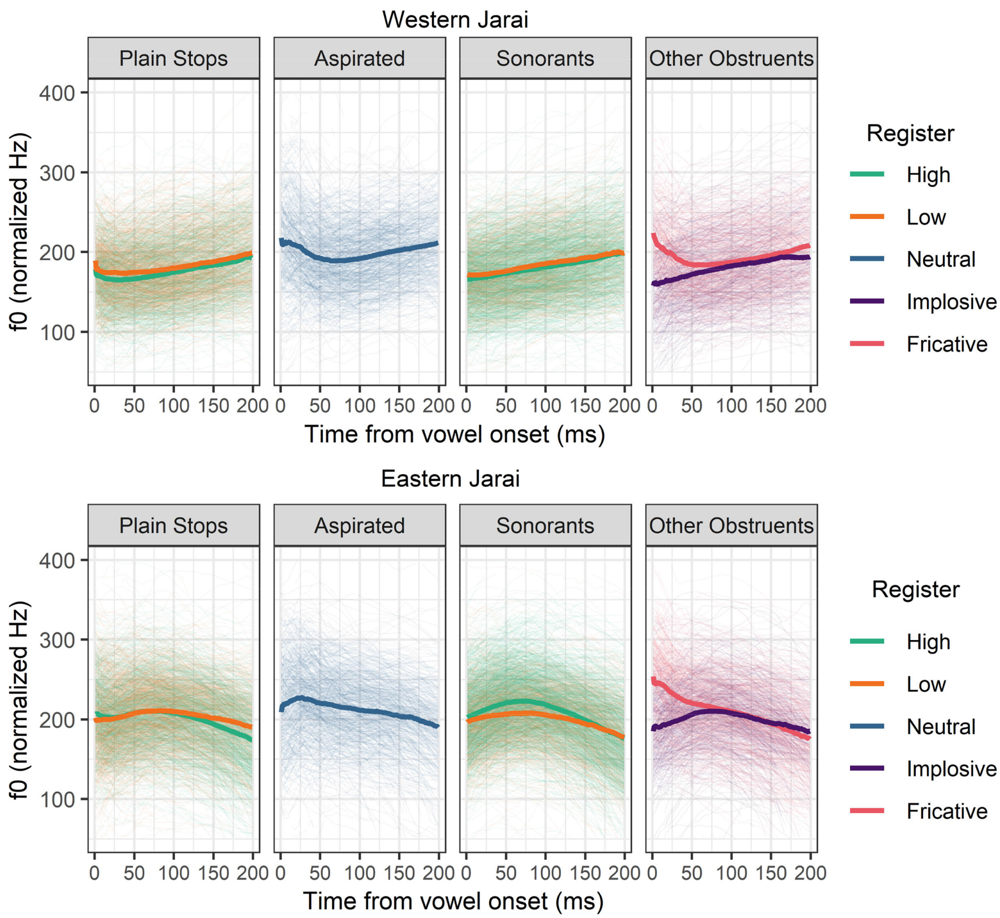

Figure 5. (Colour online) Normalized f0 of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

register language. Figure 5 shows normalized f0 after the various onsets recorded in the target words. Western Jarai seems to exhibit a slightly higher f0 during the first 50 ms of vowels after low register plain stops than after high register ones. However, this difference is only significant in the vowel /ɔː/ (RegisterLow $\beta = 36$ Hz, $t = 8.4$, $p < .001$; all other vowels have significant interactions of Vowel and Register in the opposite direction – Table W2, App. 3). The f0 of high and low register sonorants does not appear to differ. As for other obstruents, aspirates and the fricative /s/ condition a high f0 at the onset of the following vowel while the implosive /ɗ/ is followed by a slightly lower f0 than sonorants.

In Eastern Jarai, high and low register plain coronal stops have indistinct initial f0s, but velars have a lower f0 in the low register (RegisterLow $\beta = 3$ Hz, $t = 0.7$, $p = .483$; RegisterLow:PlaceVelar $\beta = -20$ Hz, $t = -3.4$, $p = .012$ – Table E2, App. 3). There does not seem to be any register difference at the onset of vowels following sonorants. As in Western Jarai, aspirates and the fricative /s/ condition a relatively high f0 on following vowels while the implosive /ɗ/ induces a relatively low f0.

Turning to voice quality, we see in Figure 6 that in Western Jarai, vowels following low register plain stops have a much higher H1*–H2* than their high register

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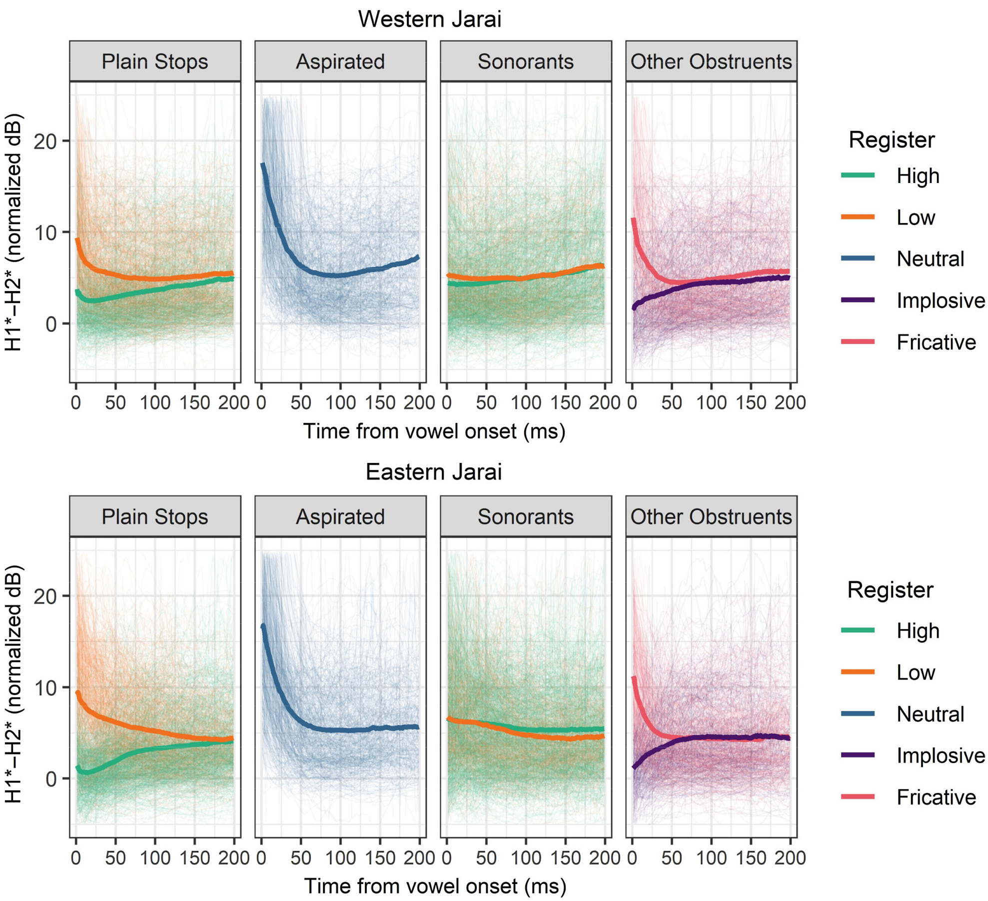

Figure 6. (Colour online) Normalized H1*–H2* of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

counterparts, indicating laxness or breathiness (RegisterLow $\beta = 4.8$ dB, $t = 8.3$, $p < .001$ – Table W3, App. 3). This difference, which lasts about 200 ms, is even greater in velars (RegisterLow:PlaceVelar $\beta = 2.1$ dB, $t = 3.8$, $p < .001$ – Table W3, App. 3), but is largely canceled out in /iː/ (RegisterLow:Voweli: $\beta = -3.7$ dB, $t = -4.1$, $p < .001$ – Table W3, App. 3). No noticeable difference in H1*–H2* is found after high and low register sonorants. As for other obstruents, aspirates and fricative /s/ are followed by a high H1*–H2*, a consequence of their wide glottal opening, and the implosive /ɗ/ is followed by a low H1*–H2*, probably caused by the narrowing of the glottis required to produce an ingressive airflow.

Eastern Jarai vowels show a much higher mean H1*–H2* after low register stops than high ones, but this effect is less robust than in Western Jarai due to a larger interspeaker variation (RegisterLow $\beta = 5.5$ dB, $t = 2.3$, $p = .052$ – Table E3, App. 3). As in Western Jarai, there is no H1*–H2 difference at the onset of vowels following sonorants. Other obstruents pattern like in Western Jarai.

Our second measure of spectral tilt, H1*–A1* is much less affected by register differences than H1*–H2*, as can be seen in Figure 7. Low register plain stops are followed by a higher H1*–A1* than high ones in Western Jarai (RegisterLow $\beta = 1.8$ dB, $t = 4.7$, $p = .004$ – Table W4, App. 3), but it is not clear if such a small difference is linguistically relevant. A slightly

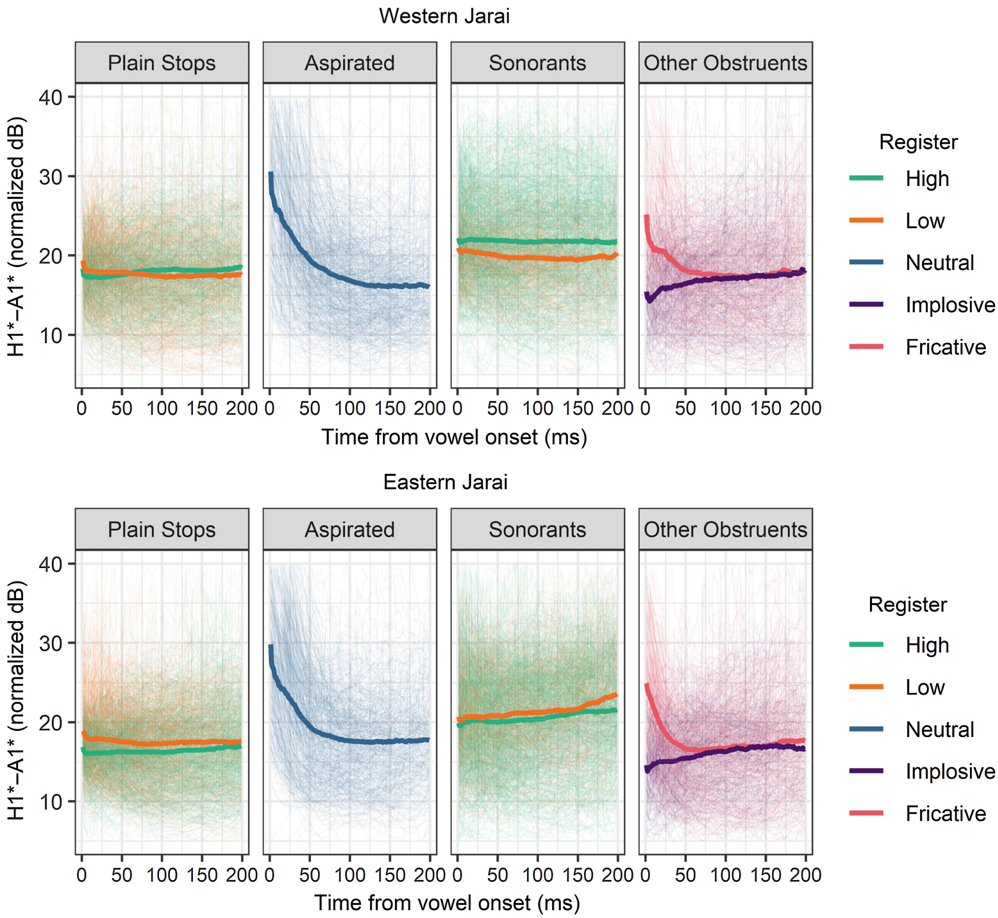

Figure 7. (Colour online) Normalized H1*–A1* of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

larger register difference is visible after sonorants, but it goes in the unexpected direction. The patterns found after other consonants largely mirror those found for H1*–H2*.

