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Acoustic phonetic study of the Sora vowel system

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ABSTRACT:
This paper is an acoustic phonetic study of vowels in Sora, a Munda language of the Austroasiatic language family. Descriptions here illustrate that the Sora vowel system has six vowels and provide evidence that Sora disyllables have prominence on the second syllable. While the acoustic categorization of vowels is based on formant frequencies, the presence of prominence on the second syllable is shown through temporal features of vowels, including duration, intensity, and fundamental frequency. Additionally, this paper demonstrates that acoustic categorization of vowels in Sora is better in the prominent syllable than in the non-prominent syllable, providing evidence that syllable prominence and vowel quality are correlated in Sora. These acoustic properties of Sora vowels are discussed in relation to the existing debates on vowels and patterns of syllable prominence in Munda languages of India. In this regard, it is noteworthy that Munda languages, in general, lack instrumental studies, and therefore this paper presents significant findings that are undocumented in other Munda languages. These acoustic studies are supported by exploratory statistical modeling and statistical classification methods.
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I. INTRODUCTION

Sora (ISO 639-3, 2007) is a Munda language of the Austroasiatic language family spoken by approximately 409 549 Sora individuals in several regions of India (Moseley, 2010; Registrar General of India, 2011). Some Munda languages spoken in India, such as Gutob and Gorum, are deemed highly endangered (Moseley, 2010). Other Munda languages, including Sora, are potentially endangered languages, and systematized speech corpora of these languages are still lacking. Whereas there are various studies on the Munda languages of India, studies based on acoustic analysis are scarce. Nevertheless, such studies are required to answer some long-standing questions regarding the features of the Munda languages, in particular, and the Austroasiatic language family, in general. For instance, although it is known that Munda languages typically have a five-vowel phonemic inventory (Jenny *et al.*, 2014), it is not known if the vowel quality of the five vowels is similar across different Munda languages. Likewise, it is not clear why the sixth, central vowel is considered phonemic in some Munda languages, such as Santali (Ghosh, 2008), while it is considered merely as an allophone in other Munda languages such as Kharia (Rehberg, 2003).

Hence, it is important to investigate the vowel systems of Munda languages of India in detail so that the physical realizations and patterns of variability of phonemes in the languages can be accounted for. Apart from the lack of adequate descriptions of Munda segments, scholars in Munda languages also have varied opinions on the suprasegmental features of Sora. For example, several studies have suggested that Sora has a trochaic word stress pattern (Donegan, 1993; Donegan and Stampe, 1983, 2004). On the other hand, recent studies have shown that Sora actually follows an iambic word stress assignment (Horo, 2017; Horo and Sarmah, 2015, 2017). Thus, it is worthwhile to investigate if the iambic stress pattern, where prominence is assigned to the second syllable, is also evident in the acoustics of vowel quality in the language.

Considering this, the current paper has two primary objectives. First, it aims at providing a comprehensive acoustic description of the vowel system of Sora as it is spoken in five different geographic locations in India. While doing that, this paper will also investigate the status of the mid central /ə/ vowel in Sora to examine whether the /ə/ vowel in Sora is a distinct phoneme in Sora or not. Second, this paper will also explore if vowel realization is distinct in the first and second syllables to determine any correlation between the vowel quality and iambicity in Sora disyllables. In order to achieve these two objectives, production experiments with acoustic analysis supported by statistical tests have been conducted on Sora vowel data collected from five different geographic areas in India.

As indicated before, there is no general agreement on the sizes and types of vowels in the phoneme inventory of different Munda languages. So is the case with Sora. One of the earliest studies indicated that Sora has ten vowels (Ramamurti, 1931). However, this study did not specify whether the ten vowels are all phonemic or if it included allophonic variations of a smaller set of distinct phonemes. Subsequently, two major

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studies have proposed that Sora has nine phonemic vowels (Stampe, 1965; Zide, 1982). Later, Mohanty (1997) argued that Sora only has five phonemic vowels. Recently, Anderson and Harrison (2008) have reported the existence of eight nonphonemic vowels in Sora. It is noteworthy that these studies on Sora vowels are primarily based on impressionistic accounts, and no instrumental studies were conducted. However, Horo and Sarmah (2015) have performed a preliminary study of vowels in Sora based on instrumental analysis of speech data recorded from 12 Sora individuals residing in Singrijhan of Assam Province in India. This work revealed that Sora has six phonemic vowels. Moreover, in the same work, it was suggested that variation in the description of the Sora vowel system could have emerged due to the misrepresentation of some vowel sounds in the earlier studies. While words in Sora are minimally disyllabic, earlier studies have reported vowel phonemes derived from elicited monosyllables (Donegan and Stampe, 2002), which may not be produced naturally. Hence, the variation in Sora vowels may have emerged from the artificial contexts used for eliciting the vowel phonemes in some of the earlier studies. Additionally, Horo and Sarmah (2015) suggested right headed syllable prominence in Sora disyllables, discarding an earlier study (Donegan and Stampe, 1983) that had proposed left headedness in the language. Thus, in addition to the identification of vowel sounds, the preliminary acoustic study of Sora spoken in Singrijhan provided insights into the vowel system that was previously misrepresented.

Precise acoustic descriptions of the vowel sounds in Sora have typological significance, particularly with regard to the categorization of the sixth vowel as a mid central vowel /ə/. Generally, non-low central vowels, such as /ə/ and /ɨ/, are considered a feature of the vowel systems of the Austroasiatic languages (Jenny *et al.*, 2014). Both /ə/ and /ɨ/ are also reconstructed for Proto-Munda (Pinnow, 1959). However, several scholars argue that while [ɨ] never existed in Proto-Munda (Sidwell and Rau, 2014), [ə] did. Still there are claims that non-low central vowels were not part of the Proto-Munda vowel system, and the existence of [ə] in a Munda language can be attributed to the neighboring Indo-Aryan languages with phonemic /ə/ (Bhattacharya, 1975). Donegan (1993) claims that Proto-Munda actually had both non-low central vowels, but they are now lost in the modern Munda languages due to their intrinsic shortness. As a result of these assertions, it appears that the vowel systems of the Munda languages have undergone reduction and are heavily influenced by Indo-Aryan or Dravidian languages. They have little resemblance to the non-Munda Austroasiatic (AA) languages such as Kammu, Chong, Car, etc. However, there are studies suggesting the existence of [ə] in Munda languages either as a phoneme or an allophonic variation. As mentioned earlier, in Santali /ə/ appears as a phonemic vowel with nasalized counterparts (Ghosh, 2008). In Kharia, [ə] only appears as an allophone of all the vowels except /i/ (Rehberg, 2003). While these descriptions are purely based on auditory impressions of the authors, the veracity of the claims are not confirmed by means of instrumental analyses. Nevertheless, it is evident that the lack of in-depth studies, and in many cases the lack of instrumental studies in Munda languages, has resulted in general disagreement on the status of non-low central vowels in Munda languages. In the case of Sora, while it was suggested that, unlike other Munda languages, Sora has both /ə/ and /ɨ/ (Donegan, 1993), the preliminary acoustic analysis revealed that /ə/ is a phoneme in Sora, but there is no [ɨ] in the language (Horo and Sarmah, 2015). Therefore, the current work is an extension of Horo and Sarmah (2015), where we provide a comprehensive analysis of the vowel system of Sora as spoken by Sora speakers living in five different geographic locations in India.

