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Akshara-to-sound rules for Hindi

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The present paper brings to focus the main issues of regularity and inconsistency in orthography-phonology relation in Hindi arising out of an attempt at developing a program of Akshara-to-Sound rules for a pronunciation lexicon of Hindi for use in language technology for voice browser applications. The program of rules is based on interdisciplinary insights from research on writing systems, phonology and rule writing for a computer program. The paper first discusses the motivations for the Akshara-to-Sound rule set formulated to generate two levels of output—one of phoneme level and the other of phonemes and the prosodic structures of words in terms of strong and weak syllables. The irregularities in the correspondence between the Akshara and the sound are taken up next for an account. The paper ends with a discussion of the implications of the study for research on the acquisition and processing of written words in Hindi.

Keywords: Akshara-to-sound rules/ Grapheme-to-phoneme rules; Pronunciation lexicon; Devnagari script; Syllable; Prosodic structure.

My aim in the present paper is to give an account of the main factors bearing on the orthography-phonology relation in Hindi that have come to the fore in developing a program of Akshara-to-Sound rules for a pronunciation lexicon of Hindi for voice browser applications. The program was based on an interdisciplinary approach involving linguistic analysis and a computer program for language technology application. The paper has been written with the assumption that for a successful program for deriving outputs of pronounced forms in the akshara system of Devnagari for Hindi, the considerations of predicting regularities and of filtering inconsistencies in the orthography-phonology relation should be relevant for cognitive linguistic studies on orthography-phonology relation in Hindi. It is hoped that the result of the investigation reported here will complement the insights gained from cognitive-linguistic studies.

In what follows, the factors involved in the orthographic system of Hindi are taken up for elaboration before the presentation of a detailed account of the Akshara-to-Sound rules for Hindi and its use in the pronunciation lexicon of Hindi. Cases of inconsistency in correspondence between the written word and its pronunciation that are a problem for the Akshara-to-Sound rules are taken up next. These cases are expected to be a problem for acquisition as well as processing of reading of Devnagari orthography for Hindi. The paper ends with a brief discussion of the implications of the study for the acquisition and processing of Hindi orthography.

PRONUNCIATION LEXICON OF HINDI

As the issues of orthography-phonology presented below have come up in the context of developing a program for a pronunciation lexicon for Hindi, a brief introduction to pronunciation lexicons is presented in this section in order to make clear the rationale for the compulsion to distinguish between predictable regularities and recalcitrant inconsistencies that have yet to be incorporated in a program for deriving the pronunciations of words in Hindi.

Pronunciation Lexicons have come to be recognised as of critical importance in the development of speech technology for a language. They represent the interface between the interpretation and analysis of speech. In text-to-speech (TTS) synthesis, for example, phonemic transcriptions of the pronunciations of words help determine the selection of the acoustic models for generating the targeted waveform. In automatic speech recognition (ASR), too, the search module relies on transcribed forms to select appropriate acoustic models for the input utterance. For use of pronunciation lexicons in speech synthesis and automatic speech recognition engines in voice browser applications, Akshara-to-Sound rules thus play a central role.

Standard pronunciation of Hindi can be found in some dictionaries, for example, in the Oxford Hindi-English Dictionary (1993, edited by R. S. McGregor). The latter contains phonemic pronunciations of words and their Part-of-Speech (POS) tagging. However, none of the dictionaries take the issues that are of special importance in a Pronunciation Lexicon of the kind that the World Wide Consortium (W3C) is concerned with (see: http://www.w3.org/TR/pronunciation-lexicon/).

In a joint project on Pronunciation Lexicon Standards for Hindi and Bangla, being carried out at the Department of Linguistics, Jawaharlal Nehru University and the Department of Educational Technology, Indian Institute of Technology Kharagpur, respectively, the pronunciation lexicons have been prepared to include some additional features in conformity with the W3C requirements. The features included for the pronunciation lexicon of Hindi are the following:

(1)

    i.   Akshara-to-Sound conversion using IPA.
   ii.   Marking of syllable structures and labelling them as prominent and non-prominent for further TTS and ASR applications.
  iii.   Specifying variant pronunciations of words in terms of formal and informal speech varieties of standard Hindi.
  iv.   The surface pronunciations of words with stress marks.