The apparently larger register difference in H1*–A1* found after Eastern Jarai plain stops is not significant (RegisterLow $\beta = 2.0$ dB, $t = 1.8$, $p = .106$ – Table E4, App. 3). There is no clear register difference after sonorants, and other obstruents again pattern as they did for H1*–H2*.

Our last voice quality indicator, CPP, measures the noise component that is usually associated with non-modal phonation (Seyfarth & Garellek 2018; Garellek & Esposito 2021). A high CPP corresponds to a more modal voice. In Western Jarai, low register plain stops are followed by a significantly lower CPP than high register ones (RegisterLow $\beta = -2.1$ dB, $t = -4.2$, $p < .001$ – Table W5, App. 3), a difference that is even greater after velars (RegisterLow:PlaceVelar $\beta = -1.4$ dB, $t = -2.7$, $p = .007$ – Table W5, App. 3). Together with the spectral slope measures seen above, this would indicate the presence of breathiness after low register stops. There is no apparent register difference after sonorants, and other obstruents are all followed by a relatively low CPP. In the case of aspirates and of the fricative /s/, this low CPP is probably caused by frication noise. After the implosive /ɗ/, on the

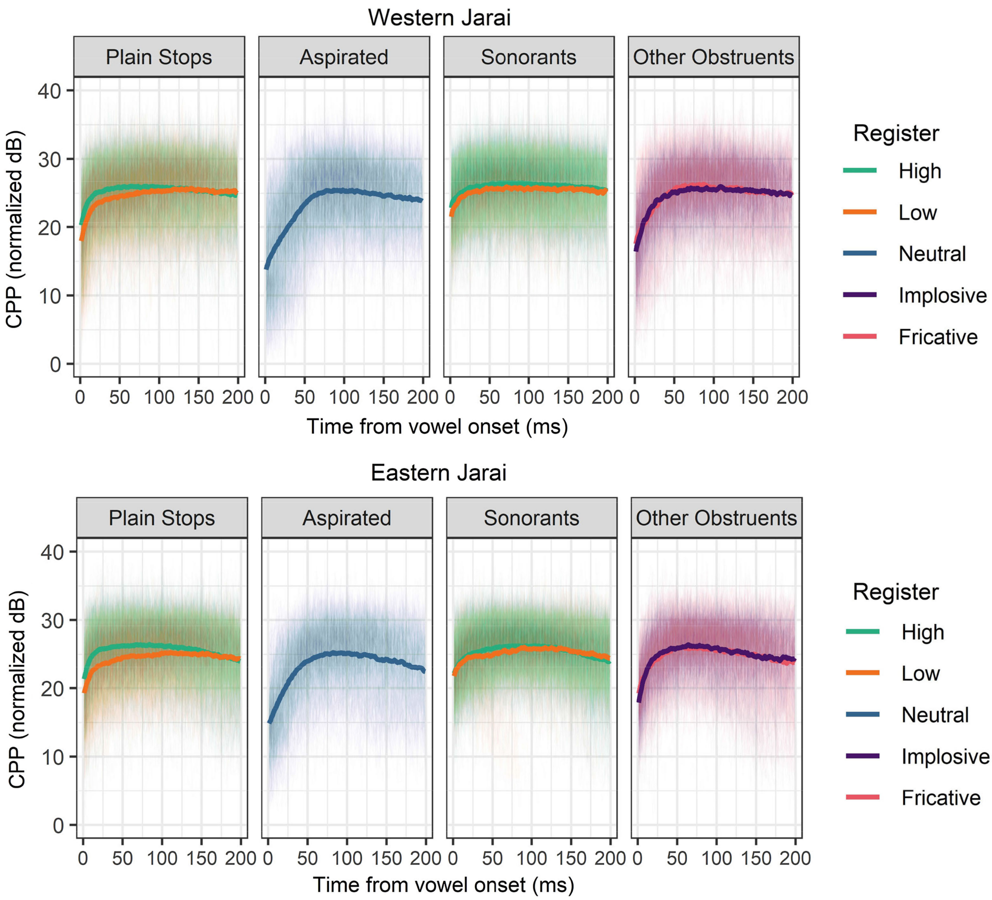

Figure 8. (Colour online) Normalized CPP of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

other hand, it is probably associated with a greater glottal constriction resulting in greater turbulence noise.

Figure 8 suggests a greater CPP difference after plain stops in Eastern than in Western Jarai, but this apparent effect does not reach significance because of important inter-speaker variation (RegisterLow $\beta = -0.9$ dB, $t = -1.1$, $p < .351$ – Table E5, App. 3). The patterns found after other onsets are similar to those found in Western Jarai.

Turning to vowel quality, we see in Figure 9 that F1 is significantly higher at vowel onset after high register stops than after low ones, a difference that lasts about 100 ms (RegisterLow $\beta = -191$ Hz, $t = -10.9$, $p = .009$ – Table W6, App. 3). This difference seems greater in low than in high vowels, and is not significant in /iː/ (RegisterLow:Voweli: $\beta = 185$ Hz, $t = 6.7$, $p = .022$ – Table W6, App. 3). There is no large register difference after sonorants, except perhaps in /ɔː/, and other obstruents mostly seem to pattern like high register plain stops.

The same general pattern seems to hold after Eastern Jarai plain stops, where register-conditioned F1 differences reach a high t-value, even if their p-value is high (RegisterLow $\beta = -117$ Hz, $t = -2.0$, $p = .117$ – Table E6, App. 3). The apparent reversal in /ɛː/ in Figure 9

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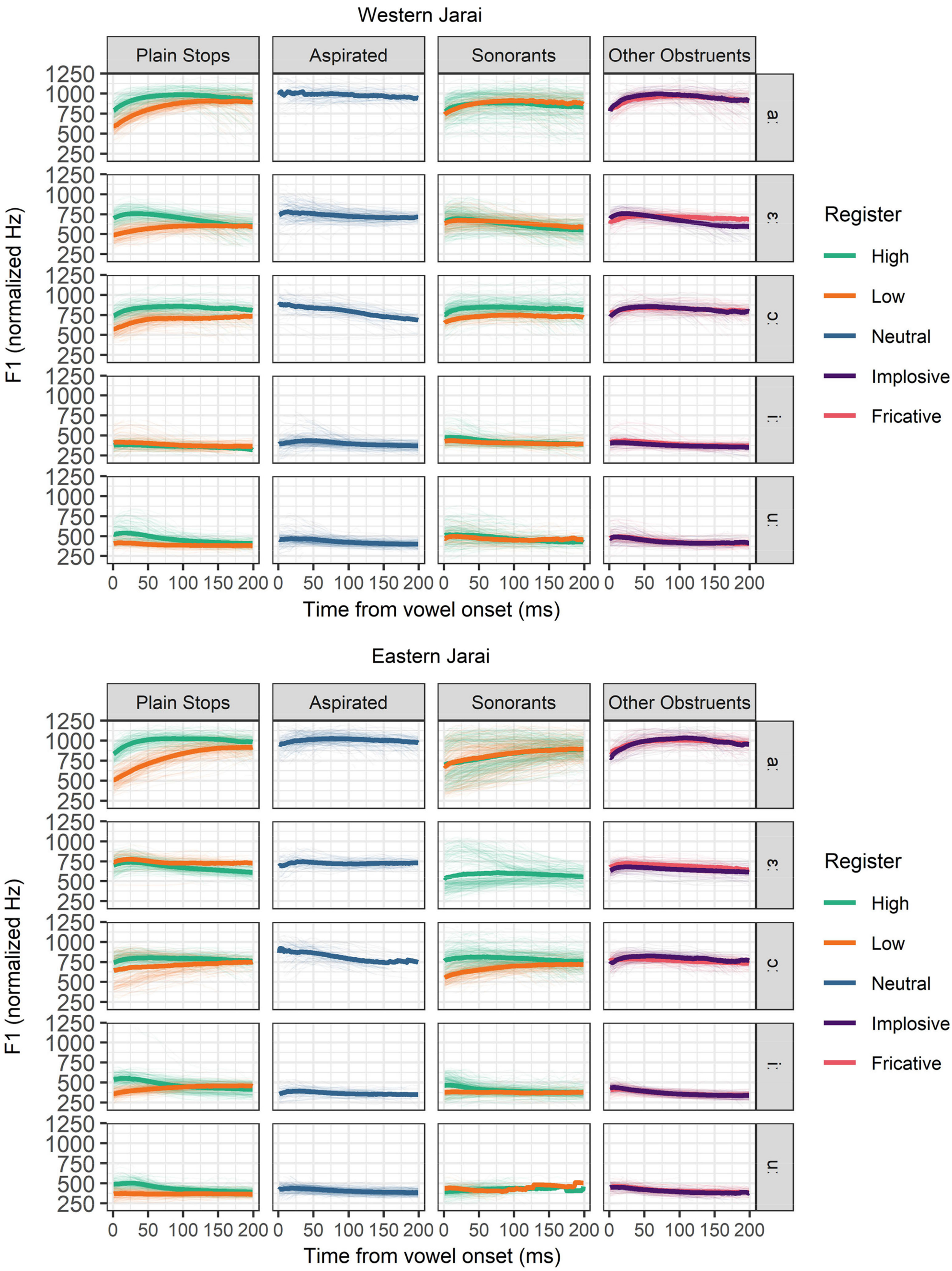

Figure 9. (Colour online) Normalized F1 of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

is not significant. Sonorants seem to have a smaller F1 difference between the high and the low registers and other obstruents again pattern with the high register plain stops.