The rest of the paper is organized as follows. Section II describes the methodology adopted in the paper and the manner in which data collection and acoustic and statistical analyses were conducted. Section III reports the results of the acoustic analyses, and Sec. IV reports the results of statistical analyses. Finally, Sec. V discusses the results and concludes the paper.

II. METHODS

A. Participants

Participants recorded in this work include Sora people living in four villages of Assam, North-East India and one village of Odisha of Eastern India. Figure 1 shows the areas of the Sora population in Assam and Odisha in grey and areas of data collection in green.

Acoustic data (recorded speech) of 50 participants, including 40 from Assam and 10 from Odisha, are used in this study, 50% of the total participants are males and 50% are females with an average age of 49 yr and a standard deviation of 12 yr. All participants recorded for this work are either bilinguals or trilinguals. While the Sora participants in Assam could speak Indo-Aryan languages, such as Assamese and/or Sadri, Sora participants in Odisha could speak only an Indo-Aryan language, namely Oriya, or could also speak a Dravidian language, namely, Telugu. The literacy level of the Sora participants in the database can be divided into three categories: never attended school, literate over grade 10, and school dropouts under grade 10. While 54% of the Sora participants in the database never attended school, 16% have received formal education after grade 10, and 30% are school dropouts before grade 10.

B. Stimuli and recording procedure

Text data used in this work are compiled from three primary sources, namely, Horo and Sarmah (2015), Ramamurti (1938), and Anderson and Harrison (2011). The text data include a total of 1160 Sora disyllabic words having the basic syllable structure $(C_1)V(C_2).(C_1)V(C_2)$ where the six vowels, /a, e, i, o, u, ə/, occur in the vowel nucleus (V) of both syllables. Onset consonants (C_1) include sonorants and obstruents but exclude the retroflex rhotic /ɽ/ in the onset of the first syllable and a velar nasal /ŋ/ and a glottal stop /ʔ/ in either syllable. Coda consonants (C_2) include nasals /m, n, ŋ, ɲ/, lateral /l/, rhotic /r/, and the glottal stop /ʔ/ in both syllables.

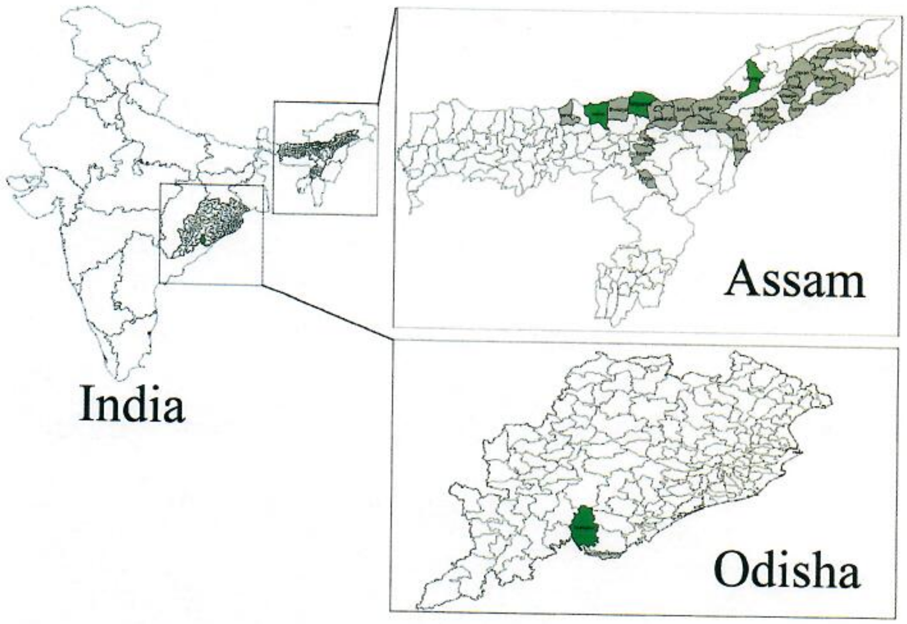

FIG. 1. (Color online) Areas of data collection. Map adopted from Horo (2017).

The entire data set was recorded in the field in a noise free environment using a Shure SM-10A unidirectional head-worn microphone (USA) connected to a Tascam DR100 MKII recorder (USA) via XLR jack. The sampling frequency was 44.1 kHz at 24 bit in .wav format. During the recordings, all participants said every word once in isolation and once in the sentence frame, "*ɲen* X *gamlai*" translated literally as "I X said," meaning "I said X."

C. Acoustic and statistical analyses

Acoustic data recorded in the field are manually annotated in Praat (Boersma and Weenink, 2019) to mark (a) word boundaries, (b) syllable boundaries, and (c) phoneme boundaries. The vowels are marked between steady-state formants. Both visual and auditory cues are taken into consideration for segmenting all the vowel sounds in the database. Visual cues considered for identifying the vowel sounds include periodic waveforms, higher amplitude in the spectrogram, and steady formant trajectories for the first and second formant frequencies. These visual cues are identified in correspondence with the audible vowel segments in the speech data. Subsequently, the acoustic analysis of Sora vowels in this work is done by measuring the frequencies of the first two formants (f_1 and f_2). The formants were extracted using a script on Praat (Boersma and Weenink, 2019) with the Burg method and a window length of 25 ms. The formant ceiling was fixed at 5500 Hz for female speakers and 5000 Hz for male speakers. Several previous works have demonstrated the reliability of average formant values in the mid 20% of the vowel in better predicting vowel categories (Williams and Escudero, 2014). Hence, we also extracted the formant values (f_1 and f_2) in the mid 20% of the vowels in this study. Additionally, Williams and Escudero (2014) also found that the vowel inherent spectral characteristics are better represented with the discrete cosine transform (DCT) of the vowel formant frequencies. Thus, following Williams and Escudero (2014), we also extracted the DCT coefficients, C0, C1, and C2 for f_1 and f_2 of each vowel. The 3 DCT coefficients were derived from calculating the f_1 and f_2 trajectories in the mid 60% of the total vowel duration at 30 equidistant points. Apart from the formant values and DCT coefficients, total duration of the vowels, average intensity, and mean fundamental frequency (f_0) were also extracted from the total vowel duration. After the formant values were collected in Hertz, they were subjected to speaker normalization using the Lobanov normalization method (Lobanov, 1971) using the *phonR* package (McCloy, 2016) on *R* (R Core-Team, 2019).