Among the main features, it is the introduction of the level of Prosodic Structure that is the main contribution of the work being reported here. To illustrate the point, look at the IPA representations of the words सितार meaning 'sitar' and बालिका meaning 'girl' in (2):

(2)

    (i) सितार
        (a) /si'taːr/
        (b) si$\sigma_w$taːr$\sigma_{\acute{s}<\text{/PS}>}$[1]
    (ii) बालिका
        (a) /'baːlikaː/
        (b) baː$\sigma_s$li$\sigma_w$kaː$\sigma_{w<\text{/PS}>}$

The representations in (a) are phonemic using IPA symbols and those in (b) additionally give the prosodic structures (labelled as </PS>) of the words in terms of syllable division and prominence. The relation between them is explained in the section on prosodic structure-based rules below. The Akshara-to-Sound rules for Hindi derive the representations in (a) from the representations in (b). The latter spell out the prominence of syllables in terms of being strong (σ_s or $\sigma_{\acute{s}}$) or weak (σ_w). The strong syllable (σ_s or $\sigma_{\acute{s}}$) is the one that is stressed. The difference between the strong syllables σ_s or $\sigma_{\acute{s}}$ is explained in the section on 'Foot construction rules implemented as syllable labelling rules' before Rule [9] below. In a word with two strong syllables, there are two stressed syllables.

The term 'Akshara-to-Sound rules' is being used here in place of a more general term 'Letter-to Sound rules' or 'Grapheme-to-Phoneme rules' or 'Grapheme-to-Phoneme Conversion' for its suitability for the writing system of which Devnāgarī is a prominent example. The term 'letter' applies better to alphabetic systems like English and French, but not to an 'alphasyllabic' system like Devnagari, as explained in the section on Devnagari orthography below. Besides, the term 'phoneme' is not entirely correct for the level of speech sounds in Hindi to which the orthography relates; it is sometimes allophonic as well, as pointed out in Pandey (2007). In order to make specific the 'alphasyllabic' character of the orthography and its relation to both the phonemic and phonetic levels that the term 'Akshara-to-Sound' is found to be more suitable. The work on other languages, however, uses either of the two general terms, which we use in the remainder of this section.

Letter-to-Sound rules must be distinguished from transliteration rules, which give a one-to-one correspondence between orthographic forms and their representations in a phonetic orthography (e.g., Ali & Ijaz, 2009). Letter-to-Sound rules, being part of a Text-to-Speech and/or an Automatic Speech Recognition system can be more detailed especially within the pronunciation standards of W3C, as discussed above. A program of Letter-to-Sound rules for a pronunciation lexicon not only gives corresponding phonemic representations in IPA, but also can optionally specify the prosodic properties of a word relevant for TTS and ASR systems. Letter-to-Sound rules are one of the text processing components of TTS and ASR systems.

A general introduction to letter-to-Sound rules can be found in Klatt and Shipman (1982), Mannell and Clark (1987), Black, Lenzo, and Pagel (1998), Chen (2003) and Lewis, McGrath, and Reupeel (2004), among others. The first of these preceded the emergence of the theory of prosodic phonology (e.g., Nespor & Vogel, 1986; Selkirk, 1984), which provides a detailed framework for the investigation of prosodic properties of

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[1]The slash in </PS> has the function of indicating closure of the element <PS> in the document, following a general convention.

units starting at the word level, and which seems to have been a motivating force in the design of pronunciation lexicon specifications of World Wide Consortium.

Although, Letter-to-Sound rules are expected to encompass many prosodic features such as syllable division, stress foot structure, tone, etc., not many studies of prosodic phenomena in pronunciation lexicons are found in the literature. Church (1985) is an attempt at formulating rules for word-stress in English speech synthesis. Kishore, Kumar, and Sangal (2002) propose using the syllable for text-processing in a TTS system for Indian languages.

Hussain (2004) presents Letter-to-Sound rules for Urdu. The study is confined to the segmental level and ignores the inclusion of prosodic features such as syllable division and stress.

For Hindi, there exists at least two studies that make an attempt at handling one of the major issues in Letter-to-Sound rules, namely word-internal schwa deletion—Narasimhan, Sproat, and Kiraz (2001) and Choudhary and Basu (2002). The latter presents a comprehensive discussion of schwa deleted forms in Hindi. The rules of Hindi schwa deletion in it, however, are rather complex, because they are limited to segmental sequences for specifying contexts. It will be shown here how it has been possible to formulate a much simpler account of schwa deletion, with the rule being based on foot structure, proposed in Pandey (1989).

Within the fields of reading acquisition and developmental dyslexia, the term Grapheme to Phoneme Conversion (GPC) is often used (see, for example, Gupta, 2004; Wimmer, 1996), albeit systematic accounts of the rules of GPC are hard to find. The discussion of such conversion rules for Hindi presented below thus pertains to an important area of research in these fields as well.

DEVNĀGARĪ SCRIPT

Hindi is written mainly in the Devnāgarī orthography. The orthography is known to incorporate both phonetic and phonological awareness of the language (see, e.g., Agrawala, 1966; Bright, 1996; McGregor, 1977; Pandey, 2007; Sproat, 2000). It differs from an orthography such as Arabic, which depends on both phonological and lexical awareness (so that reading in Arabic presupposes knowledge of lexical items, especially in the case of words with the short vowels /ə ɪ ʊ/). Both the orthographies differ from English, in which morphophonemic and lexical morphological awareness are also important. Recent studies on orthographic processing in Hindi show that it, too, makes use of lexical morphology (Rao, Soni, & Singh, 2012). We corroborate this position with additional levels of awareness found necessary in implementing the Akshara-to-Sound rules for Hindi.