Differences in F2 are more subtle, as can be seen in Figure 10. In Western Jarai, there is a higher F2 at the beginning of vowels following low register stops (RegisterLow $\beta = 173$ Hz,

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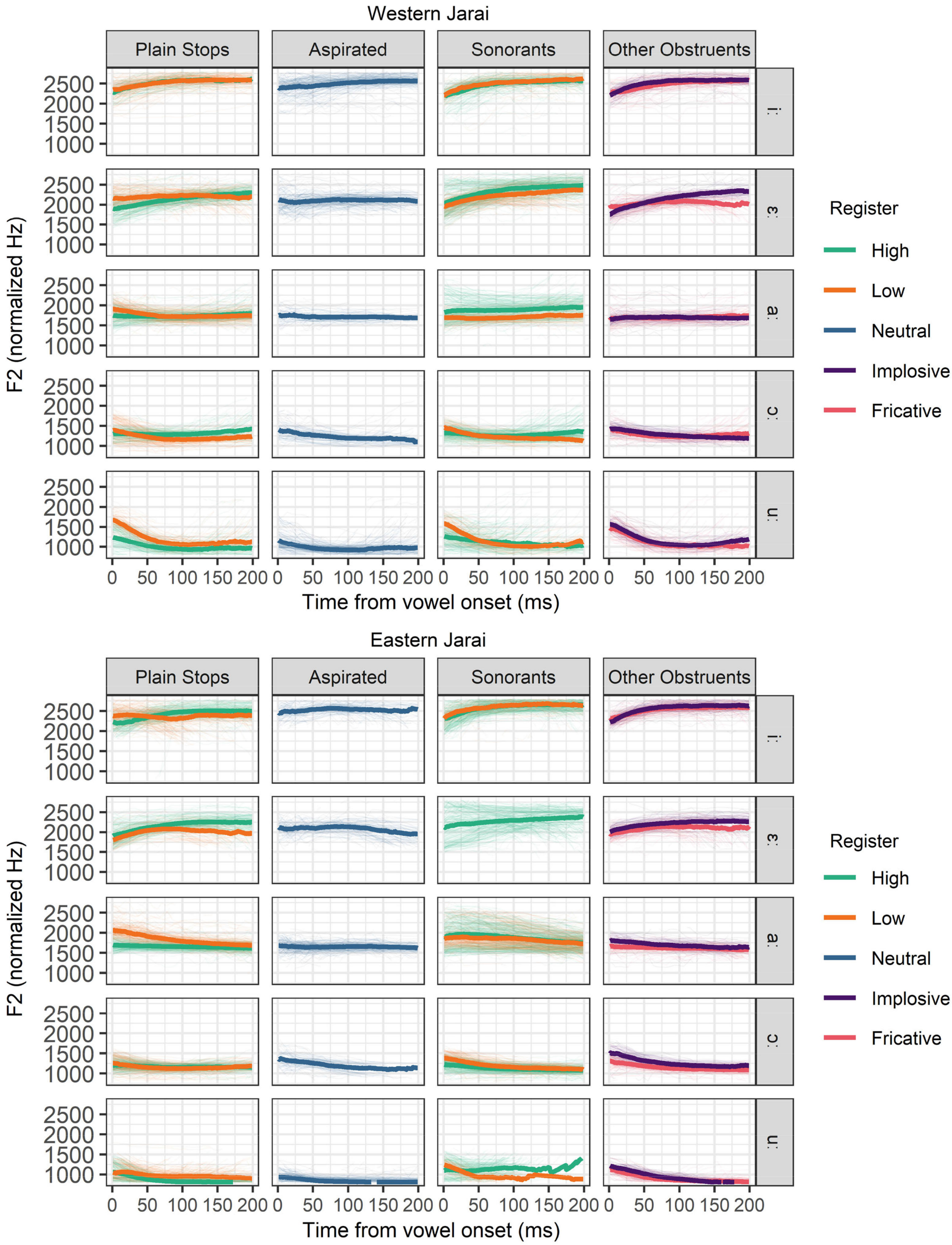

Figure 10. (Colour online) Normalized F2 of the first 200 ms of vowels following Western Jarai and Eastern Jarai onsets. Thick lines represent means, thin lines individual observations. The implosive /ɗ/ and the fricative /s/ do not contrast in register and are included for comparison.

t = 3.6, p = .069 – Table W7, App. 3). F2 after sonorants does not seem to pattern consistently and other obstruents do not clearly pattern with one register or the other.

Eastern Jarai shows some complex but robust F2 trends. While the register of plain stops does not condition a systematic F2 difference across vowels, there is a strong effect in at

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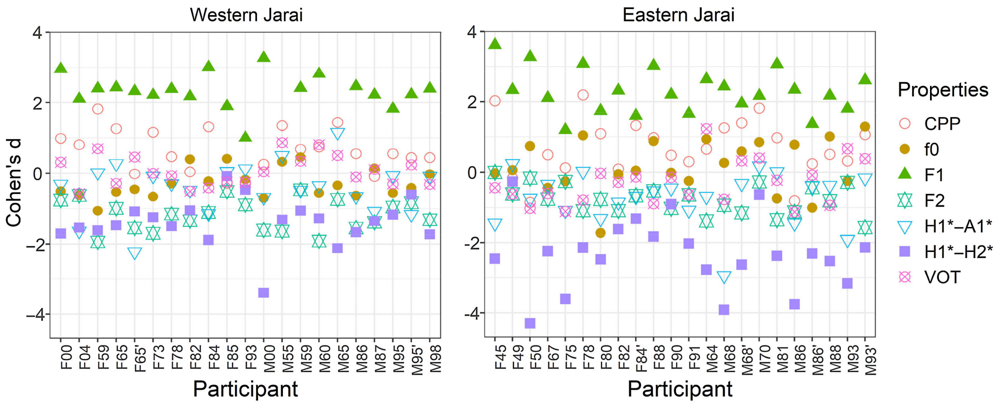

Figure 11. (Colour online) Cohen's d's of each acoustic property associated with the Jarai register contrast, per dialect and speaker. Speakers are organized by sex (F/M) and year of birth.

least /aː/ and /iː/ (RegisterLow:Vowela: $\beta = 337$ Hz, $t = 10.1$, $p = .002$; RegisterLow:Voweli: $\beta = 215$ Hz, $t = 6.4$, $p = .008$ – Table E7, App. 3). No clear patterns emerge for other onset consonants.

4.2.3 Production cue weights

In order to get a better idea of the variation in the cues used to distinguish registers across speakers and dialects, Cohen's d's were computed for each speaker. Cohen's d's above 0.8 and below −0.8 indicate a large separability between the distribution of the two registers. Positive Cohen's d's denote larger values in the high register, while negative Cohen's d's denote larger values in the low register. In Figure 11, we can see that individual production cue weights are similar across ages and sexes and that they vary little between the two dialects.

F1 seems to be the most robust production cue in both dialects, with a Cohen's d of more than 1 in all speakers. Voice quality cues also seem to distinguish the two registers: in most speakers, H1*–H2* has a Cohen's d below -1 and CPP has a Cohen's d above 1, and these two acoustic properties generally weigh heavier in Eastern than Western Jarai, but H1*–A1* is more variable and tends to have Cohen's d's much closer to 0. F2 also seems to have some distinctive value as it has consistently negative Cohen's d but some speakers have values very close to 0. The other two cues, f0 and VOT are extremely variable, with some speakers having positive Cohen's d's while others have negative ones.

Overall, this confirms the results presented in Section 4.2.2: the two Jarai dialects investigated here no longer reliably distinguish voiced and voiceless plain stops but have developed a register contrast on following vowels. The production cues that are used to distinguish these registers are F1, voice quality and, to a certain extent, F2. The only clear difference between dialects is a slightly stronger reliance on H1*–H2* in the production of voice quality in Eastern Jarai.

5. Perception experiment

A perception experiment was conducted to determine if the cues used in register identification match the acoustic properties uncovered in the previous section and if they vary across dialects and speakers. In Section 5.1, we describe the methodology used for this experiment and in Section 5.2, we present identification results. In Section 5.3, we look at the relation between production and perception in the two dialects and across speakers.

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5.1 Methodology

An experiment was designed in which listeners of both Western and Eastern Jarai had to listen to stimuli varying in acoustic parameters mirroring those found to be relevant in Section 4 and to identify them as either high or low register words. In Section 5.1.1, we describe the stimuli used in the experiment. In Section 5.1.2, we provide details about the participants and the experimental procedure. An overview of the statistical analysis is given in Section 5.1.3.

5.1.1 Stimuli

Stimuli were created using Klattgrid synthesis in Praat (Boersma & Weenink 2010). Two minimal pairs were synthesized: /taː/ 'we' ∼ /da̤ː/ 'duck' (Western Jarai), 'chest' (Eastern Jarai) and /tuː/ 'closet' ∼ /dṳː/ 'deflated'. /d/ is used to mark the low register stop because there is no standard IPA diacritic for register and because the low register has optional closure voicing.

The stimuli were resynthesized based on natural utterances produced by a middle-aged male speaker whose register contrast was representative of the mean acoustic properties presented in Section 4. Vowel duration was set to 350 ms. We manipulated the acoustic parameters shown to play the most important role in the acoustic study: voice quality, F1, F2 and onset voicing. No attempt was made at manipulating f0, the least reliable acoustic property of register (if reliable at all), as this would have resulted in an unreasonably long experiment. Three-step continua were generated for each property using the following parameters.

- Voicing. Three types of dental onset stops were generated: (1) a stop with full closure voicing (70 ms); (2) a stop with a voiceless release: voicing over the first 40 ms of its closure, a period of voicelessness at the end of the closure and 10 ms of aspiration after the release; and (3) a stop with a voiceless closure and 10 ms of aspiration after the release.
- Voice quality. Voice quality was manipulated by using two Klatt parameters: open phase (or open quotient, OQ), which modulates spectral tilt ($H1^*–H2^*$ and $H1^*–A1^*$ in the production study), and breathiness amplitude (BA), which adds aspiration noise to the vowel (CPP in the production study). At vowel onset, the breathy step had a OQ of .6 and a BA of 60 dB, the middle step had a OQ of .5 and BA of 30 dB and the modal step had a OQ of .4 and a BA of 0 dB. All three synthesized steps then reached an OQ target of .5 at 150 ms and a BA target of 0 dB at 300 ms. Manipulation of these parameters yielded stimuli with voice qualities closely mirroring those of the production results, as illustrated in Figure 13.
- F1. For /a/, targets at vowel onset were 500, 675 and 850 Hz. They all returned to 800 at 150 ms and remained stable until vowel end. For /u/, targets at vowel onset were 290, 415 and 540 Hz. They all returned to 300 at 150 ms and remained stable until vowel end.
- F2. For /a/, targets at vowel onset were set to 1600, 1750 and 1900 Hz. They all returned to 1500 Hz at 100 ms and remained stable until vowel end. For /u/, targets at vowel end were 1300, 1425 and 1550 Hz. They all returned to 900 Hz at 100 ms and remained stable until vowel end.
- f0. Pitch did not vary over the stimuli and was the same in /a/ and /u/ stimuli. It started at 120 Hz, dropped to 115 Hz at 100 ms and to 110 at vowel end.