In order to examine the overall distribution of Sora vowels in the first and second syllables, this paper also analyses vowel dispersion in the two syllable positions. For this purpose, Euclidean distance (ED) measurement is used in this paper. Generally, ED estimates the straight distance between two points in a given space. In phonetic studies, ED measurement is used in vowel analysis to estimate vowel dispersion between two vowels in an f_1-f_2 plane of a vowel acoustic space (Lindblom, 1986). In this regard, evidence suggests that greater vowel dispersion implies greater categorical distinction between vowels and vice versa. Likewise, greater vowel dispersion is associated with the expansion of vowel distribution, and lesser vowel dispersion is associated with the reduction of vowel distribution in a given vowel system. Therefore, the ED between Sora vowels in the first and second syllables is calculated using

$$d_{xy} = \sqrt{(F1_x - F1_y)^2 + (F2_x - F2_y)^2}. \quad (1)$$

In Eq. (1), d_{xy} represents the ED between two vowels based on their f_1 and f_2 frequencies. $F1_x$,$F1_y$ and $F2_x$,$F2_y$ represent the f_1 and f_2 frequencies of the two vowels, x and y, between which the ED is calculated. Also, considering the fact that vowel dispersion can vary from speaker to speaker, the ED between Sora vowels in the first and second syllables is calculated separately for every speaker, and subsequently all estimated values are presented and interpreted with the help of a box plot.

To visually examine vowel quality in Sora, the normalized f_1 and f_2 values are used to plot vowels on a two-dimensional (2-D) plot. However, considering the previously noticed vowel quality difference between the first and second syllables in Sora, vowel plots are generated for each syllable separately (Horo, 2017; Horo and Sarmah, 2015). Similarly, other features, such as vowel duration, fundamental frequency (f_0), and intensity, for the Sora vowels are also investigated by each syllable. While average intensity of each vowel across its duration is reported, for f_0, mean values are taken from the entire vowel duration.

Apart from the visual and descriptive analyses of the vowel features, the data were also subjected to statistical analysis. Three types of statistical investigations were performed. First, a quadratic discriminant analysis (QDA) was conducted to see the accuracy of vowel classification with the addition of various acoustic features. Second, one-way analysis of variance (ANOVA) tests were conducted to explore the effects of vowels on vowel duration, intensity, and fundamental frequency. Third, linear mixed effects (LME) models were constructed to determine the most appropriate model for the classification of vowels. The visual representations and statistical modeling of the data were conducted using *R* (R Core-Team, 2019). The QDA classification was conducted using the *MASS* package (Venables and Ripley, 2002) on *R* (R Core-Team, 2019). The LME models were built using the *LME4* package (Bates *et al.*, 2015), and backward-reduced optimal models were constructed using the *lmerTest* package (Kuznetsova *et al.*, 2017). In order to see the variance of factors in the LME models, we conducted type II Wald Chi-square tests using the *car* package (Fox and Weisberg, 2019). In cases where pairwise differences between categories needed to be assessed, we used *post hoc* Bonferroni tests using the *emmeans* package on *R*.

III. RESULTS OF ACOUSTIC ANALYSES

A. Vowel formant frequency

Formant frequency values extracted from Sora vowels reveal that the six vowels /i, e, a, o, u, ə/ are categorically distinct from each other, and their phonetic realizations are similar across all Sora speakers recorded in this study. The distribution of the six vowels in the Sora vowel system is presented in a vowel plot across the f_1-f_2 plane in Fig. 2.

Figure 2 shows the speaker normalized mean f_1 and f_2 frequencies of all six vowels, and the ellipsis around the mean indicates standard deviation of the f_1 and f_2 values for each vowel in the vowel system. The vowel plot in Fig. 2 supports the preliminary analysis of Sora vowels and confirms the finding that the Sora vowel system consists of six vowels. Also, it is evident that f_1 and f_2 frequencies adequately categorize the six vowels as distinct vowel segments in the language.

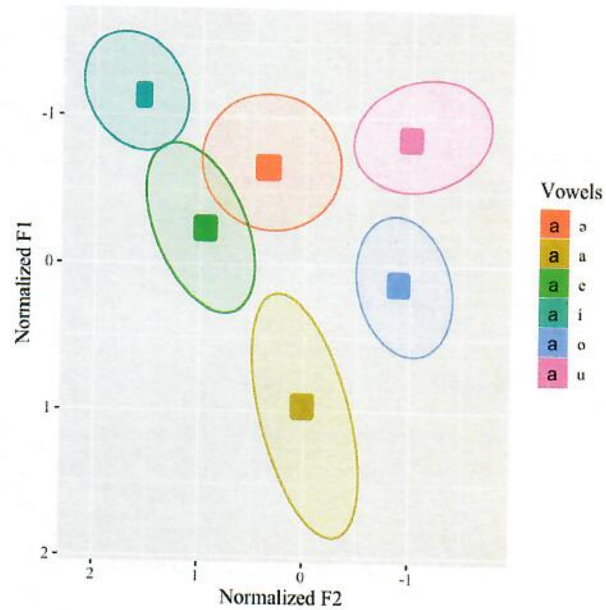

FIG. 2. (Color online) Speaker normalized Sora vowel plot showing six categorical vowels.

Regarding the mid central vowel in Sora, namely, schwa, the formant frequency measurements reveal certain new insights. A closer look at the vowel formants, particularly f_1 and f_2, shows that the mean f_1 frequency of schwa in Sora is lower than the mean f_1 frequency of the mid vowels /e/ and /o/ in Sora. Likewise, it is observed that the mean f_2 frequency of schwa in Sora is higher than the mean f_2 frequency of the low central vowel /a/ in Sora. These observations are visible in Fig. 2 where the ellipsis of schwa and the mid front vowel /e/ can be seen overlapping, and the mean of schwa is noticed to be higher than the means of both /e/ and /o/. These observations reveal that the mid central point is only an approximate vowel position for schwa /ə/ in the Sora vowel system and the schwa vowel is normally higher than the peripheral front and back mid vowels /e/ and /o/, and it is also fronter than the peripheral low central vowel /a/ in the Sora vowel system. Additionally, an important variability is observed in the Sora vowel formants when they are separated according to their syllable positions in disyllabic words. In order to demonstrate the variation, formant frequencies, separated by syllable position, are plotted on f_1 and f_2 axes. Figure 3 is a Sora vowel plot showing speaker normalized f_1 and f_2 frequencies in the first syllable, and Fig. 4 shows the same in the second syllable.

