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5pSC21. Phonetic effects of morphological structure in Indonesian vowel reduction

Daniel McCloy*

***Corresponding author's address: Institute for Learning and Brain Sciences, University of Washington, 1715 NE Columbia Rd, Seattle, WA 98195-7988, drmccloy@uw.edu**

This study investigates the effects of morphological word structure on closed-syllable vowel reduction in F2xF1 formant frequency space. In particular, it examines whether penultimate vowels followed by morphological boundaries are less apt to undergo mid-centralization than similar vowels in words lacking morphological boundaries. Results are suggestive that some degree of gradient reduction is observable when comparing penultimate vowels in words with different morphological structures, but the existence of several potentially confounding factors require interpretations to be tentative.

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This paper is an expansion of "Vowel laxing in Indonesian as a test case for interaction of morphological and syllabic structure" (McCloy, 2011), presented at the 161st Meeting of the Acoustical Society of America. Additional data analysis and statistical modeling has been performed since the conference presentation, and the title has been changed to better reflect the results of that modeling.

1 Introduction

Standard Indonesian (ISO 639-3:ind) is widely believed to exhibit vowel quality reduction in closed syllables. However, there is much disagreement in the literature about the extent of that reduction. Some authors say reduction occurs in all closed syllables (Macdonald, 1976), others say word-final closed syllables (Halim, 1981; Lapoliwa, 1981; Soderberg & Olson, 2008). Some authors also describe a harmony pattern where penultimate vowels preceding final closed syllables are reduced when phonemically identical to the final vowel (Macdonald, 1976) or when of equivalent height to the final vowel (Soderberg & Olson, 2008). There is also disagreement as to whether reduction based on syllable structure occurs for all vowels except /ə/ (Macdonald, 1976), all non-low peripheral vowels (/i,e,o,u/) (Halim, 1981; Lapoliwa, 1981; Soderberg & Olson, 2008), or only the mid-vowels /e,o/ (Adisasmito-Smith, 2004).

This study presents data suggesting that the extent of vowel quality reduction in Indonesian is strongly influenced by the morphological structure of the word, a fact that may underlie the differing claims in the literature cited above. In particular, this study compares F1 and F2 values for vowels in words of three differing morphological structures (the "experimental" conditions). Two additional word types containing "reference" vowels (vowels in word-final open and closed syllables) are included for comparison. A schematic of these morphological conditions is given in Table 1.

Condition	Description	Schematic	Sample word
1	Vowel-final root + /-kan/ suffix	V+kan	/mə+raˈgi̲+kan/
2	Consonant-final root + /-an/ suffix	VC+an	/pə+raˈki̲t+an/
3	Monomorphemic word mimicking condition 2	VCan	/ˈti̲kam/
R1	Vowel-final root (canonical unreduced)	V#	/ˈragi̲/
R2	Consonant-final root (canonical reduced)	VC#	/ˈraki̲t/

Table 1: Schematic of morphological conditions tested. The vowel measured is underlined. Stress is marked for clarity; it is not phonemically contrastive.

An underlying assumption of this study is that vowel quality reduction in Indonesian is not a purely phonological process, i.e., reduction is gradient rather than categorical. On a purely phonological view, if resyllabification occurs and morpheme boundaries are barriers to resyllabification, the words in condition 2 (consonant-final root + /-an/ suffix) would be predicted to have the same degree of reduction as condition R2 (e.g., /pə+rakit+an/ would manifest as [pə.raˈkɪt.an] rather than [pə.raˈki.tan], with [ɪ] indicating the categorically reduced or lax allophone of /i/). In contrast, a gradient view of reduction acknowledges the influence of factors like speech rate (Fourakis, 1991; Gay, 1978) usage frequency (van Son *et al.*, 2004), and semantic predictability (Clopper & Pierrehumbert, 2008), and might predict a continuous range of allophonic variation between the tense and lax extremes. On this view, if morpheme boundaries affect degree of reduction, we might expect their influence to be gradient as well (i.e., they might act as a “permeable barrier” to resyllabification rather than blocking resyllabification entirely).[1] If this were so, the final consonant of the root in words like /pə+rakit+an/ would “resist” resyllabification into the onset of the suffix, thereby retaining its affinity with the preceding vowel. This situation would yield a more reduced vowel than is typically seen in conditions 3 or R1, but not so strongly reduced as the vowel in condition R2. In contrast, the words in condition 1 (Vowel-final root + /-kan/ suffix) are predicted to show a lesser degree of reduction, since the consonant following the measured vowel is semantically bound to the following syllable already, and therefore less likely to behave as a coda to (and trigger reduction of) the preceding vowel. As already implied, words in condition 3 are predicted to fall between the other experimental conditions. Thus the general hypothesis motivating this study is that vowel quality reduction in Indonesian shows gradient properties, and that variation in the presence and location of morphological boundaries is one source of this gradience. Therefore it is predicted that the three experimental conditions (numbered 1–3 in Table 1) will show differing degrees of vowel reduction intermediate between the positions of the “canonical unreduced” and “canonical reduced” forms (numbered R1 and R2 in Table 1), as outlined above.