All possible combinations of these acoustic values were synthesized, yielding eighty-one stimuli (3 voicing steps X 3 voice quality steps X 3 F1 steps X 3 F2 steps). Spectrograms of

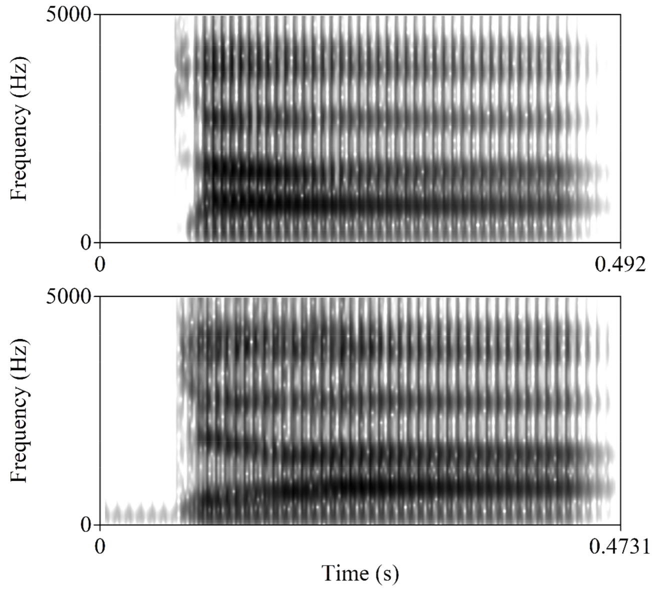

Figure 12. Spectrograms of sample stimuli. Top: Stimulus mirroring natural productions of high register /ta/ (Targets at vowel onset: OQ .4, BA 0 dB, F1 850 Hz, F2 1600 Hz). Bottom: Stimulus mirroring natural productions of low register /da/, with optional voicing (Targets at vowel onset: OQ .6, BA 60 dB, F1 500 Hz, F2 1900 Hz).

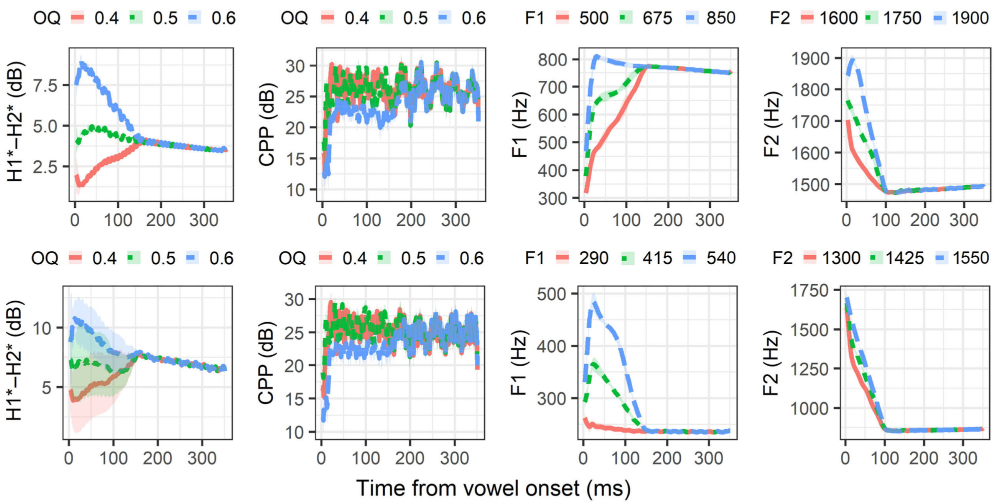

Figure 13. (Colour online) Mean values of the acoustic parameters manipulated in the stimuli used for the identification experiment. Top panel: /ta~da/. Bottom panel /tu~du/. The ribbons show one standard deviation above and below the mean (the large H1*–H2* ribbons for /tu~du/ are due to the effect of F1 on spectral slope).

stimuli representing high register /ta/ and low register /da/ are given in Figure 12. These stimuli differ in all four acoustic dimensions discussed above and mirror natural productions of the target words. The reliability of the synthesis parameters was controlled by measuring the stimuli with PraatSauce (Kirby 2018). The distribution of the stimuli along the four acoustic dimensions shown to be the most relevant in Section 4 is given in Figure 13.

5.1.2 Participants and procedure

The perception experiment on Western Jarai was conducted in July 2022 by the first and the second authors. Forty-seven participants (twenty-four women, twenty-three men) took part in it (three additional participants were excluded because they were unable to use the computer). Out of the forty-seven participants, eighteen had been speakers for the production experiment three years before. Participants all resided in Saom Kaning or the vicinity. They were either born in Saom Kaning (40/48) or within 10 kilometers (7/48), except one who was born in Mondulkiri from parents originally from Saom Kaning and returned there at the age of four. Two participants spent a few years each in Vietnam and Kompong Cham. All participants spoke Khmer (most with a high proficiency), and several also spoke Tampuan and Vietnamese.

The perception experiment on Eastern Jarai was also conducted in July 2022, by the first, third and fourth authors. Forty-four participants (twenty-two women, twenty-two men) took part in it (two additional participants were excluded because they could not be trained on the identification task). Seventeen of the forty-four participants had been speakers for the production experiment three years before. They were all born in Ea Sup, but four had spent a few years in other Vietnamese cities for study or work. Participants all spoke Vietnamese, and several also spoke Rade, Mnong and Lao.

In both venues, participants were asked to sit in front of a computer placed on a table in a quiet room or underneath a stilt house. Up to three participants took part in the experiment simultaneously, in which case the different computers were positioned on separate tables facing different directions. They had to follow instructions presented on the screen, to listen to stimuli in Sennheiser HD 280 PRO headphones and to identify the stimuli by pressing one of two computer keys associated with images representing response choices. Images were identical in the two experiments, except those associated with the word /da/, which means 'chest' in Western Jarai but 'duck' in Eastern Jarai. For each pair of target words, participants underwent three training phases: one with three repetitions of the two stimuli most closely mirroring natural productions (with feedback), one with five repetitions of the same two near-natural stimuli (without feedback), and one with ten random stimuli. They then had to identify each set of eighty-one stimuli three times, in alternating blocks. As few participants could read Jarai, visual instructions were provided, along with short written instructions in Khmer (Western Jarai) and Vietnamese (Eastern Jarai).

5.1.3 Analysis

Mixed logistic regressions were used to analyze the identification results, by syllable and dialect. The dependent variable was the responses provided by participants. The fixed effects were the types of voicing and voice quality (VQ), F1 and F2 steps. Random slopes for each main effect by participant were also included. Models were simplified using the same top-down approach as in Section 4. Interactions were dropped one by one, starting with that with the lowest F-value, as long as the resulting models had a lower Akaike information criterion (AIC) score than the previous model or a higher or equal, but not significantly different AIC.

5.2 Perception results

Figure 14 plots the proportion of high register responses to the /a/ stimuli (/ta/ vs. /da/). In both dialects, F1 is by far the factor that plays the greater role in register identification, a high F1 favoring high register responses. Voicing (VOT) seems to play a weaker role, but is not negligible in stimuli with ambiguous F1 (green lines): a negative VOT is associated with the low register, while a 10 ms VOT biases responses towards the high register. The effects of voice quality (represented by open quotient, OQ) and F2 are not immediately apparent.

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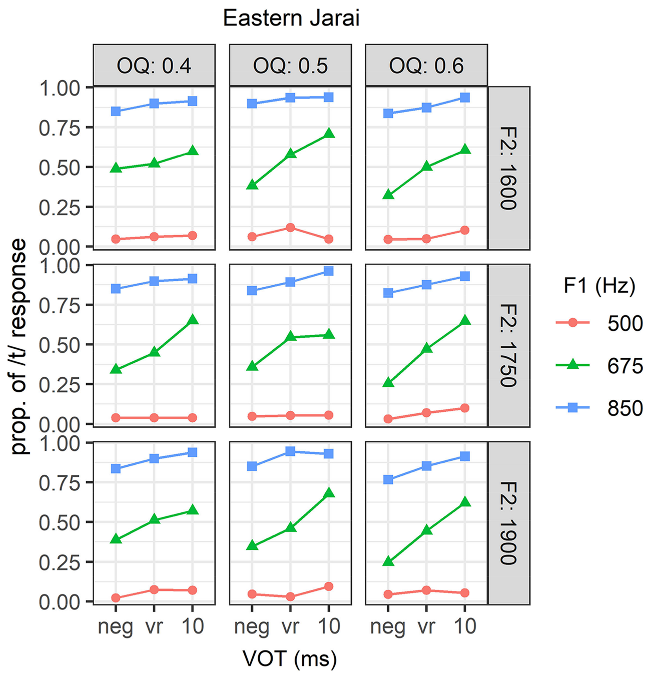

Figure 14. (Colour online) Proportion of high register /t/ responses for each type of /a/ stimulus, by F1, VOT (type of voicing), OQ (representing voice quality as a whole) and F2, for all listeners. Left panel: Western Jarai. Right panel: Eastern Jarai.

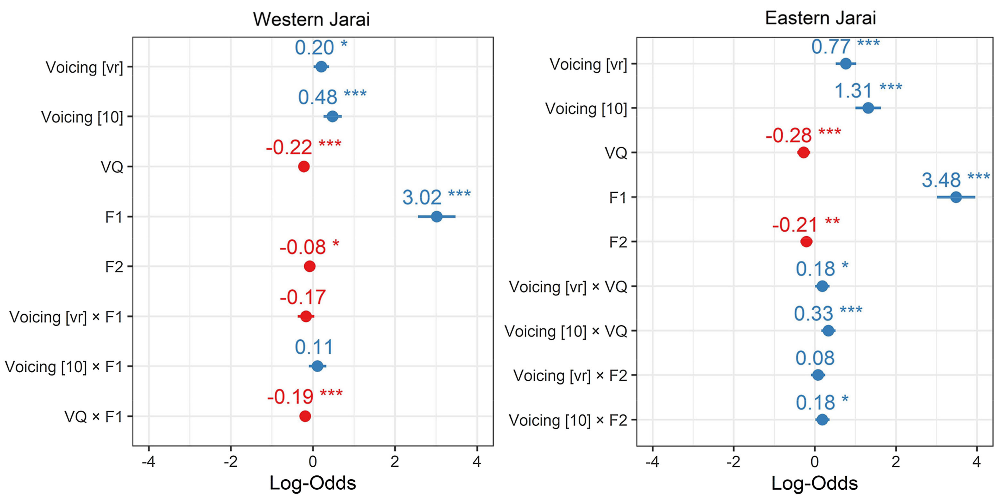

Figure 15. (Colour online) Coefficients and statistical significance of logistic regression models conducted on the responses given by Western Jarai listeners (left) and Eastern Jarai listeners (right) for /a/ stimuli. The full model summaries are provided in Tables W8 and E8, Appendix 3.