From Figs. 3 and 4 it is revealed that the formant frequency of Sora vowels changes as a function of syllable position. It is observed that there is more overlapping

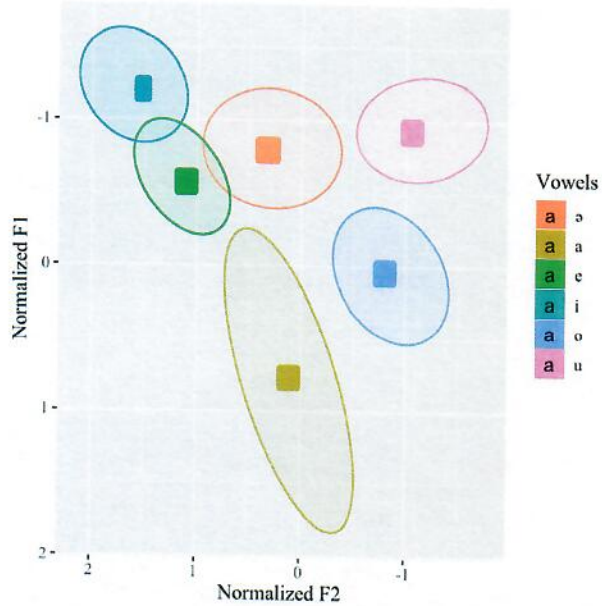

FIG. 3. (Color online) Vowel plot of speaker normalized Sora vowels in the first syllable.

between the vowel ellipses in the first syllable and lesser overlapping between the vowel ellipses in the second syllable. As a result, it is noticed that vowel distribution is reduced and centralized in the first syllable and expanded and peripheral in the second syllable. The difference is more clearly visible when the two vowel plots are merged together. This is illustrated in Fig. 5, where f_1 and f_2 of all Sora vowels in the first and second syllables are plotted on a single graph with International Phonetic Alphabet (IPA)

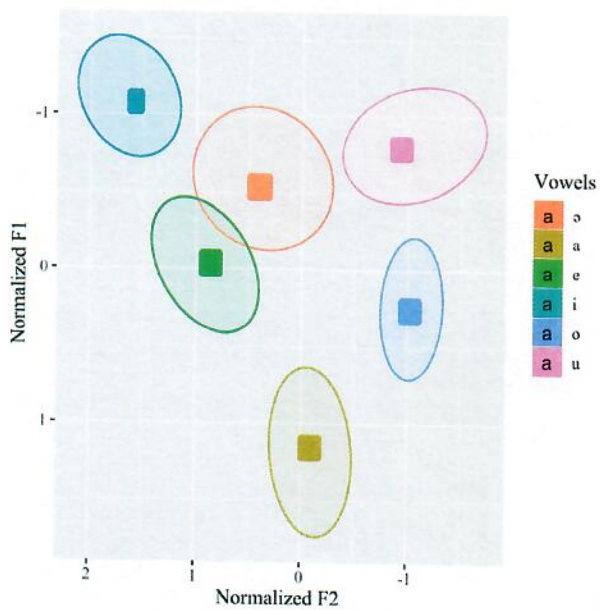

FIG. 4. (Color online) Vowel plot of speaker normalized Sora vowels in the second syllable.

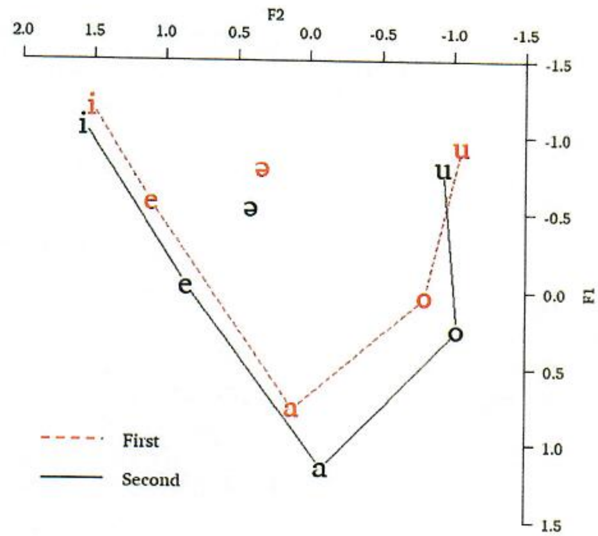

FIG. 5. (Color online) Vowel diagrams of speaker normalized Sora vowels in the first and second syllables.

characters representing mean f_1 and f_2 frequencies for each vowel phoneme in the Sora vowel system.

The vowel diagram in Fig. 5 represents speaker normalized averages f_1 and f_2 of Sora vowels in the first and second syllables. From Fig. 5 it is evident that syllable position causes the distribution of Sora vowels to be reduced or expanded. It is detectable that the distribution of Sora vowels is reduced in the first syllable and expanded in the second syllable.

Moreover, Fig. 5 reveals that the difference in the distribution of Sora vowels due to syllable position is also visible in terms of vowel dispersion. It is observed that vowel dispersion between Sora vowels is reduced or expanded depending of the position of the vowel in the first or second syllable of disyllables. To show the changes in vowel dispersion caused by syllable position, the ED is calculated between all Sora vowel pairs in the first and second syllables. Figure 6 is a graphical representation of the ED estimation between different Sora vowel pairs in the first and second syllables.

From Fig. 6 it is observed that the ED between Sora vowels is relatively different between the first and second syllables. For instance, it is observed that the ED between /i/ and /e/ is greater in the second syllable than in the first syllable. Likewise, the ED between /e/ and /a/ is greater in the first syllable than in the second syllable. Thus, the ED measurements provide evidence that vowel dispersion between Sora vowels is generally affected by syllable position. This consequently affects the acoustic space of the vowel system, whereby the vowel space appears to be smaller and centralized in the first syllable and larger and peripheral in the second syllable. This can be also seen in the vowel diagram presented in Fig. 5. In order to statistically estimate the relationship between speaker normalized f_1 and f_2 values and vowel types, we built a LME model with vowel type and syllable (whether first or second) as fixed effects. Speaker,

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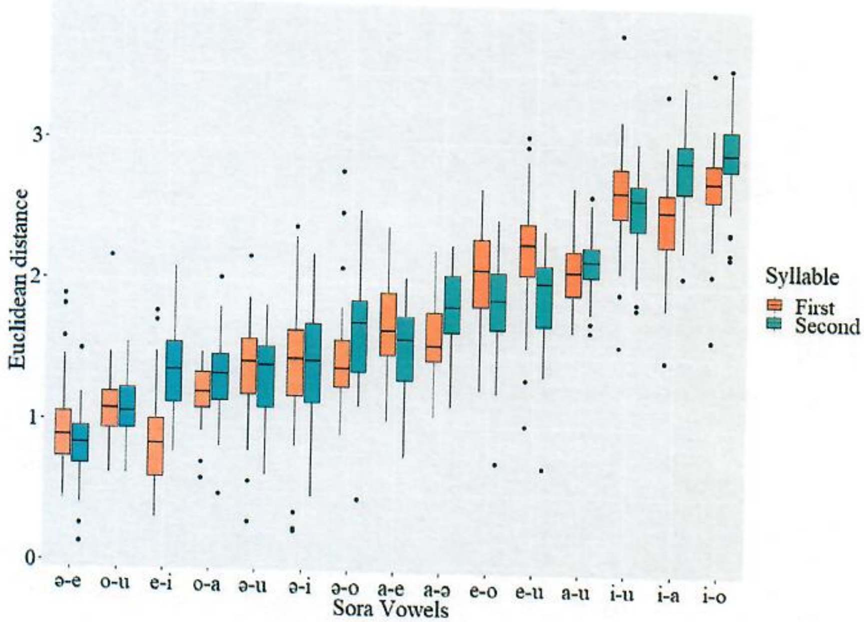

FIG. 6. (Color online) EDs between Sora vowels in the first and second syllables.

region of data collection (location), and gender were included as random effects. The model was built with the *lme4* package on *R*, and to attain the optimal model, a backward reduced model was obtained using the *step* function on the *lmerTest* package. Degrees of freedom were estimated with the Satterthwaite method, and α was set at 0.05 for both fixed and random effects. The reduced model generated retained vowel type and syllable number as fixed effects and speaker as a random effect for the first two formant frequencies. The results of the LME tests are presented in Sec. IV.