Of course, stress placement is of paramount importance in any study of vowel reduction. There is general agreement that word stress in Indonesian predictably falls on the penultimate syllable, unless the penultimate vowel is /ə/ (Cohn, 1989; Echols & Shadily, 1989; Lapoliwa, 1981; Macdonald, 1976; Soderberg & Olson, 2008). If the penultimate vowel is /ə/, some accounts say that stress always shifts rightward (Macdonald, 1976); other accounts say the stress shifts leftward unless the antepenult is also /ə/ or part of a prefix, in which case stress shifts rightward to the ultimate syllable (Cohn, 1989; Lapoliwa, 1981). The difference between these two accounts of stress shift turns out to be irrelevant for this study, since all cases of penultimate /ə/ in the word lists are in disyllabic words, so leftward stress shift is impossible. Therefore in this study the vowels measured in the experimental conditions are always in penultimate (stressed) position, but in the reference conditions the vowels are in the word-final syllable and thus sometimes stressed and sometimes unstressed.[2] Although stress in Indonesian is alleged to only affect loudness (Macdonald, 1976), it is worth keeping stress differences in mind when interpreting this study’s findings.

This study is also relatively unaffected by the differing descriptions of vowel reduction harmony mentioned above (MacDonald’s “phonemic identity” or Soderberg and Olson’s “equivalent height” rules). Since the vowels measured in this study are either in an ultimate syllable (reference conditions) or in a penultimate syllable followed by a word-final syllable containing /a/ (experimental conditions), penultimate /a/ is the only potential candidate for harmony-based

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[1] The degree of “permeability” of morpheme boundaries could certainly vary from language to language, and even affix to affix within a given language, depending on, e.g., how salient or productive the morpheme is in the minds of language users.

[2] Only five of the forty reference words in this study have penultimate /ə/ and thus have final stress: *cerdik* /tʃərˈdik/ “smart, clever”, *cerdas* /tʃərˈdas/ “intelligent, educated”, *ceték* /tʃəˈtek/ “shallow”, *empat* /əmˈpat/ “four”, and *regu* /rəˈgu/ “team, group”.

reduction on MacDonald’s account. On Soderberg and Olson’s account /a/ does not even undergo reduction, so penultimate /a/ would not be predicted to show harmony effects. At the very least, then, harmony considerations are irrelevant to the present study for the non-low vowels /i u e o/.

2 Methods

2.1 Word selection

Words for the word list were chosen from Echols & Shadily (1989), with help from a native consultant who was not among the participants recorded. Consideration was given to the place, manner, and voicing of the flanking consonants, with preference for voiceless obstruents and for equal representation of places of articulation across the flanking consonants (onsets and codas considered separately). Ultimately, however, native consultant judgments of the word frequency or the plausibility of words being understood in isolation was allowed to override phonotactic considerations. In particular, although it was possible in considering manner to avoid non-obstruent flanking consonants almost entirely,[3] perfect balance across places of articulation was impossible to achieve (see Figure 1). Consequently, the place of articulation of the flanking consonants was included in the statistical models to account for this imbalance in consonant distribution. The related and somewhat more important issue of flanking consonant distribution with respect to the morphological conditions is shown in Figure 2 and discussed in Section 2.3.