The results of the mixed logistic regressions largely confirm these patterns. They are plotted in Figure 15 (the full models are provided in Tables W8 and E8 in Appendix 3). We see that F1 is the dominant identification cue in both dialects, a high F1 triggering more high register responses, especially in Eastern Jarai. Voicing comes second: in both dialects,

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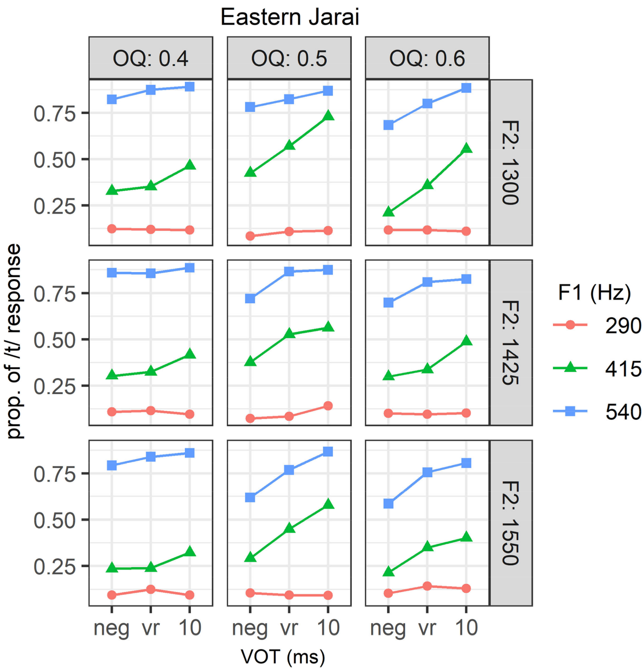

Figure 16. (Colour online) Proportion of high register /t/ responses for each type of /u/ stimulus, by F1, VOT, OQ (representing voice quality as a whole) and F2, for all listeners. Left panel: Western Jarai. Right panel: Eastern Jarai.

stimuli with a 10 ms positive VOT are more associated with the high register than stimuli with a negative VOT, while stimuli with a voiceless release fall in between. Note however that the role of voicing is greater in Eastern Jarai than in Western Jarai. Other main effects, voice quality and F2 turn out to play a weak role that was not visible in Figure 14: breathier phonation and a higher F2 both bias responses towards the low register. There are finally some weak, but significant interactions. In Western Jarai, the high register bias towards F1 is weaker when stimuli are breathier (VQ x F1). In Eastern Jarai, the effect of voice quality is reduced or cancelled out in stimuli that are not fully voiced (Voicing[vr] x F1, Voicing[10] x F1) and the effect of F2 is nullified when there is a 10 ms VOT (Voicing[10] x F2).

The overall picture is very similar for /u/ stimuli. In Figure 16, we see that a high F1 favors high register responses in both dialects. Voicing is also important: negative VOT is associated to low register responses while a 10 ms VOT yields more high register responses, especially when F1 is ambiguous. The effects of voice quality (OQ) and F2 are more subtle.

These results are again confirmed by the statistical analysis. F1 is the factor with the largest log-odds estimate in both dialects. The effect of F1 is weaker in /u/ than /a/, which is likely due to its narrower F1 range. The effect of voicing is roughly comparable to what was found in /a/. Stimuli with a 10 ms VOT yield more high register responses than stimuli with a voiceless release, which in turn yield more high register responses than stimuli with a negative VOT, and the global effect of voicing is greater in Eastern than Western Jarai. Voice quality and F2 are also significant: breathier stimuli and stimuli with a high F2 weakly bias responses towards the low register. There are also significant interactions. In Western Jarai, the effect of F1 is unexpectedly greater in stimuli with a voiceless release and a 10 ms VOT than in stimuli with a negative VOT (Voicing[vr] x F1, Voicing[10] x F1). The high register bias towards F1 is also weaker when stimuli are breathier (VQ x F1). Eastern Jarai shows the

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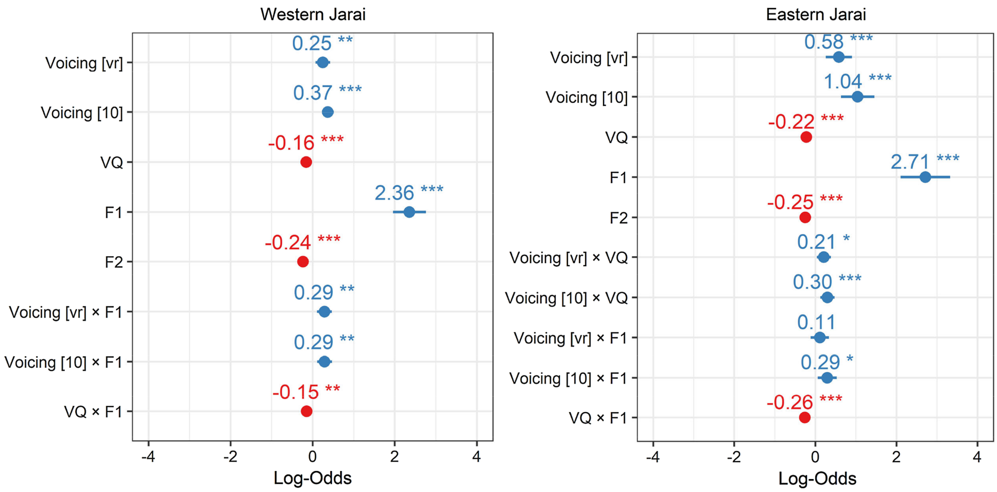

Figure 17. (Colour online) Coefficients and statistical significance of logistic regression models conducted on the responses given by Western Jarai listeners (left) and Eastern Jarai listeners (right) for /u/ stimuli. The full model summaries are provided in Tables W9 and E9, Appendix 3.

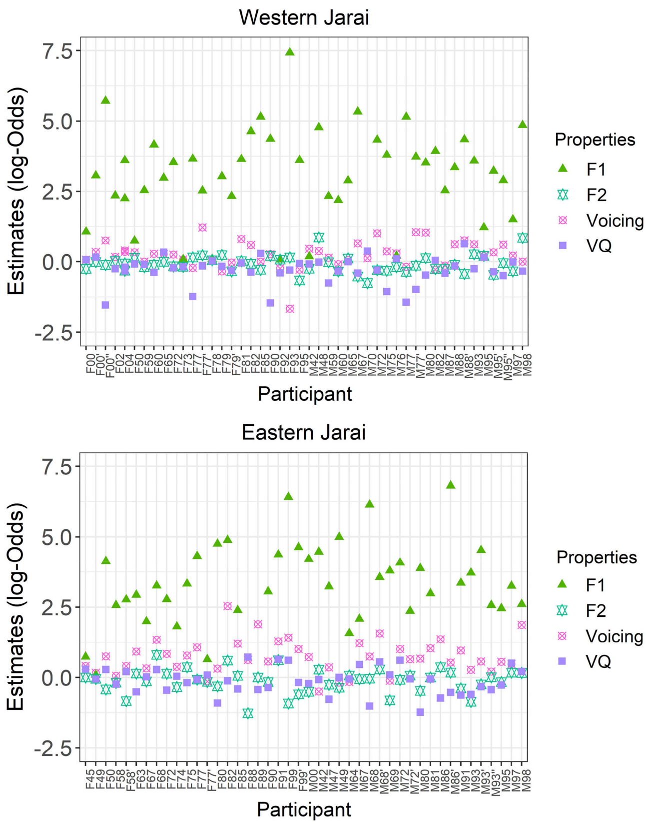

Figure 18. (Colour online) Log-odd estimates of each perceptual property by dialect and speaker, /a/ stimuli (Eastern Jarai participants F88, F89 and M86 have F1 log-odds greater than 20 that are off-scale).

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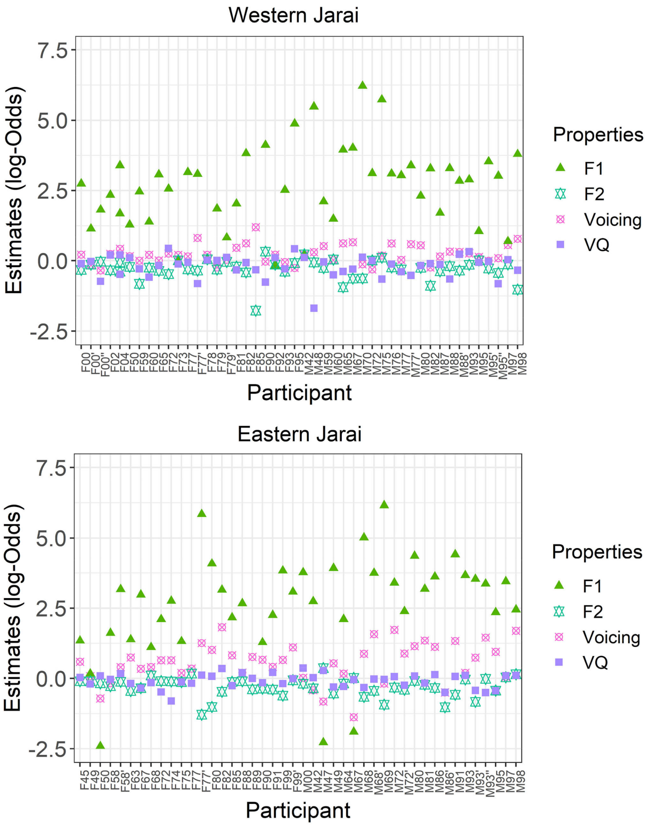

Figure 19. (Colour online) Log-odd estimates of each perceptual property by dialect and speaker, /u/ stimuli (Eastern Jarai participants F77, F89 and M86' have F1 log-odds greater than 20 that are off-scale).

same significant interactions, but in addition, the main effect of voice quality is canceled out in stimuli that do not have a negative voicing (Voicing[vr] x VQ, Voicing[10] x VQ).

In order to determine if the results of mixed logistic regressions by dialect hide individual differences, logistic regressions were conducted on each participant's data. *Voicing* was here coded as a continuous variable (negative VOT = 0; voiceless release = 1, 10 ms VOT = 2). As there are only 243 observations per syllable (three repetitions of each of the eighty-one stimuli), these models include no interactions and no random effects and are not as robust as the models presented in Figures 15 and 17. Yet, they only show limited variation across vowels, speakers and dialects, as can be seen in Figures 18 and 19. F1 is the strongest perceptual cue for all participants, with estimates typically ranging between 2.5 and 5 for /a/ and between 1.25 and 3.75 in /u/. This slightly weaker weight of F1 in /u/ duplicates what was observed in the global mixed logistic regressions models above. Other cues are all much weaker, but *Voicing* seems to weigh a bit heavier in Eastern Jarai, which also matches the results of the global models.