B. Duration, intensity, and f_0 of Sora vowels

In this section, we report the vowel duration, vowel intensity, and fundamental frequency for each vowel category in Sora. In previous work it has been claimed that the second syllable is always prominent in Sora disyllables, whereby the vowel nuclei in the second syllables are always longer, louder, and pitched higher than the first syllables (Horo, 2017; Horo and Sarmah, 2015). Therefore, in this section we report the measures for the six Sora vowels categorized by syllable location. Generally, open syllables are longer in duration than closed syllables. Hence, to avoid syllable type induced duration differences, we considered vowel duration only for the CVC syllables. Figure 7 presents the average vowel duration of Sora vowels with their standard errors categorized by syllable location, that is, by first and second syllables.

From Fig. 7 it is clear that the duration of all vowels in the first syllable is shorter than in the second syllable in Sora. Again, among all vowels, the schwa vowel is the shortest in duration, both in the initial and final syllables.

Vowel duration, as seen in Fig. 7, point toward a few interesting findings. First, vowel duration is not significant among vowel pairs in the first syllable. This indicates that vowel reduction, as also claimed in Horo (2017) and Horo and Sarmah (2015), reduces vowel specific durational characteristics and induces similar vowel durations for all vowels of about 70 ms. Second, although the /ə/ vowel seems shorter than the other vowels in the first syllable, the variation of duration in that particular vowel is very high, as indicated by the larger standard error bar for /ə/ in Fig. 7. It probably contributes to making the duration of /ə/ statistically nonsignificant in *post hoc* multiple comparisons. Third, it is also noteworthy that there is no significant

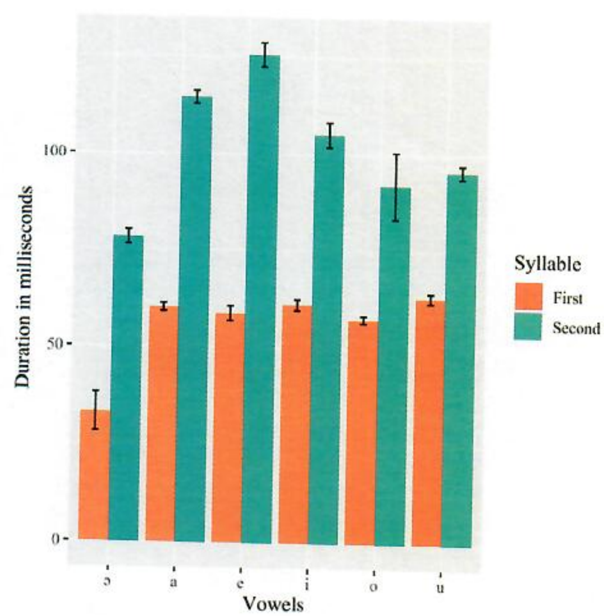

FIG. 7. (Color online) Average duration of Sora vowels in the first and second syllables.

difference between the duration of vowels produced in the isolation and vowels produced in the sentence frame in the first syllables. These observations indicate that in the first syllables, Sora vowels attain phonetically induced vowel durations that supersede vowel inherent and context induced durational differences. At the same time, the /ə/ vowel has a considerable amount of variation in the first syllable.

In order to see the relationship between vowel duration and vowel type, we built a LME model with vowel type, syllable, and context (isolation or sentence embedded) as fixed effects and speaker, region of data collection (location), and gender as random effects. The model was built with the *lme4* package on *R*, and a backward reduced model was obtained using the step function on *lmerTest* package. Degrees of freedom were estimated with the Satterthwaite method, and α was set at 0.05 for both fixed and random effects. The reduced model retained vowel type, context, and syllable number as fixed effects and speaker and location as random effects. Apart from this, two separate LME models were built for the first and second syllables to see the pairwise variability of duration of vowels. The results of the LME tests are presented in Sec. IV.

Intensity is an indicator of syllable prominence. Prominent syllables have higher intensity than non-prominent syllables. This indicates that there is more acoustic energy in prominent syllables than in non-prominent syllables. As seen in Fig. 8, we compared the average intensity of each vowel separately in the first and second syllables. Figure 8 provides the average intensity of each vowel along with its standard error. A visual examination clearly indicates that the intensity of the vowels in the initial syllables is systematically lower than the second syllables.

In order to see the interaction between vowel type and intensity more closely, we built a full LME model with vowel type and syllable number as fixed factors and speaker, context, location, and gender as random factors. The model built was subjected to a backward reduction of fixed factors using the *lmerTest* package, which dropped gender from the random factors. The LME test is discussed later in Sec. IV.

Fundamental frequency (f_0) is positively correlated with vowel height. This positive correlation of vowel height and f_0 is termed intrinsic f_0 (If_0). According to Lieberman, If_0 is correlated to the shape of the vocal tract during vowel production (Lieberman, 1974). It has also been claimed that If_0 variation can be deliberate, aimed at improving auditory salience, and If_0 is used as an additional cue in vowel perception (Diehl and Kluender, 1989). Thus, evidence suggests that languages having a large vowel inventory may use If_0 as an additional feature to saliently perceive vowel categories. In this regard, while Whalen and Levitt (1995) did not see any correlation between vowel inventory size and If_0, Van Hoof and Verhoeven (2011) reported a strong correlation between the two. Hence, in this work, we decided to investigate the vowel specific f_0 values in Sora. Again, considering the difference in vowel realization in the first and second syllables, the results are presented and categorized into syllable location. As mentioned earlier, the f_0 values are normalized for speaker variation as f_0 is known to be highly influenced by speaker variation. Fundamental frequency obtained at the vowel mid position for all Sora vowels is presented in Fig. 9. As noticed in Fig. 9, vowel height and f_0 seem to be highly correlated. Again, the distinction between vowels, in terms of f_0, is noticeable more in the second syllables than in the first syllables. Interestingly, the /ə/