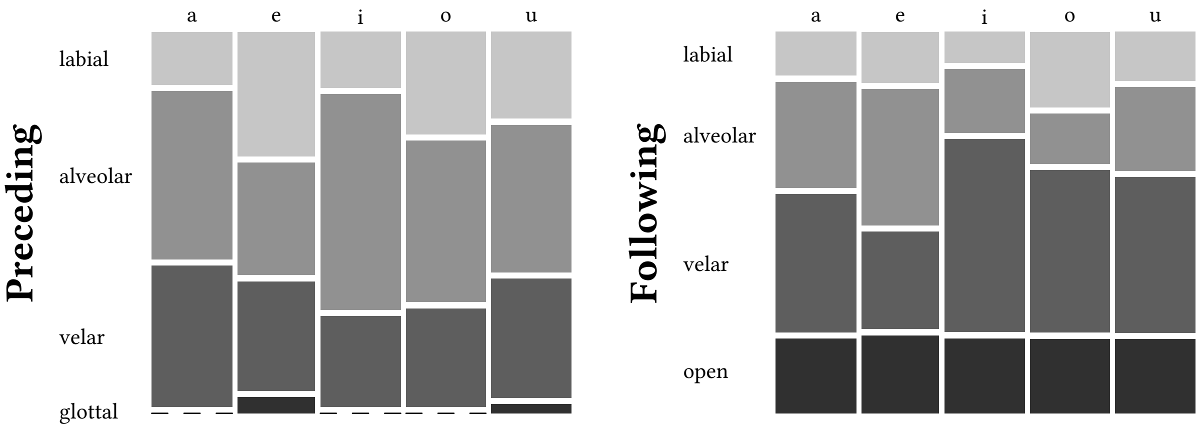

Figure 1: Mosaic plots of flanking consonant place of articulation by vowel

2.2 Data collection

All subject protocols were approved by the University of Washington Institutional Review Board. Thirteen native speakers of Indonesian were recruited for this study, and compensated at an hourly rate. Five participants were excluded prior to transcription and data analysis due to

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[3] Only five words had non-obstruent onsets [l,m,r] for the syllable in question, and only one word had a non-obstruent coda [r].

difficulty with the task or excessive hyperarticulation. Of the remaining participants (four male, four female), all had been born and raised in Indonesia (five from Jakarta, three from Surabaya) and had been in the United States for a maximum of five years (mean 2.9 years). All reported that they still used Indonesian on a daily basis. Participants were recorded reading wordlists in a sound-attenuated booth with an ElectroVoice RE20 microphone. The signal passed through a low-noise amplifier (Shure FP32A) before digitization (M-Audio Profire 620, 44.1kHz, 16 bits per sample), and was recorded direct-to-disk using Sound Studio (Kwok, 2007).

Each participant read 300 words (75 target words + 25 distractor words, repeated blockwise three times, each block uniquely randomized). Participants were asked to review the 100 unique words prior to the recording and to indicate any words they were unfamiliar with; any such words were omitted from that participant's word list and replaced with preselected alternate words from the same morphological condition (if replacements were available). The wordlist was presented onscreen by a custom Flash script, advanced by the experimenter after each word at a casual pace. Participants were allowed breaks at any time throughout the recording.

2.3 Data analysis

Recordings of the retained participants were broadly transcribed and the vowels of interest were marked in TextGrid files using Praat (Boersma & Weenink, 2011). Vowel boundaries were marked carefully in a 250ms window, with vowel edges marked at zero crossings and with some effort to include an integer number of complete cycles of the vowel waveform. In the few cases where the vowel-adjacent consonant was a periodic sonorant, the edge of the vowel was judged by reference to waveform amplitude changes, with uncertainties resolved by reference to changes in the complexity of the repeating waveform and by changes in energy (e.g., antiformants) visible on the spectrogram.

As mentioned above, some word-final vowels were included in the study as points of comparison (serving as the canonical unreduced form of the vowel). Because word-final vowels were significantly lengthened and often transitioned smoothly into a voiced glottal fricative, the vowel endpoint was marked at the point where F2 and F3 became indistinct and the complexity of the repeating waveform showed a significant change in shape (i.e., a change in the number of inflection points). This word-final lengthening of vowels also would have made any comparisons of duration extremely difficult, so a choice was made to mark out only the modally voiced portion of all vowels, thereby avoiding many problems of formant measurement at the expense of reliable duration measures.[4] For such purposes, modal voicing was defined as a subjective judgment of low cycle-to-cycle changes, minimal aperiodic noise, and visible glottal pulses above 3000 Hz. Formant measures were extracted either at the midpoint of the modally voiced portion (so defined), or at 50ms into the vowel for word-final vowels with modally-voiced portions exceeding 100ms (to minimize the chance of measurements being skewed by utterance-final laxing).

F1 and F2 values for all marked vowels were extracted by custom Praat script. After extraction of formant measurements, z-scores were calculated within talker for each vowel phoneme, and

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[4] The choice to mark modal voicing helps avoid faint or missing F1 due to breathy voicing, and midpoint measures that would have fallen during the aspirated portion of the vowel. This is of course not the typical way of marking vowel boundaries when measuring duration. However, the present study did not examine duration for the reasons mentioned, so the methods described were chosen to maximize reliability of the F1 and F2 measurements.

any vowel token with formant values exceeding two standard deviations was marked for remeasurement by hand. This process was iterated (z-scores recalculated and outliers remeasured) until all remaining outliers showed hand-measured values that were in agreement with the script-extracted values. After this hand-correction was complete, subject-interal z-scores were recalculated to allow direct comparison of the male and female data, and these normalized formant values were entered into a series of mixed models using `lmer()` from the lme4 package (Bates *et al.*, 2012) in the R statistical computing environment (R Development Core Team, 2012), with a random effect for talker and fixed effects for morphological condition and flanking consonant place. Significance values for the fixed-effect predictors were calculated via Markov-chain Monte Carlo simulations using `pvals.fnc()` from the languageR package (Baayen, 2011).