5.3 Relation between production and perception

The Cohen's d's used as a proxy for production cue weights in Section 4.2.3, can be compared with the log-odds estimates used to assess perception cue weights in the previous

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section. A first general observation is that there is limited variation in cue weights (production or perception) across speakers and that this variation does not seem structured by age and sex. The second important observation is that production and perception cue weights largely match each other. F1 is the dominant property for all speakers in both production and perception. Voicing is a stronger cue in perception than production, but this seems to reflect biases in our stimuli more than natural speech. The stimuli with a strong negative VOT that we tested in the identification experiment are relatively rare in natural production, as can be seen in Figure 4. The identification weight of voicing would be much weaker if we focused exclusively on stops with a voiceless release and stops with a 10 ms VOT, which are more representative of natural productions. Voice quality seems to be stronger in production (CPP and H1*–H2* in Figure 11) than in perception (VQ in Figures 18 and 19), which could indicate that speakers produce a relatively salient voice quality contrast between registers but do not use it as systematically for identification. It could also be due to the difficulty of synthesizing stimuli with voice quality modulations perfectly matching those used in Jarai, given the rich and non-monotonic acoustic properties of voice quality. Finally, F2 is a weak cue in both production and perception.

6. Discussion and conclusion

The acoustic results presented in Section 4 show that neither of the two Jarai dialects described here preserve the original voicing contrast that is reconstructed for Proto-Chamic (Lee 1966; Burnham 1976; Thurgood 1999). Full closure voicing is rare (especially in women), and more than half of the stops that were described as voiced in previous descriptions of Jarai are totally voiceless. Saom Kaning and Ea Sup Jarai have both developed register contrasts in which closure voicing is at best an optional secondary cue of the low register.

The acoustic properties of register are almost identical in the two dialects. Register is primarily realized through modulations of F1 that result in ongliding immediately after onset stops. As can be seen in Figure 9, low register vowels start with a lower F1. In low vowels this results in a falling diphthong (/a/ realized as [ᵋa]), while in high vowels, it is the high register that is realized with a weak rising onglide (e.g., /i/ realized as [ᶦi]). This diphthongization pattern is widely attested in register languages (Huffman 1985).

Vowels also bear weaker register cues like voice quality and F2 modulations. The first 150 ms of the low register vowels has a higher H1*–H2* than that of high register vowels, which indicates breathiness or laxness (Figure 6). Other spectral slope measurements, like H1*–A1* show a weaker difference (Figure 7). CPP differences between registers (Figure 8) are minimal and do not clearly reach significance in Western Jarai, suggesting that there is little breathiness noise and that the low register may contrast a lax voice with the modal voice of the high register, but overall, voice quality (H1*–H2*) seems to be slightly more salient in Eastern than in Western Jarai. F2 differences between registers are subtle, but there tends to be a slightly higher F2 in the low register immediately at vowel onset. Whether this is caused by active tongue-fronting or by a lengthening of the supraglottal cavity remains unclear. Finally, f0 does not seem to be a reliable register cue, contrary to what was found in related Eastern and Western Cham (Phú, Edmondson and Gregerson 1992; Brunelle 2005, 2006, 2009).

Against our initial expectations, there is little evidence that the register contrast found after stops was extended to vowels following sonorants. Since we tested a relatively small number of sonorant-initial syllables, this should be further investigated, but we can safely say that if there were any register contrast in that context, it would be more subtle than after stops.

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Our perception experiment establishes that the cues used in register identification largely match those used in production, with F1 being the primary identification cue and voice quality and F2 playing secondary roles. It also confirms that closure voicing, even if it is optional in production, is associated with the low register.

The absence of structured variation in age and sex across participants, in perception as well as production, suggests that both dialects under study have stable register systems. More importantly, the near absence of differences in the phonetic realization of register in two Jarai dialects that are not in contact and have no recent genetic relation is a strong indication that Jarai as a whole may be registral. An investigation of dialects spoken in Gia Lai province, Vietnam, would be needed to confirm this contention.

If Jarai has such a clear register system, how can we explain that it has always been described as preserving the original Proto-Chamic obstruent voicing contrast (Dournes 1964; Headley 1965; Lafont 1968), except for brief mentions of a register contrast in Williams and Siu (2013) and Jensen (2014)? A first possible explanation is that it underwent registrogenesis recently. However, it is unlikely that two Jarai dialects that have no direct contact would have developed registers independently, especially since they are not in contact with the same languages. Moreover, the fact that even a recent Jarai dictionary omits any mention of register suggests that there is more at play (Siu 2009). We hypothesize that the pioneer linguists that developed Jarai orthography were unaware of the existence of register, which was first explicitly discussed by Henderson (1952) but only became a well-known concept in the late 1960s, and transcribed the low register syllables with voiced stops because that was the closest available category in their native languages (French and English). This L1 bias may have been reinforced by an overrepresentation of optional closure voicing in the careful speech typically used in the elicitation sessions that are a necessary first stage of language documentation. In fact, Jarai is not the only language in which register was 'missed' by descriptive linguists before the 1960s: other examples include Chrau (Tạ, Brunelle and Nguyễn 2022), Chru (Brunelle et al. 2020) and Central Mnong (Brunelle, Đinh and Tạ 2023).

The existence of register in Jarai forces us to reconsider what is known about the development of register in Chamic languages, a difficult task because there is no consensus on Chamic internal subgrouping (Lee 1966; Burnham 1976; Thurgood 1999; Brunelle 2023). The only point of agreement between authors is that Jarai and Rade form a subgroup, here *Highlands Chamic*; other subgroups are more controversial and have been proposed based on geographical criteria (see Map 30.1 in Brunelle and Jensen 2023) or ill-described innovations (Brunelle 2023: for a recent review). Despite this absence of consensus on subgrouping, previous reconstructions of proto-Chamic all postulated that it had a voicing contrast in obstruents, assuming that only three Chamic languages spoken close to the coast, Tsat, Cham and Haroi, have developed register (Blood 1967; Friberg & Hor 1977; Lee 1977; Mundhenk & Goschnick 1977; Hoàng 1987; Headley 1991; Maddieson & Pang 1993; Thurgood 1993; Đoàn 2009). The recent discovery of a register contrast in three other Chamic languages spoken in the foothills of the Annamite Cordillera, Cát Gia Raglai, Chru, Southern Raglai was already a problem for these reconstructions (Lee 1998; Brunelle et al. 2020; Brunelle, Brown & Hà 2022), but now that register is even attested in a Highlands Chamic language like Jarai, there seems to be sufficient evidence to propose that register has been a feature of Chamic languages for much longer than previously assumed. That said, two elements currently prevent us from reconstructing it all the way to Proto-Chamic. First, Northern Raglai still clearly has an obstruent voicing contrast (Brunelle, Brown and Hà 2022). Unless we claim that this voicing contrast is a modern reflex of an earlier register contrast, this forces us to maintain a conservative standpoint. Second, the register systems of Chamic languages do not all have the same primary register cue. While Tsat and Cham are primarily pitch-based (Phú, Edmondson and Gregerson 1992; Maddieson & Pang 1993;

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Brunelle 2005, 2006, 2009), Southern Raglai, Haroi, Chru and Jarai mainly rely on F1 (Đoàn 2009; Brunelle et al. 2020; Brunelle, Brown and Hà 2022). Unless we can establish paths of change through which register systems can drift from one primary cue to others, it remains unclear if all Chamic register systems have a common source.

This in turn has implications for models of the development of register systems in Mainland Southeast Asian languages. Many of these models assume that voice quality is the primary acoustic property of register and that other cues developed as a consequence of original voice quality modulations (Huffman 1976; Thurgood 2002; Wayland & Jongman 2002). However, the fact that voice quality is never a primary property of register in the varieties of Chamic studied so far suggests that voice quality may not be as instrumental in registrogenesis as previously claimed. Two alternative scenarios emerge. The first one is that early register is always realized through multiple phonetic features, like vowel quality, voice quality and possibly pitch, and that each language then enhances and drops some of these properties. The other is that various types of phonetic properties can transphonologize directly as a result of the loss of onset voicing. This would be parallel with cases of tonal contrasts developing from the loss of onset voicing without any sign of voice quality developments (Svantesson & House 2006; Howe 2017; Coetzee et al. 2018; Kirby, Pittayaporn & Brunelle 2023).

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Appendix 1. Western Jarai wordlist

(' ̥ ' is used for purported low register sonorants)

Target word	English gloss	Khmer gloss
tiːŋ tiːŋ	sound of a drum	ទីងៗ
(p^{h}un) kətɛː	Beng tree	ដើមបេង
taː	eye	ភ្នែក
pətɔː	to teach	បង្រៀន
tuː	closet	ទូ
pət^{h}iː	funeral	បុណ្យសព
t^{h}ɛːl	flying termites	មេភ្លៀង
t^{h}aːn	branch	មេក
t^{h}ɔːw	to know	ចេះ

Target word	**English gloss**	**Khmer gloss**
t^huː	dry	ស្ងួត
diː	crazy	ឆ្កួត
dɛːŋ	to curse by causing foreign matter to be in a person's stomach	ធ្វើធ្មប់
da	duck	ទា
dɔːŋ	to help	ជួយ
dəduː	to do something softly	ខ្សោយៗ (តិចៗ)
kəɗiː	legal or criminal matter	ក្ដី
kəɗɛː	to be stunted in growth	ក្រិន
pəɗaːŋ	to fall down on one's back	ផ្ងារ
kəɗɔːŋ	to be stuck	ជាប់
(ɲaːm) ɗuːl	twill, weave pattern	ក្បាច់
siː	hand of banana	ស្និត
sɛːm	to search for	ស្វែងរក
saː	one	មួយ
sɔː	to scrub, polish with water	សំអាត
(kə)suː	to shake a liquid, agitate	ក្រឡុក
niːm	slow	យឺតៗ (ថ្នមៗ)
nɛː	here	នេះ
naː	rice paddy	ស្រែ
nɔː	term of address for younger male	អាអូន
hanuːn	over there (medial distance)	នោះ
bən̥iː	thank you	អរគុណ
n̥ɛː	that's it!	ហ្នឹង!
n̥ul	river otter	ឆ្មាទឹក
kəliː	laborer	គូលី
lɛː	leg, foot	ជើង
laː	pancreas	លំពែង
ʔəlɔː	sorcerer	មេធ្មប់
kəluː (kɔʔ)	to shave the head	កោរ

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Target word	English gloss	Khmer gloss
l̥ɛːn	money	លុយ
bl̥aː (m̥an)	tusk	ភ្លុកដំរី
gl̥ɔːŋ	tall	ខ្ពស់
pəkkɛː	tokay gecko	តុកកែ
kaː	not yet	នៅទេ
təkɔːl	lumpy, not smooth (of food)	កាកសំណល់ (ទឹកកង្វក់)
(gl̥aj) ləkuː	pristine forest	ព្រៃស្រោង
khiː	male name	ឃី (ឈ្មោះមនុស្ស)
k^hɛːn	to be stunted in growth (humans)	ក្រិន
ak^huː	pair	គូរ
giː (gl̥aːn)	to be blocked	ជាប់ភ្លូវ
gɛːm	busy, occupied	រវល់ (ជាប់រវល់)
gaːl	to be jealous (of love)	ប្រច័ណ្ឌ
(gaŋ) gɔː	rigid, hard	រឹង (មាំ)
(naːʔ) ŋɛː	newborn child	កូនង៉ែត
ŋaː	sesame	ល្ង
(poːʔ) ŋɔːl	old/abandoned village or well	ចាស់ ឬ ចោល
ŋuːj	to play, visit	លេង