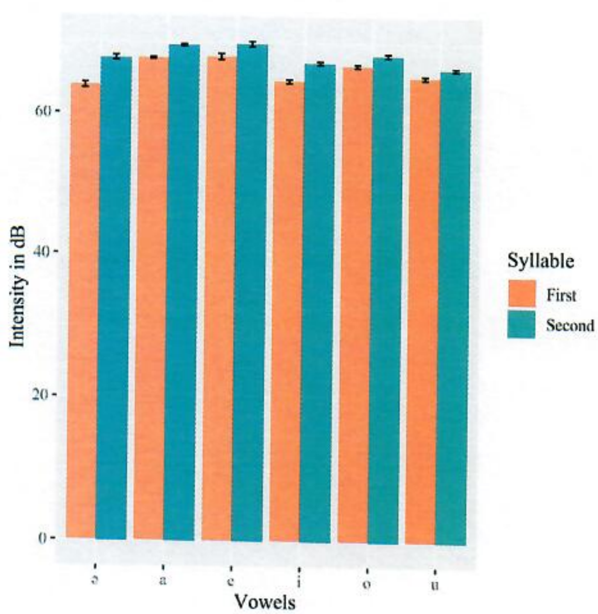

FIG. 8. (Color online) Average intensity of Sora vowels in the first and second syllables.

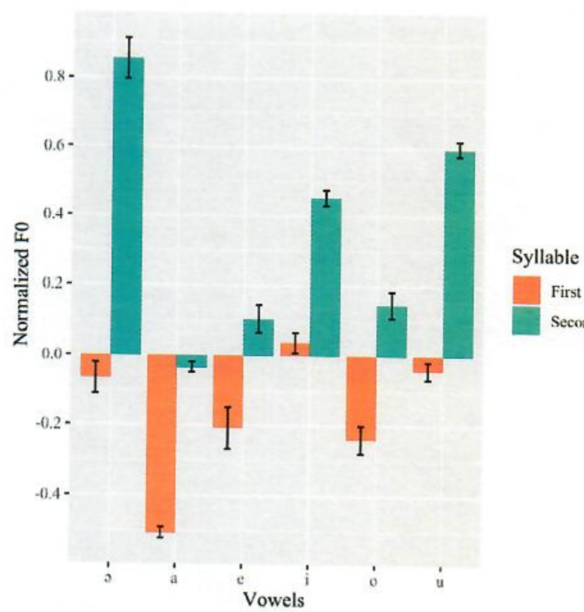

FIG. 9. (Color online) Normalized average fundamental frequencies of Sora vowels in the first and second syllables.

vowel has higher f_0 values than other vowels in the second syllable.

IV. RESULTS OF STATISTICAL ANALYSES

In order to see the robustness of acoustic features in the salient classification of vowels, we adopted two statistical methodologies. First, we used the QDA method to determine the features that contribute to the robust classification of vowel classes in Sora. Second, to see the effects of various factors on spectral and temporal features, we conducted a series of mixed effects and one-way ANOVA tests.

A. QDA and vowel classification

We attempted the classification of the vowels in Sora using QDA, where f_1 values in the mid 20%, f_2 values in the mid 20%, total vowel duration, average intensity, and mean fundamental frequency are used as vectors. QDA classification of vowels was performed on each syllable separately as seen in Table I.

The results in Table I indicate several important aspects of vowel classification in Sora. First, it is noticed that vowel classification is always better in the second syllable than in the first syllable. Second, the addition of extra-spectral features, such as intensity, duration, and mean f_0 significantly improves vowel classification in Sora. The addition of the DCT coefficients, C0, C1, and C2, significantly improves the classification accuracy. Table II presents the classification of individual vowels with the model with the best overall accuracy [model (k) in Table I]. As seen in Table II, the /ə/ vowel has the worst accuracy among all the vowels. Moreover, the classification of the /ə/ vowel is worse in the initial syllable, and it improves substantially in the second syllable.

The results of the QDA classification confirm that the vowel classification is poor in the first syllable. This may be due to the vowels failing to reach their targets in the initial syllable as they are not prominent in Sora, as discussed in Horo (2017) and Horo and Sarmah (2015). Among all vowels, the vowel /ə/ has the lowest accuracy in classification, both in the first and second syllables. The classification accuracy of the /ə/ vowel is particularly low in the first syllable. However, in spite of the overlap with the /e/ vowel, in QDA classification, the highest confusion of /ə/ is with the /u/ vowel (about 14.1% of the time). The observations in the QDA classification indicate that apart from f_1 and f_2 values, duration, relative f_0, and intensity may provide cues in the identification of the vowels in Sora.

TABLE I. Percentage of correct classification of vowels using f_1, f_2, duration, intensity, and fundamental frequency separated by the first and second syllables (Int, intensity; Dur, duration; f_0, fundamental frequency).

	Features	First syllable	Second syllable
(a)	f_1	44.6	49.9
(b)	f_2	48.6	52.8
(c)	f_1+f_2	71.3	79.1
(d)	f_1+f_2+ Int	72.3	79.5
(e)	f_1+f_2+ Dur	74.8	81.3
(f)	$f_1+f_2+f_0$	71.3	79.9
(g)	f_1+f_2+ Dur + Int	75.3	82.4
(h)	f_1+f_2+ Int $+f_0$	71.9	80.0
(i)	$f_1+f_2+f_0+$ Dur	75.3	82.3
(j)	f_1+f_2+ Dur + Int $+f_0$	76.0	83.4
(k)	f_1+f_2+ Dur + Int $+f_0$ + C0 + C1 + C2	83.3	88.2

TABLE II. Percentage of correct classification of individual vowels, separated by the first and second syllables.

Vowels	First syllable	Second syllable
a	91.2	96.7
e	75.0	85.4
i	89.4	95.1
o	87.4	91.9
u	87.6	85.5
ə	68.9	74.6

B. Exploratory statistical analyses

In order to see the effect of various factors on the acoustic features of Sora vowels, we conducted a series of LME tests on the collected data. The results of the LME tests are provided in Table III, where the null models with sets of variables dropped were compared to the full models using one-way ANOVA tests with p-values and Chi-square (χ^2) reported.

The LME tests were conducted on the two formants in Sora with the optimal model as mentioned in Sec. III A and compared to null models. For formant frequencies, f_1 and f_2, two null models were constructed separately and compared to the full model with vowel type and syllable number (i.e., whether the vowel appeared in the first or the second syllable) as fixed effects and speaker as a random effect. For both f_1 and f_2, one null model was constructed without the syllable number and another one without the vowel type as a fixed effect. When compared to the full model by means of an ANOVA test, all four null models were significantly

TABLE III. Comparison of full and null models with ANOVA.