Devnāgarī also belongs to a class of writing systems known as alpha-syllabic, that is, a combination of alphabetic and syllabic systems. Writing systems are *alphabetic*, if their units stand for vowels and consonants (e.g., English, German). They are *syllabic*, if each orthographic unit in them represents a syllable (e.g., *Hankul* for Korean). As is well known, there are also other forms of writing systems, such as *logographic*, in which the orthographic unit is a character, which represents a lexical unit (e.g., *Kanji* for Chinese). Some languages use multiple orthography types, for example, Korean, which uses both *Kanji*, a logographic script, and *Hankul*, a syllabic script, and Japanese, which uses *Kanji*, and the syllabic scripts known as *Hiragana, Katakan* and *Siddham* (by Japanese Shingon Buddhists). There has been considerable interest in the recent years in the universal properties of writing systems (e.g., Dehaene, 2009) and phonological principles of reading (e.g., Perfetti, Zhang, & Berent, 1992).

The alpha-syllabic orthography of Devnāgarī is derived from Brāhmī, along with many other scripts used for Dravidian, Indo-Aryan and Munda languages, among others. It is used for many languages within India, such as Marathi, Konkani, Rajasthani and Nepali, as well as outside India, such as Cham (Comboida & Vietnam), Dehong Dai (Southwest China), Akshara Carakan (Javanese), Lontara (for Bugis, Makassarese, Mandar languages of Indonesia), Ranjana (Newari, Nepal), Thai and Tibetan, among others.

Alpha-syllabic scripts, of which Devnāgarī is an instance, have also come to be known as akshara systems, and are being studied intensively today, especially in the fields of neuro-cognitive processing of writing systems (see, e.g., Patel, 1995, 2007; Padakannaya, Vaid, & Gupta, 2002; Sproat, 2000; Nag, 2011; Padakannaya, in press; Sircar & Nag, in press)

The main features of an alpha-syllabic orthography as a writing system are the following[2].

(3)

i. The consonant akshara has an inherent vowel, which is the mid central vowel /ə/.

ii. The absence of an inherent vowel is indicated with a subscript diacritic known as *halanta* (◌्). Without the *halanta*, the consonant akshara can take vowel other than the inerent vowel by adding a diacritic known as *mātrā* (mora), as shown in Table 3. In such a case the inherent vowel is assumed to give way to the other vowel. For example, the consonant letter <क> without a diacritic stands for [kə], and with a diacritic, as in <का>, <की>, <को>, the akshara stands for [ka:], [ki:], [ko:], respectively.

iii. When not preceded by a consonant or when preceded by another vowel, a vowel occurs alone with a full syllabic and vocalic value, e.g., आई /a: i:/ 'came'.

iv. Two or three consonant clusters form ligatures, with one of the consonants (usually the last, except when it is /r/) occurring full but the others occurring half. For example, the consonant akshara for the sounds [t s p l k ṣ] appear as <त स प ल>. In clusters, they appear half as the first member, as in त्स /ts/, स्प्ल /spl/, ल्प /lp/). Occasionally they form a new akshara, e.g., क्ष (from क्+ ष) /k+ṣ/, as shown in Table 1.

In addition to the above consonant Aksharas, the orthography as used for Hindi has the following Aksharas without a unique segmental description: ऋ[3], pronounced /ri/, and ॐ pronounced /om/, also alternatively written as ओम्.

The list of vowel Aksharas in isolation as well as with their diacritic representations with consonants is given in Table 2 and Table 3.

Note that while all the vowel diacritics are added below, above and after a consonant akshara, only one is added to its left, namely, for short /i/.

In addition, the following two diacritics are used for phonemic nasal vowels and phonemic and allophonic nasal consonants: <◌ं> *Bindu*, and <◌ँ> *Chandrabindu*. The following minimal pairs illustrate the distinction between them:

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[2]The discussion on Devnāgarī below draws from a recent document entitled, 'Devanagari Script Behaviour for Hindi' prepared by the Expert Committee on Linguistic Resources and Language Technology Standards for the TDIL programme of the Department of Information Technology, Govt of India. The present author has been a member of the Committee.

[3]Listed as a vowel in Sanskrit grammar, it has lost its vocalic quality in all the present-day pronunciations of Sanskrit, alternatively pronounced as /ru/ in languages of south India.