Although it would have been possible to model data from all vowels simultaneously by including an additional random effect for vowel, the choice was made to model each vowel separately, so that the magnitude and direction of effects would be more readily interpretable. For example, reduction along the F2 dimension is likely to manifest as a backing of front vowels, a fronting of back vowels, and presumably little to no change in /a/, while reduction in the F1 dimension is likely to manifest as a lowering of the high and mid vowels and a raising of /a/. Modeling each vowel separately allows the model estimates to be directly compared to the expected direction of reduction.

As mentioned above, balancing place of articulation of the flanking consonants was not always possible when creating the word list. Most importantly, it was impossible to control the following consonant context for the experimental condition “V+kan” (V-final stem plus /-kan/ suffix) and the reference condition “V#” (final open/canonical unreduced). This imbalance is shown graphically in Figure 2. Accordingly, the “V+kan” and “V#” conditions cannot be entered into a mixed model that includes following consonant as a predictor, since the identity of the following consonant is completely confounded with morphological condition in those cases. Therefore, the first statistical models include all morphological conditions but do not include following consonant as predictors; subsequent models include following consonant as predictors but exclude some of the morphological conditions (see Section 3 for details).

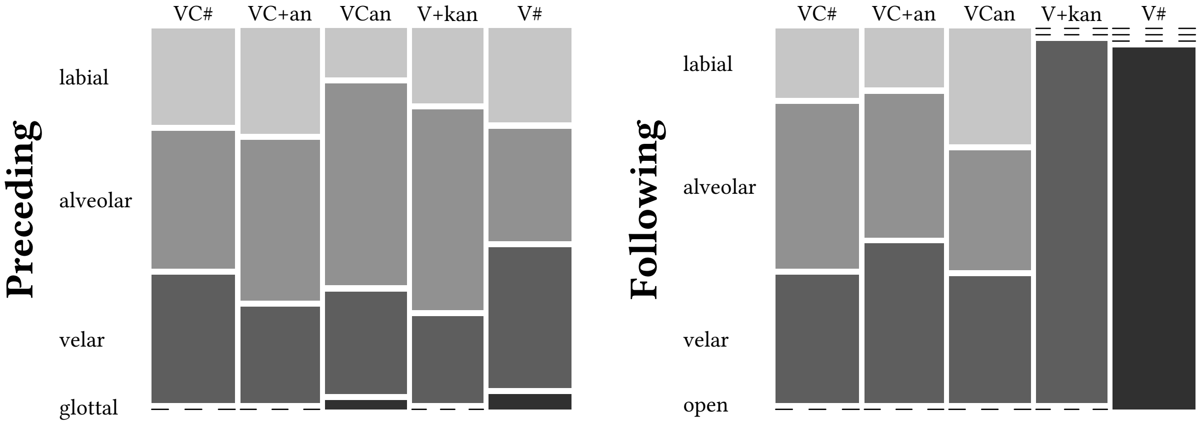

Figure 2: Mosaic plots of flanking consonant place of articulation by morphological condition

3 Results

Figure 3 shows F2×F1 plots of z-transformed means and standard errors of each morphological condition by vowel. Since these plots do not represent the effects of flanking consonants, we must be cautious in interpreting any visual patterns. However, one observation that seems warranted on the basis of the plots alone is that for the vowels /i e u/ there is a consistent pattern of the experimental conditions (open symbols) showing partial reduction that falls somewhere in between the extremes of the reference conditions V# and VC# (filled symbols). The vowel /o/ shows an unusual pattern where two of the morphological conditions (VCan and VC+an) show extreme reduction in the F1 dimension, and the vowel /a/ shows virtually no difference among the five morphological conditions. Thus on first impression it would seem that reduction occurs in Indonesian for the non-low vowels in both ultimate and penultimate syllables, and reduction is not in this instance a purely phonological (i.e., categorical) phenomenon.

These observations are generally supported by the first set of statistical models, shown in Table 2, which include data from all morphological conditions but do not include following consonant place as a predictor.[5] The results show significant differences among all morphological conditions for all non-low vowels in both the F1 and F2 dimensions, with the exception of the VCan ~ VC# groups for the vowel /e/. However, as seen visually in Figure 3, substantial by-vowel variability is seen in the direction of the various relationships. As one example, for the vowel /i/, the hypothesis that condition VC+an will be more reduced and condition V+kan will be less reduced seems to be borne out: this can be seen by the relative proximity of the open circle (VC+an, condition 2) to the filled circle (VC#, condition R2), and the relative proximity of the open square (V+kan, condition 1) to the filled square (V#, condition R1). These relationships are reflected in the Wald Z scores in Table 2, where increasingly negative Wald Z scores indicate less and less reduction in F1, so that in terms of lowering of /i/, condition V# < V+kan < VCan < VC+an < VC#. In contrast, the positions of the open circle and open square are more tightly clustered for the vowel /u/, and likewise the Wald Z values for /u/ in F1 show a pattern of V# < VCan < V+kan < VC+an < VC#, with relatively small differences among the Wald Z values for the experimental conditions.