	Feature	Variable(s)	χ^2	p-value
(a)	f_1	Syllable number	20 991	<0.001
(b)	f_1	Vowel	1101.7	<0.001
(c)	f_2	Syllable number	20 232	<0.001
(d)	f_2	Vowel	108.6	<0.001
(e)	Duration	Vowel	1729.9	<0.001
(f)	Duration	Syllable number	485.59	<0.001
(g)	Duration	Context	1985.4	<0.001
(h)	Duration	Syllable number + context	401.85	<0.001
(i)	Duration	Vowel + context	1653.2	<0.001
(j)	Duration	Vowel + Syllable number	91.58	<0.001
(k)	Intensity	Syllable	2193.8	<0.001
(l)	Intensity	Vowel	1292.1	<0.001
(m)	f_0	Vowel	985.29	<0.001
(n)	f_0	Syllable	988.49	<0.001

different from the full model, indicating a significant effect of the fixed factors on f_1 and f_2 as seen from rows (a)–(d) in Table III. However, when the Chi-square values are compared for both f_1 and f_2, the Chi-square values show that the models with a vowel as a fixed factor fit better with the full model than the models with the syllable number as the fixed factor. This confirms that the addition of vowel type as a factor can explain f_1 and f_2 variation better than other factors.

For duration, we decided to consider the duration of vowels only in CVC syllables in both the first and second syllables, as it is well known that syllable type has a predictable effect on vowel duration. As mentioned earlier, the full LME model was built with vowel type, context and syllable number are considered fixed effects, and speaker and location are considered random effects. The full models were compared with null models with all possible combinations of fixed factors, as seen in rows (e)–(j) of Table III. All comparisons of full models with null models showed significant differences. However, the Chi-square values showed that the model with vowel type and syllable number is best able to explain the variation of duration.

Apart from that, the LME models built for each syllable were subjected to a type II Wald Chi-square test that yielded significant effects of vowel and context on the duration in both the first and second syllables. The results of the Chi-square tests are summarized in Table IV. To assess the pairwise variability between the vowel pairs, the models were also subjected to *post hoc* Bonferroni tests. In the case of the first syllable, vowel pairs /ə/-/u/ and /o/-/u/ were significantly different in terms of duration. However, in the second syllable all vowel pairs, except /a/-/i/, /a/-/o/, /i/-/o/, /u/-/o/, were significantly different from each other in terms of duration.

The full model for intensity had vowel type and syllable number as fixed effects and location, speaker, and context as random effects. Null models, as seen in rows (k)–(l) of Table III, show that both vowel type and syllable number have a significant effect on the intensity of the vowels. The low Chi-square value in comparing the full model with the model with vowel type as a fixed factor confirmed that the latter model is better capable of explaining the intensity variation. We also compared the null model with syllable number and the null model with vowel type as the fixed factor. The two models were significantly different from each other [$\chi^2(4) = 901.75, p < 0.001$].

In order to see the syllable-wise effect of vowel type on intensity, we constructed LME models for each syllable separately. The models built for each syllable were then subjected to type II Wald Chi-square tests as summarized in Table V. The results show a significant effect of vowel type on intensity. *Post hoc* Boneffoni tests conducted on the models showed that /a/-/e/, /e/-/o/, and /i/-/u/ vowel pairs are not significantly different in terms of intensity in both syllables. Other than that, /ə/-/u/ and /a/-/o/ vowels are not different in terms of intensity in the first syllable.

Finally, we also conducted a LME test on the speaker normalized mean f_0 associated with vowel types in Sora. As mentioned in Sec. II, we constructed a full model with vowel type and syllable number as fixed effects and location and speaker as random effects. Null models created with only vowel type as the fixed effect were significantly different from the full model as was the null model with syllable number as fixed effects. This confirmed that both vowel type and syllable number had a significant effect on the f_0. From the Chi-square values, it seemed that the model with syllable number can explain the variation in f_0 better than the model with vowel type as the fixed effect. However, an ANOVA conducted to compare the two models did not yield any significant difference [χ^2 (4) $= 3.2, p = 0.5$], allowing us to conclude that both syllable number and vowel type are responsible for the variation in the fundamental frequency.

We also explored the effect of vowel type on f_0 by constructing LME models for both first and second syllables. As seen in Table V, type II Wald Chi-square tests showed significant effects of vowel type on f_0. A *post hoc* Bonferroni test conducted on the models showed that in both syllables /e/-/o/ vowels do not differ in terms of f_0. Other than that, in the first syllable, the f_0 of /ə/ is not significantly different from the f_0's of /e/, /i/, and /u/. In the first syllable, the /u/-/i/ pair also does not differ in terms of f_0. In the second syllable, except for the /e/-/o/ pair, all vowel pairs differ significantly in terms of f_0.

The results of the LME tests reported in this section confirm that vowel type has significant effects on the first two formants in Sora, which is as expected. However, we have also confirmed from the statistical analyses that other features, namely, duration, intensity, and f_0, also vary significantly with the change in vowel type. This conclusion is consistent with our previous observation in Sec. IV A, where we have noticed that apart from formant frequency other features also aid vowel classification. Next, the statistical results also confirmed the significant role of the syllable number, which is whether the vowel is in the first or the second syllable, in determining the acoustic features. All features showed a significant effect of the syllable number, indicating salience of vowel realization in the two syllables of Sora.

TABLE IV. Results of the type II Wald Chi-square test on LME models constructed for vowel duration.

	First syllable	Second syllable
Vowel	$\chi^2(5) = 27.4, p < 0.001$	$\chi^2(5) = 541.8, p < 0.001$
Context	$\chi^2(1) = 4.9, p < 0.05$	$\chi^2(1) = 118.0, p < 0.001$

TABLE V. Results of the type II Wald Chi-square test on LME models constructed for intensity and f_0.

Variable	First syllable	Second syllable
Intensity	$\chi^2(5) = 1176.9, p < 0.001$	$\chi^2(5) = 1436.2, p < 0.001$
f_0	$\chi^2(5) = 365.3, p < 0.001$	$\chi^2(5) = 902.4, p < 0.001$

V. DISCUSSION AND CONCLUSION

A. General discussion about Sora vowels

The results of acoustic and statistical analyses in this work confirmed that Sora has six distinct vowels, of which five are peripheral vowels /i, e, a, o, u/ and one, /ə/, is a mid central vowel. This pattern is uniform across all five geographic locations reported in this work. While four of these locations are within the same province and within 300 km of each other, Sora in Odisha as spoken in the Raiguda village is approximately 2000 km away from the other four areas. Despite the distance, vowel characteristics of the five areas did not significantly differ from each other. The six vowel system confirmed in this work follows the general Munda vowel inventory system as reported in Jenny *et al.* (2014). Hence, the findings of this study also disprove earlier claims about larger numbers of vowels in Sora, such as Donegan (1993) and Donegan and Stampe (2002). It should also be noted that, while not implausible, a large vowel system with more than six vowels is a typological rarity. Maddieson (2013), for example, shows that about 51.2% of world's languages have either a five or a six vowel system.