TABLE 1
Consonants with phonetic values read vl = voiceless, vd = voiced, Asp = aspirated, Uasp = unaspirated

	vl Uasp	*vl Asp*	*vd Uasp*	*vd Asp*	*vd Uasp*	*vd Uasp*	*vd Uasp*	*vl*	*vd*
Laryngeal								ह	
Uvular	क़								ग़
Velar	क	ख	ग	घ	ङ			ख़	
Palato-alveolar								श	
Palatal	च	छ	ज	झ	ञ				य
Retroflex	ट	ठ	ड	ढ	ण			ष⁴	
Flap									
Dental/Alveolar	त	थ	द	ध	न	र	ल	स	ज़
Labio-dental								फ़	
Bilabial	प	फ	ब	भ	म				व

(4) बँटा /bə̃ʈaː/ 'divided'   बंटा /bənʈaː/   ('a name')

हँस /hə̃s/ 'laugh-IMP'   हंस /həns/   'swan'

The *Chandrabindu* always denotes a nasal vowel, known as *Anunāsika*, and a *Bindu* denotes a nasal consonant known as *Anuswāra* in an akshara with lateral or subscript, but not superscript, vowel mātrās, namely, ◌ ◌ा ◌ु ◌ू /ə a: u u:/. With the superscript mātrā vowels, namely, ि◌ ◌ी े◌ ◌ै ो◌ ◌ौ /ɪ i: e: æ: o: ɔ:/, a *Bindu* alone is used to stand ambiguously for both a nasal vowel and a nasal consonant. Lexical knowledge of the function of the diacritic in the words with the *Bindu* is presumed.

Hindi also preserves the use of a *Visarga* (more commonly used in Sanskrit), ◌:, with both a specific phonetic value, namely /h/, as in वस्तुतः /ʋəstutəh/ 'in fact', and a null value, as in दुःख /dukʰ/ 'sorrow'. The phonetic value is found only word-finally. The use of the *Visarga* with a null value in Hindi is on account of the continuity of the use of the orthographic forms that are originally Sanskrit, in which they had the phonetic value that has been lost. The phonetic value is found only word-finally.

TABLE 2
Vowels in Devanāgarī

Vowel	*Unicode Code-point*
अ	U+0905
आ	U+0906
इ	U+0907
ई	U+0908
उ	U+0909
ऊ	U+090A
ए	U+090F
ऐ	U+0910
ओ	U+0913
औ	U+0914
ऑ	U+0911

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⁴Although traditionally श and ष are in the abstract distinguished as palate-alveolar and retroflex voiceless fricatives, in isolation the distinction between them is neutralised in all varieties of standard Hindi. The grapheme, however, is retained in the orthography; the retroflex allophone is pronounced consonant clusters preceding retroflex plosives, e.g कष्ट /kəʂʈ/ 'pain', पृष्ठ /prɪʂʈʰ/ 'page', कृष्ण /krɪʂɳ/ 'Krishna'.

TABLE 3
Illustration of the mātrā diacritics for the vowels

Vowel grapheme	Unicode Code-point	Mātrā sign	Consonant shapes formed
अ	U+0905	Nil	क् + अ = क
आ	U+0906	ा	क् + आ = का
इ	U+0907	ि	क् + इ = कि
ई	U+0908	ी	क् + ई = की
उ	U+0909	ु	क् + उ = कु
ऊ	U+090A	ू	क् + ऊ = कू
ए	U+090F	े	क् + ए = के
ऐ	U+0910	ै	क् + ऐ = कै
ओ	U+0913	ो	क् + ओ = को
औ	U+0914	ौ	क् + औ = कौ
ऑ	U+0911	ॉ	क् + ऑ = कॉ

In consonant clusters with a preceding <र> /r/, the /r/ is represented as a superscript, e.g., /ɪp/ र्प, /rj/ र्य, etc. In clusters with /r/ as the last consonant, it is represented in three different shapes: (1) as a subscript as in /ɖr/ ड्र, /ʈr/ ट्र, etc., (2) as a lateral script, e.g., /kr/ क्र, /pr/ प्र, etc., and (3) an inscript, e.g., /hr/ ह्र.

HINDI PHONOLOGY AND ITS MAIN FEATURES

A brief sketch of Hindi phonology is presented below in a skeletal form. More detailed descriptions are available in Kelkar (1968), Ohala (1983) and Kachru (2006). The present description is based on all of them and Pandey (in press).

Consonant phonemes

The inventory of consonant phonemes in Hindi is given in the Table 4.

Vowel phonemes

The inventory of vowel phonemes is given in Table 5 and Table 6.

a. Oral vowels
b. Nasal vowels

TABLE 4
Consonant phonemes in Hindi

	Bilabial		Lab-Dental	Dental		Alv	Post-Alv	Retroflex		Palatal	Velar		Uvu.	Glottal
Plosive	p	b		t	d			ʈ	ɖ		k	g		
	pʰ	bʱ		tʰ	dʱ			ʈʰ	ɖʱ		kʰ	gʱ	(q)	
Nasal		m				n					(ŋ)			
Nasal Flap								ɽ̃						
Tap						ɾ								
Fricative		f	(v)			s	z ʃ				x	(ɣ)		h
Approx		ʋ								j				
Lat Appr						l								
Affricate										ʧ ʤ				
										ʧʰ ʤʱ				

TABLE 5
Oral vowel phonemes in Hindi

	Front	Central	Back
Close	ɪ iː		ʊ uː
Close-mid	eː		oː
Open-mid	ɛː (æː)	ə	ɔː
Open		aː	

Phonological processes

The following processes are taken into account in pronouncing the words. They are under-represented in the orthography.