Appendix 2. Eastern Jarai wordlist

(' ̥ ' is used for purported low register sonorants)

Target word	English gloss	Vietnamese gloss
kətiː	red thread at the edge of weaved fabric or bell clapper	sợi chỉ màu đỏ trên mép vải hay lắc chuông
(p^hun) kətɛː	beng tree	cây kate
taː	incl. we	mình
pətɔː	teach	dạy học
tuː	closet	tủ
pət^hiː (săt)	ceremony of abandonment of the tomb	bỏ (mả)

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Target word	**English gloss**	**Vietnamese gloss**
tʰɛ:r	termite	mối
tʰa:n (kjɔ:w)	branch	cành (cây)
tʰɔ:w	to know	biết
tʰuː	dried up, dry	cạn, khô
(puj) di:r	mythological fire	một đóng lửa to trong chuyện cổ tích
dɛ:l	k.o. bird	chim rộc rộc
təda	chest	ngực
dɔ:ŋ	to hit a gong	đánh (chiêng)
(kə)duː	to do something softly	(làm) nhẹ nhàng
kəɗiː	criminal or work case	vụ án, vụ viêc
ɗɛː	Rade	Êđê
ɗa:ŋ	facing up	ngửa
ɗɔ:m (dɛh)	stuck (in traffic)	kẹt (xe)
ɗu:ŋ	coconut	dừa
siː	hand of banana	nải (chuối)
sɛ:m	to search for	tìm
saː	one	một
sɔː	to scrub with water	chà (nồi)
suː	to shake, agitate	lắc
həniː	bee	con ong
nɛː	here	đây
naː	rice paddy	ruộng
kənɔː	male	đực, trống
bən̥iː (hjɛm)	to thank	cảm ơn
(ɗɛ:ŋ) n̥aː	mother/main (thumb)	(ngón) cái
bən̥ɔ:ŋ	Mnong	M'nông
(ŋăʔ) kəliː	laborer	cu li
lɛ:l	timid, shy	nhút nhát
laː	snake	rắn
kəmlɔː	mute	câm

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Target word	**English gloss**	**Vietnamese gloss**
luːr	to lie under	chui
bl̥aː (ma̤n)	tusk	ngà (voi)
gl̥ɔːŋ	tall	cao
gl̥uːŋ	roll away	lăn
(tə)kiː	horn	sừng
pak kɛː	gecko	tắc kè
kaː	not yet	chưa
kɔːl	lumpy, not smooth	không có loãng, không đều
kuː	tail	đuôi
k^{h}aː	root	rễ
(h)ak^{h}uː	pair (esp. tongs)	đôi (riêng là dép)
gi	tomorrow	ngày mai
gaːr	jealous (of love)	ghen tị
(phun) gɔːl	calamea	cây mây
gun (gan)	busy	bận rộn/vươn này vươn kia
məɲiː	noise	tiếng động
(naːʔ) ɲɛː	newborn child	trẻ sơ sinh
ɲaː	sesame	mè, vừng
həɲɔː	pine tree	cây thông
ɲuːj	play, have fun	chơi
bəɲ̊aː	flower	bông hoa

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Appendix 3. Mixed models

Table W1. Table of estimates for mixed model on VOT in Western Jarai plain stops with positive VOT

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	5.959	3.720	40.478	1.602	.117
RegisterHigh	4.501	3.017	1416.957	1.492	.136
Placevelar	20.154	1.914	1416.925	10.531	.000
Vowela:	−5.769	2.721	1416.972	−2.120	.034
Vowelɛ:	−9.661	2.705	1416.975	−3.572	.000
Voweli:	−10.016	2.704	1416.941	−3.704	.000
Vowelu:	−8.756	3.429	1416.895	−2.553	.011
RegisterHigh:Placevelar	−7.631	2.709	1416.904	−2.817	.005
RegisterHigh:Vowela:	4.577	3.833	1416.949	1.194	.233
RegisterHigh:Vowelɛ:	6.851	3.822	1416.981	1.792	.073
RegisterHigh:Voweli:	−3.654	4.386	1416.988	−0.833	.405
RegisterHigh:Vowelu:	9.259	4.380	1416.917	2.114	.035

Table E1. Table of estimates for mixed model on VOT in Eastern Jarai plain stops with positive VOT

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	11.253	1.608	4.258	6.997	.002
RegisterHigh	−1.382	1.823	2.987	−0.758	.504
Placevelar	19.113	1.825	3.004	10.472	.002
Vowelu:	2.387	2.019	3.125	1.182	.319
Vowela:	2.573	1.999	3.002	1.287	.288
Vowelɛ:	1.805	2.193	2.977	0.823	.471
Voweli:	7.960	1.999	3.000	3.983	.028
RegisterHigh:Placevelar	−6.805	1.636	3.032	−4.159	.025
RegisterHigh:Vowelu:	−2.605	2.316	3.041	−1.125	.342
RegisterHigh:Vowela:	−0.024	2.307	2.998	−0.010	.992
RegisterHigh:Vowelɛ:	−1.077	2.940	2.991	−0.366	.738
RegisterHigh:Voweli:	−7.414	2.310	3.012	−3.209	.049
Placevelar:Vowelu:	1.145	2.316	3.041	0.494	.655
Placevelar:Vowela:	−2.526	2.307	2.998	−1.095	.354
Placevelar:Vowelɛ:	−5.214	2.953	3.048	−1.766	.174
Placevelar:Voweli:	−5.261	2.310	3.012	−2.277	.107

Table W2. Table of estimates for mixed model on mean normalized f0 over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	163.521	5.665	59.391	28.867	.000
RegisterLow	36.386	4.435	1369.245	8.204	.000
Vowela:	1.901	5.406	1368.997	0.352	.725
Vowelɛ:	−4.628	5.406	1369.011	−0.856	.392
Voweli:	31.580	5.871	1369.156	5.379	.000
Vowelu:	37.961	5.784	1368.998	6.563	.000
PlaceVelar	−19.099	4.433	1368.936	−4.308	.000
RegisterLow:Vowela:	−29.799	6.234	1369.077	−4.780	.000
RegisterLow:Vowelɛ:	−15.108	6.234	1369.065	−2.424	.015
RegisterLow:Voweli:	−40.810	7.615	1369.089	−5.359	.000
RegisterLow:Vowelu:	−53.726	7.547	1368.955	−7.119	.000
Vowela::PlaceVelar	27.456	6.234	1369.003	4.404	.000
Vowelɛ::PlaceVelar	21.689	6.233	1368.969	3.480	.001
Voweli::PlaceVelar	19.912	7.580	1368.951	2.627	.009
Vowelu::PlaceVelar	0.605	7.629	1368.999	0.079	.937

Table E2. Table of estimates for mixed model on mean normalized f0 over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	184.334	6.979	21.128	26.414	.000
RegisterLow	2.929	3.950	6.985	0.741	.483
Placevelar	16.346	6.898	6.925	2.370	.050
Vowela:	10.449	6.229	6.908	1.677	.138
Vowelɛ:	16.305	6.233	6.929	2.616	.035
Voweli:	41.074	6.234	6.931	6.588	.000
Vowelu:	27.267	6.250	7.003	4.363	.003
RegisterLow:Placevelar	−19.920	5.924	6.976	−3.363	.012
Placevelar:Vowela:	−6.987	8.821	6.946	−0.792	.455
Placevelar:Vowelɛ:	−11.538	10.215	7.252	−1.130	.295
Placevelar:Voweli:	−31.345	8.809	6.906	−3.559	.009
Placevelar:Vowelu:	−13.401	8.832	6.980	−1.517	.173

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Table W3. Table of estimates for mixed model on mean normalized H1*–H2* over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	1.445	0.722	50.814	2.000	.051
RegisterLow	4.832	0.576	1368.151	8.386	.000
Vowela:	0.841	0.613	1368.046	1.371	.170
Vowelɛ:	−0.712	0.613	1368.056	−1.160	.246
Voweli:	9.458	0.681	1368.160	13.880	.000
Vowelu:	1.507	0.672	1368.062	2.243	.025
PlaceVelar	0.103	0.581	1368.034	0.177	.859
RegisterLow:Vowela:	−0.388	0.707	1368.106	−0.548	.584
RegisterLow:Vowelɛ:	1.092	0.707	1368.096	1.543	.123
RegisterLow:Voweli:	−3.731	0.908	1368.080	−4.107	.000
RegisterLow:Vowelu:	1.214	0.901	1368.003	1.347	.178
RegisterLow:PlaceVelar	2.173	0.576	1368.085	3.770	.000
Vowela::PlaceVelar	−0.530	0.707	1368.050	−0.749	.454
Vowelɛ::PlaceVelar	0.736	0.707	1368.025	1.041	.298
Voweli::PlaceVelar	−7.082	0.907	1368.018	−7.812	.000
Vowelu::PlaceVelar	2.543	0.913	1368.092	2.784	.005

Table E3. Table of estimates for mixed model on mean normalized H1*–H2* over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	−0.533	1.830	8.542	−0.291	.778
RegisterLow	5.518	2.415	8.001	2.285	.052
Vowela:	0.322	2.416	8.012	0.133	.897
Vowelɛ:	0.276	2.417	8.017	0.114	.912
Voweli:	0.397	2.416	8.011	0.164	.874
Vowelu:	1.464	2.416	8.016	0.606	.561
Placevelar	1.953	1.139	8.010	1.715	.125
RegisterLow:Vowela:	4.014	3.416	8.005	1.175	.274
RegisterLow:Vowelɛ:	−4.722	3.862	8.011	−1.223	.256
RegisterLow:Voweli:	3.814	3.416	8.002	1.117	.297
RegisterLow:Vowelu:	4.005	3.416	8.007	1.172	.275

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Table W4. Table of estimates for mixed model on mean normalized H1*–A1* over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	19.141	0.540	24.656	35.476	.000
RegisterLow	1.765	0.434	7.600	4.067	.004
Vowela:	0.727	0.424	6.972	1.714	.130
Vowelɛ:	−1.352	0.425	7.016	−3.185	.015
Voweli:	−4.397	0.536	7.318	−8.199	.000
Vowelu:	−3.200	0.431	7.447	−7.426	.000
PlaceVelar	−0.269	0.214	7.167	−1.261	.247
RegisterLow:Vowela:	1.256	0.608	7.314	2.068	.076
RegisterLow:Vowelɛ:	−0.816	0.605	7.204	−1.348	.218
RegisterLow:Voweli:	−1.376	0.689	7.380	−1.997	.084
RegisterLow:Vowelu:	−1.714	0.684	7.187	−2.505	.040