To further investigate these data, a second set of models was generated that included place of articulation of the following consonant as predictor, but necessarily excluded data in conditions V# and V+kan because of the aforementioned confound between condition and coda consonant. Results of this second set of models is given in Table 3. These models show a significant effect of morphological condition on F1 for the non-low vowels /i e u o/ and a significant effect of morphological condition on F2 for the front vowels /i e/. However, examination of the Wald Z scores again reveals substantial vowel-by-vowel differences. In particular, the vowels /i e u/ show the expected pattern of VCan < VC+an < VC# in the F1 dimension, i.e., the VC# shows the greatest reduction, VC+an shows less reduction, and VCan shows the least reduction of the three. The vowel /o/ shows a different pattern, where both VC+an and VCan are *lower* than VC# (cf. Figure 3). In the F2 dimension, only the vowel /i/ shows the hypothesized pattern of VC# being most centralized and VCan being least centralized.

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[5] Model results for /a/ are excluded for brevity; predictors for /a/ were uniformly nonsignificant for morphological condition (except for a marginally significant F2 difference for the VCan condition) and uniformly significant (p<0.0001) for all levels of the "consonantal onset" predictor.

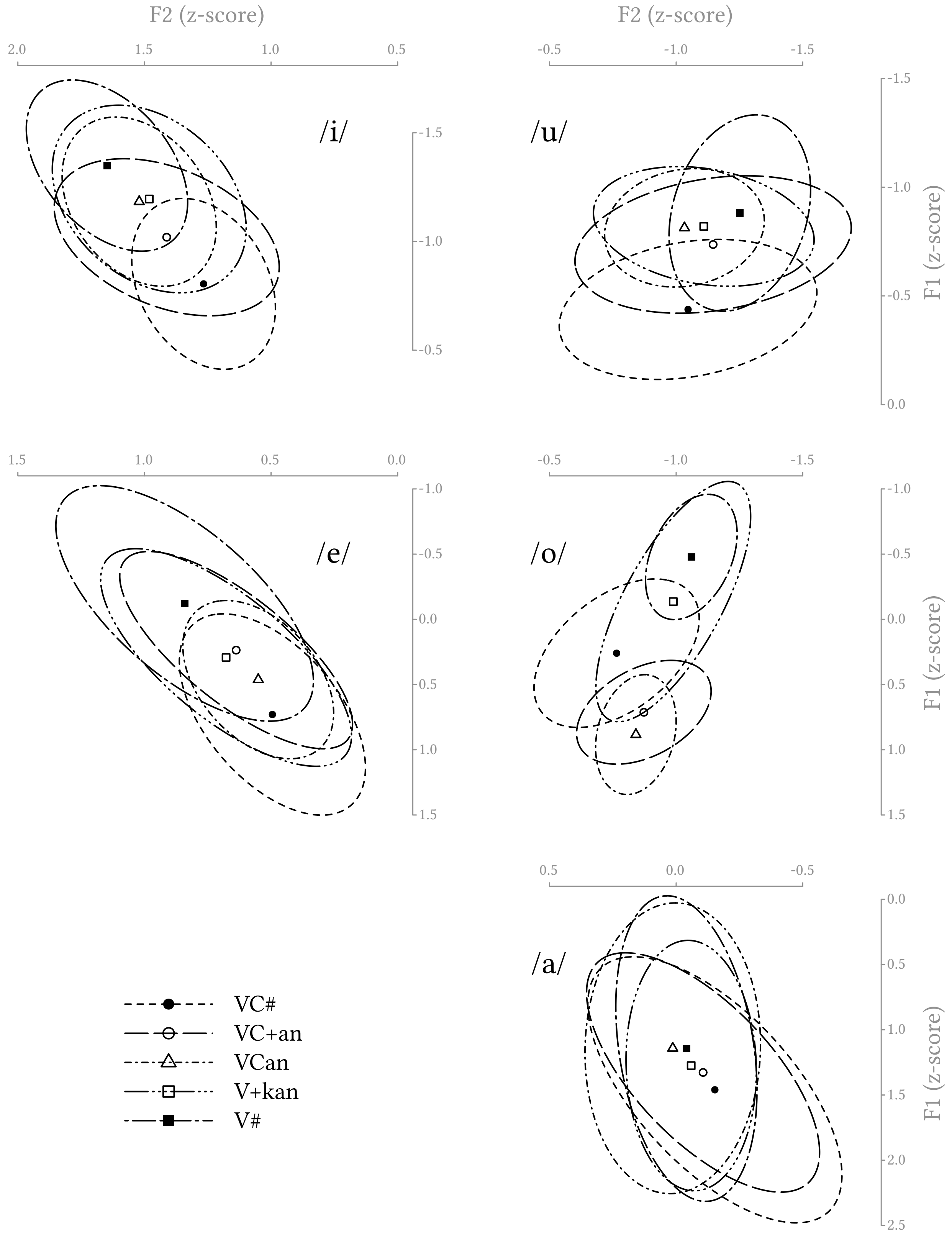

Figure 3: F2×F1 plots of z-transformed mean values, by vowel and morphological condition. Ellipses indicate ±1 standard error along the bivariate normal density contours for each condition.

Vowel	Outcome	Log-likelihood	Predictor	Coefficient	*SE*	Wald *Z*	*p*
/i/ n=348	F1	-10.62	cond = VC+an	−0.220	0.039	−5.65	< 0.0001
			cond = VCan	−0.433	0.045	−9.62	< 0.0001
			cond = V+kan	−0.441	0.040	−10.98	< 0.0001
			cond = V#	−0.535	0.039	−13.88	< 0.0001
			onset = alveolar	0.131	0.040	3.23	< 0.005
			onset = velar	0.101	0.041	2.45	< 0.05
	F2	14.07	cond = VC+an	0.152	0.036	4.18	< 0.0001
			cond = VCan	0.318	0.042	7.54	< 0.0001