Consonants

(5)

    1. Consonants are lengthened before /j w r/ non-initially. Aspirated plosives and affricates have their plosive parts lengthened, e.g., [pˑʰ tˑʰ] etc.

Vowels

(6)

    1. Vowels are lengthened word-finally, so that vowel lengthen distinction in Hindi is neutralised word-finally, e.g., /ətɪtʰɪ/ > [ətɪtʰiː] 'guest', /əpɪtʊ/ [əpɪtuː] 'but'.

Phonetic processes

Among the phonetic processes applying in the pronunciation of written words, the ones relating to vowels should be noted. The vowel sounds are represented in their phonemic forms, but have different allophonic pronunciations in the contexts mentioned below.

Vowels

(7)

    1. [e] < /ə/ occurs when followed by /h/, and a vowel other than /a aː/ in the next syllable.
    2. [e o] < /eː oː/ occur before /h/, e.g., /koːhraː/ > [kohraː] 'fog'; /meːhtaː/ > [mehtaː] (a last name).
    3. [əɪ]: < /ɛː/ and [əʊ] < /ɔː/ occur before vowels and semivowels, e.g., /bhɛːjaː/ > [bhəɪjaː] 'brother' (mainly vocative).

TABLE 6
Nasal vowel phonemes in Hindi

	Front	Central	Back
Close	ĩː ĩ		ũː ũ
Close-mid	ẽː		õː
Open-mid	ɛ̃ː	ə̃	ɔ̃ː
Open		ãː	

SYLLABLE STRUCTURE

Canonical syllable structure in Hindi

(8)

(C)(C)(C)V(C)(C)(C)

E.g., /aː/ 'come IMP', /ʃaːstr/ 'learned book'; /striːtʋ/ 'womanhood'.

Consonant clusters

The following consonant clusters are represented orthographically.

(9)

2 Consonant Clusters:

Initial   : (i) C+L/G; (ii) s+C.

Final   : general

Medial : general.

3 Consonant Clusters:

Initial   : /spr-, str-, smr-/

Final   : / -NPlr (e.g., -ntr, -ndr), -N-Pl-Appr (e.g., -ntj, ŋkhj), -str, -ʂʈr, -rdr, -tsj)

Medial : general.

AKSHARA-TO-SOUND RULES FOR DEVNĀGARĪ

Before attempting to formulate the Akshara-to-Sound rules for Hindi, it was found necessary to clarify the issue of the variety of Hindi to be described. The proposal was for the official variety of Hindi commonly used by the educated. We have encountered two versions of the official standard varietiy—one, the formal variety that is close to standard spoken Hindi, being called 'Spoken Formal Hindi' (SFH), and the other a frozen variety, called 'Frozen Formal Hindi' (FFH), that is highly Sanskritised, and marked by certain features, such as the following:

(10)

    i. the presence of final short vowels found represented in written Hindi, e.g., <अपितु> /əpɪtʋ/ 'but', <अतिथि> /ətɪtʰɪ/ 'guest', etc.

    ii. word-internal schwas that are normally deleted in spoken Hindi may be kept, e.g., <कमला> is pronounced as /kəməlaː/ instead of the more common form /kəmlaː/.

The Akshara-to-Sound rules proposed here are for the Spoken Formal Hindi, not the Frozen Formal Hindi. The rules proposed in six sets are described below.

Akshara-to-sound rules set 1 (correspondence rules)

[11] The first sub-set of Akshara-to-Sound correspondence rules is regarding a one-to-one correspondence between the two arrays of symbols given in a specified

order—the Devnāgarī Aksharas in the Unicode for consonants and vowels (see Tables 1 and 2), on the one hand, and the IPA symbols, also in the Unicode, for consonant and vowel phonemes (see Tables 3 and 4), on the other. The rule of correspondence specified the presence of the inherent vowel with each consonant Akshara, e.g., the Akshara <क> = /kə/ and <प> = /pə/.

[12]. The second sub-set of Akshara-to-Sound correspondence rules is regarding the IPA equivalents of the Devnāgarī consonant + vowel mātrās as illustrated in Table 3, e.g., <का> = /ka:/, <कि> = /ki/, etc.

[13]. The third sub-set of Akshara-to-Sound correspondence rules is regarding the complex Devnāgarī Aksharas with two- and three-consonant clusters, e.g., <स्व> = /swə/, <क्त> = /ktə/ and <र्म> = /rmə/.