Table E4. Table of estimates for mixed model on mean normalized H1*–A1* over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	16.708	0.882	10.279	18.936	.000
RegisterLow	2.018	1.103	7.836	1.829	.106
Vowela:	1.383	1.103	7.827	1.253	.246
Vowelɛ:	−0.351	1.104	7.844	−0.318	.759
Voweli:	−2.574	1.106	7.903	−2.328	.049
Vowelu:	−2.241	1.117	8.219	−2.006	.079
Placevelar	0.612	0.522	7.947	1.173	.275
RegisterLow:Vowela:	1.272	1.561	7.844	0.815	.439
RegisterLow:Vowelɛ:	−3.060	1.765	7.848	−1.734	.122
RegisterLow:Voweli:	0.415	1.562	7.869	0.266	.797
RegisterLow:Vowelu:	0.608	1.571	8.034	0.387	.709

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Table W5. Table of estimates for mixed model on mean normalized CPP over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	22.482	0.557	70.758	40.340	.000
RegisterLow	−2.089	0.503	1413.092	−4.154	.000
Vowela:	0.523	0.534	1413.042	0.980	.327
Vowelɛ:	0.250	0.533	1413.033	0.469	.639
Voweli:	−2.242	0.592	1413.093	−3.791	.000
Vowelu:	0.382	0.591	1413.025	0.646	.518
PlaceVelar	−0.230	0.504	1413.045	−0.457	.648
RegisterLow:Vowela:	−0.310	0.619	1413.087	−0.501	.616
RegisterLow:Vowelɛ:	0.455	0.618	1413.135	0.737	.461
RegisterLow:Voweli:	1.198	0.796	1413.057	1.505	.132
RegisterLow:Vowelu:	−1.655	0.796	1413.015	−2.080	.038
RegisterLow:PlaceVelar	−1.370	0.505	1413.021	−2.714	.007
Vowela::PlaceVelar	1.221	0.619	1413.073	1.971	.049
Vowelɛ::PlaceVelar	0.674	0.617	1413.048	1.092	.275
Voweli::PlaceVelar	3.196	0.796	1413.064	4.013	.000
Vowelu::PlaceVelar	−2.486	0.806	1413.112	−3.083	.002

Table E5. Table of estimates for mixed model on mean normalized CPP over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	24.089	0.740	4.988	32.554	.000
RegisterLow	−0.888	0.805	2.994	−1.103	.351
Vowela:	−0.008	0.883	3.008	−0.009	.993
Vowelɛ:	−0.334	0.969	2.992	−0.345	.753
Voweli:	−0.102	0.883	3.009	−0.116	.915
Vowelu:	−1.505	0.882	3.002	−1.706	.186
Placevelar	−1.868	0.805	2.994	−2.321	.103
RegisterLow:Vowela:	−0.978	1.019	2.999	−0.960	.408
RegisterLow:Vowelɛ:	0.411	1.298	2.992	0.317	.772
RegisterLow:Voweli:	−1.451	1.019	2.999	−1.424	.250
RegisterLow:Vowelu:	−0.787	1.019	3.002	−0.772	.496
RegisterLow:Placevelar	−1.593	0.721	3.005	−2.210	.114
Vowela::Placevelar	1.865	1.019	2.999	1.831	.164
Vowelɛ::Placevelar	1.911	1.305	3.060	1.465	.238
Voweli::Placevelar	1.654	1.019	2.999	1.623	.203
Vowelu::Placevelar	−0.730	1.019	3.002	−0.717	.525

Table W6. Table of estimates for mixed model on mean normalized F1 over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	813.249	14.788	2.578	54.994	.000
RegisterLow	−191.032	17.511	1.985	−10.909	.009
Vowela:	48.897	18.567	1.983	2.634	.120
Vowelɛ:	−42.210	18.559	1.979	−2.274	.152
Voweli:	−434.946	20.540	1.988	−21.176	.002
Vowelu:	−213.795	20.683	2.044	−10.337	.009
PlaceVelar	−101.427	17.522	1.990	−5.788	.029
RegisterLow:Vowela:	−24.724	21.499	2.005	−1.150	.369
RegisterLow:Vowelɛ:	−39.566	21.473	1.995	−1.843	.207
RegisterLow:Voweli:	185.392	27.693	1.987	6.695	.022
RegisterLow:Vowelu:	3.821	27.810	2.021	0.137	.903
RegisterLow:PlaceVelar	18.629	17.534	1.996	1.062	.400
Vowela::PlaceVelar	15.889	21.499	2.005	0.739	.537
Vowelɛ::PlaceVelar	−0.577	21.472	1.995	−0.027	.981
Voweli::PlaceVelar	161.778	27.727	1.997	5.835	.028
Vowelu::PlaceVelar	−18.466	27.867	2.037	−0.663	.575

Table E6. Table of estimates for mixed model on mean normalized F1 over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	866.262	52.725	4.085	16.430	.000
RegisterLow	−120.556	60.557	3.999	−1.991	.117
Vowela:	28.394	74.162	3.998	0.383	.721
Vowelɛ:	−91.092	80.098	3.996	−1.137	.319
Voweli:	−302.806	74.189	4.003	−4.082	.015
Vowelu:	−300.774	74.287	4.025	−4.049	.015
Placevelar	−219.552	60.557	3.999	−3.626	.022
RegisterLow:Vowela:	−217.449	85.640	3.999	−2.539	.064
RegisterLow:Vowelɛ:	98.325	104.878	3.997	0.938	.402
RegisterLow:Voweli:	−61.704	85.649	4.000	−0.720	.511
RegisterLow:Vowelu:	−35.617	85.689	4.008	−0.416	.699
Vowela::Placevelar	157.687	85.640	3.999	1.841	.139
Vowelɛ::Placevelar	97.032	104.900	4.001	0.925	.407
Voweli::Placevelar	192.158	85.649	4.000	2.244	.088
Vowelu::Placevelar	143.908	85.689	4.008	1.679	.168

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Table W7. Table of estimates for mixed model on mean normalized F2 over the first ten sampling points after Western Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	1372.931	39.059	2.250	35.151	.000
RegisterLow	172.760	48.028	2.011	3.597	.069
Vowela:	212.502	50.724	1.977	4.189	.054
Vowelɛ:	310.104	50.959	2.014	6.085	.026
Voweli:	935.087	56.079	1.977	16.674	.004
Vowelu:	40.581	56.152	1.988	0.723	.545
PlaceVelar	−143.580	47.883	1.987	−2.999	.096
RegisterLow:Vowela:	68.778	58.699	1.995	1.172	.362
RegisterLow:Vowelɛ:	177.939	58.752	2.002	3.029	.094
RegisterLow:Voweli:	−166.966	75.748	1.991	−2.204	.159
RegisterLow:Vowelu:	56.742	75.826	1.999	0.748	.532
RegisterLow:PlaceVelar	−156.292	47.932	1.995	−3.261	.083
Vowela::PlaceVelar	456.662	58.699	1.994	7.780	.016
Vowelɛ::PlaceVelar	552.493	58.752	2.002	9.404	.011
Voweli::PlaceVelar	379.218	75.924	2.010	4.995	.037
Vowelu::PlaceVelar	−238.968	75.849	2.002	−3.151	.088

Table E7. Table of estimates for mixed model on mean normalized F2 over the first ten sampling points after Eastern Jarai plain stops

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	1341.401	23.301	4.208	57.569	.000
RegisterLow	54.845	26.377	2.940	2.079	.131
Vowela:	286.264	28.895	2.940	9.907	.002
Vowelɛ:	420.156	31.736	2.930	13.239	.001
Voweli:	674.331	29.653	3.248	22.741	.000
Vowelu:	−97.937	28.964	2.968	−3.381	.044
Placevelar	−227.273	26.351	2.929	−8.625	.004
RegisterLow:Vowela:	336.560	33.169	2.872	10.147	.002
RegisterLow:Vowelɛ:	20.931	42.269	2.868	0.495	.656
RegisterLow:Voweli:	214.763	33.438	2.962	6.423	.008
RegisterLow:Vowelu:	66.912	33.492	2.980	1.998	.140
RegisterLow:Placevelar	−49.131	23.644	2.965	−2.078	.130
Vowela::Placevelar	358.852	33.168	2.872	10.819	.002
Vowelɛ::Placevelar	580.029	42.567	2.950	13.626	.001
Voweli::Placevelar	475.599	33.437	2.962	14.224	.001
Vowelu::Placevelar	−139.765	33.489	2.981	−4.173	.025

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Table W8. Table of estimates of the final logistic regression model for /a/ stimuli in Western Jarai. Estimates represent the log odds of high register responses. VQ, F1 and F2 are centered.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−0.942	0.111	−8.503	.000
Voicingvr	0.205	0.097	2.120	.034
Voicing10	0.478	0.113	4.216	.000
VQ	−0.222	0.054	−4.102	.000
F1	3.017	0.232	12.995	.000
F2	−0.081	0.037	−2.221	.026
Voicingvr:F1	−0.171	0.104	−1.641	.101
Voicing10:F1	0.112	0.108	1.041	.298
VQ:F1	−0.188	0.053	−3.537	.000

Table E8. Table of estimates of the final logistic regression model for /a/ stimuli in Eastern Jarai. Estimates represent the log odds of high register responses. VQ, F1 and F2 are centered.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−0.794	0.196	−4.049	.000
Voicingvr	0.766	0.129	5.933	.000
Voicing10	1.314	0.161	8.144	.000
VQ	−0.276	0.081	−3.404	.001
F1	3.482	0.241	14.463	.000
F2	−0.206	0.076	−2.694	.007
Voicingvr:VQ	0.184	0.090	2.038	.042
Voicing10:VQ	0.334	0.090	3.706	.000
Voicingvr:F2	0.079	0.090	0.877	.381
Voicing10:F2	0.185	0.090	2.051	.040

Table W9. Table of estimates of the final logistic regression model for /u/ stimuli in Western Jarai. Estimates represent the log odds of high register responses. VQ, F1 and F2 are centered.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−0.790	0.093	−8.460	.000
Voicingvr	0.246	0.090	2.724	.006
Voicing10	0.368	0.073	5.048	.000
VQ	−0.155	0.047	−3.302	.001
F1	2.357	0.206	11.463	.000
F2	−0.239	0.038	−6.266	.000
Voicingvr:F1	0.287	0.093	3.094	.002
Voicing10:F1	0.289	0.092	3.129	.002
VQ:F1	−0.149	0.047	−3.168	.002

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Table E9. Table of estimates of the final logistic regression model for /u/ stimuli in Eastern Jarai. Estimates represent the log odds of high register responses. VQ, F1 and F2 are centered.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−1.121	0.226	−4.968	.000
Voicingvr	0.579	0.164	3.523	.000
Voicing10	1.041	0.210	4.956	.000
VQ	−0.224	0.066	−3.373	.001
F1	2.712	0.312	8.683	.000
F2	−0.251	0.041	−6.071	.000
Voicingvr:VQ	0.208	0.088	2.348	.019
Voicing10:VQ	0.300	0.089	3.348	.001
Voicingvr:F1	0.109	0.115	0.949	.343
Voicing10:F1	0.291	0.120	2.435	.015
VQ:F1	−0.263	0.056	−4.693	.000

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