Sora is minimally disyllabic, and it has been noted that the initial syllables have less prominence than the final syllables (Horo, 2017; Horo and Sarmah, 2015). Considering that, we have conducted acoustic analysis on the vowels in the initial and final syllables of disyllabic words separately. The results of the current study confirm that the f_1 and f_2 locations for the vowels are salient as seen in Figs. 3 and 4. Figures 3 and 4 also confirm that the salience of the vowels in the vowel space is dependent on the syllable number, that is, whether the vowel is in the first or the second syllable. Individual vowel distributions show more overlaps in the first syllable than in the second syllable. Vowel duration did not differ among the vowels in the first syllable except for the /u/-/o/ pair. However, in the second syllable, all vowels were significantly different from each other except for the /o/-/i/, /u/-/o/, and /ə/-/o/ pairs. Intensity also differs significantly according to vowel type; however, significant vowel type and syllable number interaction was also noticed, confirming that intensity of vowels differed depending on whether they occurred in the initial or the final syllable. As far as f_0 is concerned, it was considerably different for each vowel. Again, significant vowel type and syllable number interaction confirmed that such differences were dependent on whether the vowel is in the first or the second syllable. Thus, it can be implied that apart from f_1 and f_2 values, duration, intensity, and f_0 may also have salience in terms of vowel type. In fact, this implication is further supported by the QDA results reported in Sec. IV A, where it is shown that automatic vowel categorization fares the best when, apart from f_1 and f_2, duration, intensity, and f_0 information are also included. This section also shows that DCT features that capture the long term characteristics of formants also significantly enhance vowel type categorization.

While it is conclusively proven in this work that Sora has a six vowel system, the characteristics of the sixth vowel /ə/ require more discussion as the variability of the sixth vowel has resulted in a multitude of descriptions of the vowel in the Munda languages. Apart from that, the Tibeto-Burman languages spoken in North-East India have also shown similar variability, prompting some to assume this variation to be an areal feature. Section V B provides a discussion on the variability of the sixth vowel /ə/ in Sora. Also, the discussion on Sora vowels has revealed vowel quality differences in the initial and second syllables of Sora disyllabic words. This prompted us to discuss prominence and vowel quality in Sora, in Sec. V C.

B. Status of the mid central vowel in Sora

The existence of the mid central schwa /ə/ vowel in Sora and other languages of the Austroasiatic language family is significant. Previous studies have reported that while non-Munda AA languages have larger vowel systems, languages in the Munda branch mostly have five vowels. However, previous reports of the Sora vowel inventory and the field accounts of G.D.S.A. have confirmed the existence of a sixth vowel in other Munda languages (see Table VI).

Table VI shows that /ə/ is relatively rare in Munda languages. The sixth vowel appears only in Sora, Santali, and possibly in Gtaʔ as well. Nevertheless, it has to be noted that all other descriptions of vowels in Munda languages are largely impressionistic and, hence, may not be able to demonstrate the existence of the sixth vowel in the other Munda languages.

However, in the case of Sora, we are confident that the sixth vowel is categorically distinct from the five peripheral vowels. Also, compared to the central /a/ vowel, the /ə/ vowel in Sora is slightly front. Also, compared to the mid vowels /e/ and /o/, /ə/ is slightly lower in f_1 values. Just as with the other five vowels, the /ə/ in Sora is distinct in terms of duration, intensity, and f_0. As with the other vowels, the quality of the /ə/ changes from the first syllable to the second syllable.

Previously, it was claimed in Donegan (2009) that the sixth vowel in Sora has restricted distribution, and such vowels in the Munda languages are phonetically reduced.

TABLE VI. Vowel system of different Munda languages. (Revised Munda vowel system from the one reported in Anderson, 2014, by GDSA.)

Santali	a	i	u	o	e	ɛ	ɔ	ə
Mundari	a	i	u	o	e			
Keraʔ	a	i	u	o	e			
Ho	a	i	u	o	e			
Korku	a	i	u	o	e			
Juang	a	i	u	o	e		ɔ	
Kharia	a	i	u	o	e			
Sora	a	i	u	o	e			ə
Gorum	a	i	u	o	e			
Remo	a	i	u	o	e			
Gutob	a	i	u	o	e			
Gtaʔ	a	i	u	o	e	ɛ/æ/ə[a]		

[a]Variability of the sixth vowel.

However, from this discussion, it is evident that the /ə/ vowel in Sora is a categorically distinct vowel and behaves like any of the other five vowels in Sora. The /ə/ vowel occurs in both the first and second syllables of disyllabic words in Sora and attracts prominence when it occurs in the second syllables.

C. Prominence and vowels in Sora

The minimal word template in Sora is disyllabic, and it has been argued that word stress in the language is iambic, leading to prominence on the second syllable when compared to the first syllable. This has also been reported previously in Horo and Sarmah (2015) and Horo (2017). The current work shows that the variation of prominence has some significant effects on the vowels in the two syllables of the disyllabic words in Sora. As seen in Sec. III A, the vowel formants in the first syllable tend to overlap with each other more than in the second syllable. It is also noticed that the vowel space in the first syllable is reduced. When checked for durational differences, it was noticed that the vowels in the first syllable are significantly shorter than the vowels in the second syllable. It is also noteworthy that the durational difference among vowels is significantly minimized in the first syllable. Similarly, in terms of f_0 and intensity too, it is noticed that the first syllables have lower intensities and f_0 values than the second syllables. The lack of prominence in the first syllable has also resulted in reduced salience among vowels in the initial syllable. This is apparent from the QDA classification results reported in Table I, where vowel classification is significantly poor in the first syllable when compared to the second syllable. Vowel formants show reduction of the vowel space and centralization of vowels in the first syllable. On the other hand, the second syllables have an expanded vowel space and salience among peripheral vowels. Vowel quality in the non-prominent syllable is expected to be relatively more stable than in the prominent syllable.

The results of vowel quality in the disyllables of Sora confirm the existence of an iambic stress pattern in the language. The results showed that prominence and also the lack of it has significant effects on the vowels. The difference of prominence is not only manifested in the formant properties of the vowels but also in phonetic features such as vowel duration, vowel intensity, and fundamental frequency. The effect of prominence is observed to be equal in all vowels in Sora. Table II shows that the classification of all vowels improves significantly in the second syllable, indicating a decrease in the salience of phonetic features of vowel phonemes in the first syllable.

D. Conclusion

This work confirmed the existence of six vowels in Sora, namely /i, u, e, ə, o, a/. The six vowels, including the /ə/ are phonologically salient. This study also confirms the difference of prominence in the two syllables of a disyllabic word in Sora. The first syllables are unstressed, resulting in the lack of prominence. Vowel salience is reduced in the first syllable due to the lack of prominence in the syllable. The results of the study also contribute to the body of literature on the Munda languages by confirming that Sora has a six vowel system with a fully realized /ə/, different than what has been claimed in several previous works. Similarly, the study also confirms the existence of an iambic word stress pattern for Sora. This finding is also unlike what was claimed in the previous literature. While this work contributes to science through debunking some previous notions about Sora and Munda languages in general, we hope other studies like this will be taken up and arrive at a definitive conclusion about the family resemblance in terms of vowel inventory and stress patterns in the Munda branch of the Austroasiatic language family.

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