AKSHARA-TO-SOUND RULES DEPENDENT ON LINGUISTIC PROCESSES

Segmental rules

After the preliminary correspondence rules between the Devnāgarī Aksharas and their IPA equivalents, the next step was to formulate rules for incorporating two generalisations about the word forms in Hindi. One is the fact that there are no final schwas, and the second is that short vowels are lengthened finally. These are formulated as follows:

[14] Final Schwa Deletion (FSD) or, put as a constraint, *FINAL SCHWA (i.e., 'No final Schwa').

Choudhary (2003) note that there are exceptions to this generalisation in consonant clusters ending in a /w/ or a /j/. However, we did not find strong evidence for the exception, so we have let FSD apply in general.

[15]. Final Vowel Lengthening (FVL): The short vowels (/ɪ ʊ/ are lengthened word-finally to /i: u:/.

This rule is also allowed to apply in general in the style chosen for description here.

Prosodic structure rules

Recent proposals for refined TTS systems have argued for incorporating prosodic structure processes not only at the levels of the phrase and the sentence, but also at the level of the word. Thus FESTIVAL has provision for the specification of the prosodic structures of words.

Two aspects of prosodic structure characterise words—the syllable structure and the foot structure. Foot structures predict stress(es) in words.

One main difficulty in having too many units, such as the Syllable and the Foot, at the word level is that the Akshara-to-Sound rules for accounting for them will be too complex to formulate. We have found a way around this problem by introducing only syllables (σ) as units, and incorporating feet in terms of labels to syllables in the way described in the section on Foot Construction below.

[16] Syllabification rules

This set of rules specifies grouping of segments into syllables within a word, e.g., /səma:tʃa:r/ is syllabified as consisting of three syllables: /sə. ma:.tʃa:r/. A syllabification rule is the following:

   a. #C$^+$V = #C$^+$Vσ [i.e., There is a syllable division following a vowel after one or more consonants word-initially.]
   b. VCC$^+$V = VCσ C$^+$V [i.e., Between two vowels, there is a division between the first and the other consonants]

The logic of the computational rule for syllable division is shown in the following pseudocode, that is, informal rules mixing formal and ordinary language. The terms *"char array"* and *"vowel array"* refer to the lists of the segments in general and of the vowels.

   a. String s ⟵ ipa equivalent after end schwa deletion.
   b. Find the length of string s and assign it to integer variable *len*
   c. char s1[] ⟵ char array for storing characters of string S.
   d. Count the number of vowels in the char array (By comparing the char array elements with the elements of vowel array using equals function in java) and find its position in the array.
   e. Count the number of consonants between two consecutive vowels.
   f. If count = 0 then V ⟵ V/ (forward slash is for syllable break)
   g. If count = 1 then v ⟵ V/CV
      etc.

The syllable division rules for intervocalic consonants given in (7) above has been treated variously. Linguistically there are various ways to account for intervocalic clusters such as C+l/r/w/j, because they often have geminate consonants on the surface, CC+l/r/w/j, e.g., /səbʰjəta:/ → /səbbʰjəta:/. Thus Choudhury and Basu (2002) go into a long discussion of these clusters based on their treatment in the literature (e.g., Ohala, 1983) and propose complex rules. We have accounted for the facts simply in terms of two rules—one as given in (7), and the other as a rule of gemination:

[17]. Consonant Gemination

   C+r/l/w/j → CC+r/l/w/j.

Rule [16] is ordered after rule [17].

Foot construction rules implemented as syllable labelling rules

Foot construction rules are instrumental in predicting word-stress (see Hayes, 1995). In the work on a pronunciation lexicon for Hindi being reported here, the notion of stress feet is translated in terms of strong syllables (σs), according to the generalisations of word-stress in Hindi. In the paragraph below, we explain how parsimony and simplification in the Akshara-to-Sound rules have been achieved by treating a Foot as equivalent to a strong syllable. We then go on to discuss the main parameters in predicting stress in Hindi.

The most important feature of a Foot is that it has one strong syllable (σs) and, optionally, one or more than one weak syllable; it is the strong syllable that is stressed. Once syllables are labelled as strong (σs) and weak (σw), the need to include the Foot is

circumvented. We simply count the number of strong syllables to count stresses in words. IPA distinguishes between two degrees of stress—primary, marked as a superscript before the stressed syllables /'/, and secondary stress, marked as a subscript before the stressed syllable. Thus, in the words /'si:.ta:/ '(a name)' and /'sə.ma:.'ʧa:r/ 'news', we have one and two stresses, respectively These are accounted for in terms of labelled syllables- <सीता> /si:σsta:σw/ and <समाचार> /səσsma:σwʧa:rσs/. In the first word, there is only one strong syllable, whereas in the second word there are two strong syllables. The difference in the degrees between stresses within words in Hindi is variable. Thus, the word /'sə.ma:.'ʧa:r/ can be said with primary stress on the last syllable or the first: [ˌsəma:'ʧa:r] ~ ['səma:ˌʧa:r]. The middle syllable, however, is not stressed.