			cond = V+kan	0.270	0.038	7.15	< 0.0001
			cond = V#	0.367	0.036	10.14	< 0.0001
			onset = alveolar	−0.155	0.038	−4.11	< 0.0001
			onset = velar	−0.091	0.039	−2.35	< 0.05
/e/ n=335	F1	-223.7	cond = VC+an	−0.608	0.080	−7.64	< 0.0001
			cond = VCan	0.005	0.084	0.06	> 0.9
			cond = V+kan	−0.270	0.094	−2.86	< 0.005
			cond = V#	−0.373	0.115	−3.25	< 0.005
			onset = alveolar	0.648	0.091	7.15	< 0.0001
			onset = velar	0.273	0.089	3.08	< 0.005
			onset = glottal	−0.143	0.132	−1.08	> 0.2
	F2	-18.07	cond = VC+an	0.222	0.042	5.23	< 0.0001
			cond = VCan	−0.093	0.045	−2.08	< 0.05
			cond = V+kan	0.145	0.050	2.89	< 0.005
			cond = V#	0.124	0.061	2.03	< 0.05
			onset = alveolar	−0.333	0.048	−6.91	< 0.0001
			onset = velar	−0.055	0.047	−1.17	> 0.2
			onset = glottal	0.180	0.070	2.56	< 0.05
/u/ n=347	F1	29.51	cond = VC+an	−0.297	0.035	−8.44	< 0.0001
			cond = VCan	−0.403	0.035	−11.39	< 0.0001
			cond = V+kan	−0.390	0.038	−10.25	< 0.0001
			cond = V#	−0.431	0.036	−11.87	< 0.0001
			onset = alveolar	0.066	0.030	2.22	< 0.05
			onset = velar	−0.054	0.033	−1.64	> 0.1
			onset = glottal	−0.031	0.078	−0.40	> 0.6
	F2	19.2	cond = VC+an	−0.098	0.036	−2.69	< 0.01
			cond = VCan	−0.107	0.037	−2.92	< 0.005
			cond = V+kan	−0.091	0.039	−2.30	< 0.05
			cond = V#	−0.214	0.038	−5.68	< 0.0001
			onset = alveolar	0.353	0.031	11.53	< 0.0001
			onset = velar	−0.027	0.034	−0.80	> 0.4
			onset = glottal	0.368	0.080	4.59	< 0.0001
/o/ n=346	F1	-131.5	cond = VC+an	0.470	0.060	7.87	< 0.0001
			cond = VCan	0.345	0.064	5.40	< 0.0001
			cond = V+kan	−0.419	0.059	−7.11	< 0.0001
			cond = V#	−0.681	0.059	−11.60	< 0.0001
			onset = alveolar	0.443	0.052	8.49	< 0.0001
			onset = velar	0.049	0.057	0.86	> 0.3
	F2	151.8	cond = VC+an	−0.107	1.026	−0.10	< 0.0001
			cond = VCan	−0.208	7.028	−0.03	< 0.0001
			cond = V+kan	−0.234	4.026	−0.06	< 0.0001
			cond = V#	−0.262	2.026	−0.13	< 0.0001
			onset = alveolar	0.197	9.023	0.02	< 0.0001
			onset = velar	−0.001	9.025	−0.00	> 0.9

Table 2: Model summaries for all morphological conditions but excluding coda consonant place. Intercepts are excluded for reasons of space.