The main parameters of a foot structure in Hindi are the following (Hayes, 1995; Pandey, 1989):

i. Quantity sensitivity. It has been argued (Kelkar, 1968; McCarthy & Prince, 1993; Pandey, 1989) that Hindi has three degrees of syllable weight: Light (L)- CV, the first syllable in किताब /ki'ta:b/ 'book', Heavy (H)- CV:/ CVC, both syllables in वाजिब / 'ʋa:ʤib/ 'just, correct', and Superheavy (H')- CV:C/ CVCC, the final syllables in किताब /ki'ta:b/ 'book' and पदस्थ /pə'dəstʰ/ 'in position'.

ii. Rhythm. Feet in Hindi are moraic trochees, i.e., a foot has two morae, of which the left is stressed. In other words, given a sequence of Light Light, the left one is stressed- 'LL. A Heavy syllable is stressed, as it has two morae- 'H.

iii. Extrametricality. Heavy syllables are not stressed finally, e.g., /bə'ha:na:/ 'excuse', / 'kəʋita:/, etc. The final Heavy syllable must be marked as extrametrical- bə'ha: <na:>. We will not go into details here (see Hayes, 1995), as the discussion will lead us away from the main topic.

iv. Stress clash. Two adjacent stressed syllables do not occur. A Heavy syllable before a stressed syllable is not stressed. The exception to this is the Superheavy syllable. We have argued elsewhere (Pandey, 1989) that this is so on account of Superheavy syllables behaving actually like a sequence of Heavy and Light syllables. Whereas a heavy syllable before a Superheavy syllable is not stressed, a Superheavy syllable before a Heavy syllable is, as the grounds for stress clash are not met in such a situation:

(18)

/ 'səma:'ʧa:r/   */se'ma:'ʧa:r/   'news'
/ 'a:n'do:lən/   */a:n'do:lən/   'agitation'

v. Degenerate feet. In Hindi, a Light syllable is stressed when it is the only syllable that can be stressed. The situation arises in words with L + H structures, like / 'kəla:/ 'art', / 'kəməl/ 'lotus'. In these words, the final Heavy syllable is extrametrical, / 'kə<la:>/, / 'kə<məl>/. And thus the Light syllable is stressed. In L + H' (i.e., Light + Superheavy) syllables, the situation does not arise, as e.g., /si'ta:r/ 'sitar', /mə'ha:n/ 'great'.

The above facts are translated into the following Akshara-to-Sound rules.

Syllable labelling rules

[19] All Light, Heavy and Superhavy syllables are labelled as σ$_w$, σ$_s$ and σ$_S$, respectively.

Syllable relabelling rules

Three relabelling rules are proposed:

[20]. Extrametricality rule to mark all final heavy syllables as extrametrical
   i. $\sigma_s \rightarrow \langle\sigma_s\rangle$ / X__ #, where X is not #.
[21]. A rule to relabel σ_s into σ_w in given contexts.
[22] A rule to relabel σ_w into σ_s, as in /pəσ_w riσ_w ʋaːrσ_s/ $\rightarrow$ / pəσ_s riσ_w ʋaːrσ_s/ 'family'.

[23] Internal Schwa Deletion

Based on the prosodic structure dependent labelling and relabelling of syllables as strong and weak, the deletion of all internal schwas in Standard Formal Hindi are accounted for by the following rule (Pandey, 1990):

$$\text{ə} \rightarrow \varnothing / \_\_ \sigma_w$$

I.e., [ə] is deleted if it occurs in an open weak syllable.

The rule applies in forms such as /təσ_sbə$\sigma_w$$\langle$laː$\rangle$/ > /tə$\sigma_sb\sigma_w$$\langle$laː$\rangle$/

The derivation above is intermediate and is followed by resyllabification.

[24] Re-resyllabification

Following the internal schwa deletion, the syllabic groupings of the segments is affected, leading to the consonant before the deleted schwa being resyllabified, but not affecting the labelling.

The full derivation of a form involving all the Akshara-to-Sound rules is given below.
(25)

कमला	Akshara
/kəmalaː/	IPA conversion and mātrā vowel assoiation
/kəʊ məʊ laːʊ/	Syllable division
/kəσ_w məσ_w laːσ_s /	Syllable labelling
/kəσ_w məσ_w laː$\langle\sigma_s\rangle$/	Syllable relabelling- extrametricality
/kəσ_s məσ_w laː$\langle\sigma_s\rangle$/	Syllable relabelling ($\sigma s \rightarrow \sigma w$; $\sigma w \rightarrow \sigma s$)
/kəmσ_s laː$\langle\sigma_s\rangle$/	Internal Schwa Deletion and Resyllabification
	(This is the $\langle$/PS$\rangle$ level of the entry of the Hindi lexicon, as illustrated in (3))
/ 'kəmlaː/	Output of Akshara-to-Sound rules (This is the $\langle$/phoneme$\rangle$ level of the entry of the Hindi lexicon, as illustrated in (2))

Based on the above rules, the program of Akshara-to-Sound rules in Hindi can be run through a text of any size.