Vowel	Outcome	Log-likelihood	Predictor	Coefficient	*SE*	Wald *Z*	*p*
/i/ n=202	F1	13.93	cond = VC+an	−0.207	0.035	−5.94	< 0.0001
			cond = VCan	−0.349	0.040	−8.84	< 0.0001
			coda = alveolar	0.253	0.051	4.99	< 0.0001
			coda = velar	0.016	0.046	0.35	> 0.7
	F2	3.779	cond = VC+an	0.151	0.037	4.08	< 0.001
			cond = VCan	0.283	0.042	6.75	< 0.0001
			coda = alveolar	0.041	0.053	0.77	> 0.4
			coda = velar	0.119	0.049	2.43	< 0.05
/e/ n=205	F1	-123.6	cond = VC+an	−0.470	0.076	−6.17	< 0.0001
			cond = VCan	−0.736	0.101	−7.27	< 0.0001
			coda = alveolar	−0.694	0.107	−6.52	< 0.0001
			coda = velar	−0.792	0.139	−5.70	< 0.0001
	F2	-4.9	cond = VC+an	0.118	0.041	2.86	< 0.01
			cond = VCan	0.153	0.055	2.79	< 0.01
			coda = alveolar	0.129	0.058	2.24	< 0.05
			coda = velar	0.224	0.075	2.96	< 0.01
/u/ n=224	F1	38.51	cond = VC+an	−0.296	0.032	−9.29	< 0.0001
			cond = VCan	−0.390	0.033	−11.94	< 0.0001
			coda = alveolar	0.005	0.037	0.15	> 0.8
			coda = velar	0.047	0.037	1.28	> 0.2
	F2	18.34	cond = VC+an	−0.099	0.035	−2.79	< 0.01
			cond = VCan	−0.034	0.036	−0.94	> 0.3
			coda = alveolar	0.493	0.041	12.09	< 0.0001
			coda = velar	0.059	0.041	1.45	> 0.1
/o/ n=214	F1	-62.42	cond = VC+an	0.428	0.055	7.83	< 0.0001
			cond = VCan	0.607	0.056	10.86	< 0.0001
			coda = alveolar	−0.051	0.069	−0.74	> 0.4
			coda = velar	0.077	0.056	1.39	> 0.1
	F2	78.45	cond = VC+an	−0.161	0.028	−5.67	< 0.0001
			cond = VCan	−0.011	0.029	−0.37	> 0.7
			coda = alveolar	0.196	0.036	5.52	< 0.0001
			coda = velar	0.158	0.029	5.45	< 0.0001
/a/ n=213	F1	-215.6	cond = VC+an	−0.178	0.110	−1.61	> 0.1
			cond = VCan	−0.186	0.113	−1.64	> 0.1
			coda = alveolar	−0.530	0.129	−4.10	< 0.001
			coda = velar	−0.290	0.133	−2.18	< 0.05
	F2	17.87	cond = VC+an	0.079	0.036	2.22	< 0.05
			cond = VCan	0.054	0.036	1.48	> 0.1
			coda = alveolar	0.450	0.042	10.75	< 0.0001
			coda = velar	0.052	0.043	1.22	> 0.2

Table 3: Fixed effects of single-vowel models for conditions **VC#**, **VCan**, **VC+an**. Intercepts are excluded for reasons of space.

A conservative interpretation of this second set of models would allow that the results seen here may be due to stress differences between the reference condition VC# and the two experimental conditions VC+an and VCan, since in this study 611 of 719 tokens (comprising 35 of 41 types) of the reference conditions are unstressed, while the vowels in the experimental conditions are always stressed. However, stress cannot account for differences between conditions VCan and VC+an, or between either of those conditions and the V+kan condition. To investigate such differences, a final set of models was generated comparing only the three experimental conditions, in which data are restricted to words in which the following consonant place of articulation is velar.[6] Results of this final set of models are seen in Table 4, and show that in some cases significant differences do exist between experimental conditions, even after accounting for place of articulation of the preceding consonant, and holding following consonant (and stress) constant. However, as before, the pattern of results is mixed: significant differences emerge for the high vowels between VC+an and VCan (in F2 for /i/ and in both F1 and F2 for /u/), whereas significant differences emerge for the mid vowels between VC+an and V+kan (in F1 for /o/ and in both F1 and F2 for /e/). The direction of the significant effects is also inconsistent: the VC+an condition is significantly lower in /o/ and more central in /i u/, but is also unexpectedly higher in /u/ and both higher and fronter in /e/.

4 Discussion

Overall, the results of this study support a view in which vowel reduction in Indonesian occurs in closed syllables (both penultimate and ultimate), but occurs in a gradient fashion, not categorically. As expected, reduction in the penultimate syllables in general fell between the extremes of the word-final open-syllable and word-final closed-syllable vowels. The effects of flanking consonants were mixed, as were the effects of morpheme boundaries, with substantial vowel-to-vowel variability. There are a number of possible reasons for this variability. For example, it is often the case (especially among Austronesian languages) that the back rounded vowels are highly variable in their realization, in which case this study may have been underpowered to detect a systematic effect of morphological structure on vowel quality. In other words, the subtle effect of morphological structure (if there is one) may have been swamped by the inherent variability of those vowels. Relatedly, the patterns that emerged (both the predicted and the unexpected ones) may have been a result of lexeme-specific pronunciations, along the lines of Pierrehumbert's "word-specific phonetics" (2002); this explanation is especially tempting for the abnormally high F1 values for /o/ in the VCan and VC+an conditions. Finally, although a larger study might help clarify some of these uncertainties, it may well be the case that Indonesian is not the ideal language in which to test hypotheses about the interaction between morphological structure and phonetic/phononological processes of reduction, because of limitations of experimental design imposed by the affixal morphemes that happen to occur in the language.

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[6] This restriction allows the inclusion of the V+kan condition in the model while avoiding the confound between condition and following consonant place.

Vowel	Outcome	Log-likelihood	Predictor	Coefficient	*SE*	Wald *Z*	*p*
/i/	F1		Intercept	−1.053	0.076	−13.83	< 0.0001
n=138			cond = VCan	0.055	0.058	0.94	> 0.3
			cond = V+kan	0.010	0.049	0.20	> 0.8
			onset = alveolar	−0.099	0.074	−1.34	> 0.1
			onset = velar	−0.421	0.097	−4.35	< 0.0001
	F2		Intercept	1.525	0.072	21.27	< 0.0001
			cond = VCan	0.158	0.058	2.73	< 0.01
			cond = V+kan	0.070	0.049	1.41	> 0.1
			onset = alveolar	−0.113	0.074	−1.53	> 0.1
			onset = velar	−0.057	0.096	−0.59	> 0.5
/e/	F1		Intercept	−0.185	0.174	−1.07	> 0.2
n=81			cond = VCan				
			cond = V+kan	0.368	0.092	4.00	< 0.0001
			onset = alveolar	0.194	0.086	2.25	< 0.05
			onset = velar				
	F2		Intercept	1.012	0.099	10.22	< 0.0001
			cond = VCan				
			cond = V+kan	−0.226	0.068	−3.34	< 0.01
			onset = alveolar	−0.244	0.063	−3.86	< 0.001
			onset = velar				
/u/	F1		Intercept	−0.747	0.050	−14.93	< 0.0001
n=125			cond = VCan	0.207	0.071	2.92	< 0.01
			cond = V+kan	0.068	0.055	1.24	> 0.2
			onset = alveolar	−0.194	0.059	−3.27	< 0.01
			onset = velar	−0.248	0.059	−4.20	< 0.0001
	F2		Intercept	−1.414	0.044	−31.82	< 0.0001
			cond = VCan	−0.166	0.065	−2.53	< 0.05
			cond = V+kan	0.058	0.051	1.14	> 0.2
			onset = alveolar	0.517	0.055	9.46	< 0.0001
			onset = velar	0.120	0.054	2.20	< 0.05
/o/	F1		Intercept	0.411	0.074	5.54	< 0.0001
n=131			cond = VCan	−0.081	0.088	−0.91	> 0.3
			cond = V+kan	−0.681	0.071	−9.55	< 0.0001
			onset = alveolar	0.614	0.072	8.57	< 0.0001
			onset = velar	−0.250	0.096	−2.61	< 0.05
	F2		Intercept	−1.097	0.022	−49.19	< 0.0001
			cond = VCan	0.017	0.031	0.57	> 0.5
			cond = V+kan	−0.039	0.025	−1.55	> 0.1
			onset = alveolar	0.308	0.025	12.39	< 0.0001
			onset = velar	0.081	0.033	2.42	< 0.05

Table 4: Fixed effects for the “velar-only” models, conditions **V+kan**, **VCan**, and **VC+an**. Blank entries indicate combinations of predictor levels that were not attested in the word lists. Models for vowel /a/ were non-convergent and are not reported.

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