WRINKLES IN AKSHARA-TO-SOUND RULES

In spite of a very high degree of regularity of the application of the Akshara-to-Sound rules, there are certain wrinkles, having to do with the irregularity in the language itself.
   These are briefly discussed below.

i. The orthography-phonology correspondence is occasionally irregular in two ways. One, a corresponding sound vis-à-vis a certain Akshara may be absent in actual use, although a very formal style has it, as the example in (26a) below shows. The more common pronunciation of the lexeme doesn't have a final /j/ in it. The Pronunciation Lexicon Specifications have the option <prefer> to show preference for a more common variant. Two, the addition of a suffix Akshara may follow a word-internal schwa deletion, yielding an output-output relation, as exemplified in (26b). Given the orthographic representations कसरती /kəsərəti:/ 'exercised' and कुदरती /kudərəti:/ 'natural', their pronunciations take into account the internally deleted schwa (/kəsrət/ and /kudrət/) as the input for the addition of the suffix vowel /i:/. These instances have to be entered as individual items to avoid wrong outputs.

(26)

	Akshara	Common pronunciation	Corresponding pronunciation	Word structure	Gloss
a)	पाण्डेय	/pa:ɳɖe:j/	/pa:ɳɖe:/	------	'(a name)'
b)	कसरती	/kəsərəti:/	/kəsrəti:/	[[kəsrət] i:]	'muscular/ having exercised'
	कुदरती	/kudərəti:/	/kudrəti:/	[[kudrət] i:]	'natural'
	मसनदों	/məsənədõ:/	/məsnədõ:/	[[məsənəd] õ:]	'a kind of cushion + Pl-OBL'

The case in (26a) is an example of irregular Akshara to sound correspondence on account of frequency of use; the final /j/ sound tends to be dropped. Examples such as these appear to be limited in number, and have to be thoroughly investigated. The cases in (26b) are much larger in number, and involve what has been called in recent phonological literature (see, for example, Benua, 1997; Kager, 1999; McCarthy, 1995) as Output-to-Output (OO) relation between forms. Here the complex word (e.g., /kəsrəti:/) takes the output form of the stem (e.g., ['kəsrət] from /'kəsərət/ after internal schwa deletion) as the input for the addition of the suffix vowel /i:/ and gives the output ['kəsrəti:]. Had the output taken the orthographic form of the complex word, wrong output would result *[kə'sərti:].

ii. There is evidence for POS sensitive word-stress in Hindi in a limited way. Examples in (27) and (28) show identical graphemic representations of words with different POS tags. The words in (27) are all imperative forms with final stress on Heavy syllables, which are in general extrametrical, as shown for the past tense forms of the verbs in (28)[5].

(27)

/di'kha:/ 'show CAUS+IMP+NH'   /ʧə'la:/ 'move CAUS+IMP+NH'

/gi'ra:/ 'fall CAUS+IMP+NH'   /su'na:/ 'hear CAUS+IMP+NH'

/pə'ʈha:/ 'read CAUS+IMP+NH'   /mi'la:/ 'mix CAUS+IMP+NH'

(28)

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[5]The grammatical used in the glosses have their full forms as follows: CAUS= CAUSATIVE, IMP= IPERATIVE, NH= NON-HONORIFIC, VTR= VERB TRANSITIVE, VINTR= VERB INTRANSITIVE, 3PS= THIRD PERSON SINGULAR, PST= PAST

/ ˈdikha:/ 'was seen'   / ˈʧəla:/ 'move VINTR+3PS+PST'

/ ˈgira:/ 'fall VINTR+3PS+PST'   / ˈsuna:/ 'hear VINTR+3PS+PST'

/ ˈpəʈha:/ 'read VTR+3PS+PST'   / ˈmila:/ 'meet VTR/ VINTR+3PS+PST'

There is evidence for Indic languages to show the need for Part-of-Speech (POS) tags in the pronunciation of words. Das Mandal, Lata, and Chandra (2010) discuss the need for Bangla pronunciation. Rao et al. (2012) discuss evidence for the role of morphological context in orthographic feature encoding in Hindi.

The role of POS in the subset of forms exemplified in (27) and (28) can be included as a variable, as licensed by the SSML document within the specifications of the World Wide Consortium. The difference between the forms in (27) and (28) can be accounted for by specifying that one of the rules, namely, extrametricality, does not apply to the forms in (27).

iii. As pointed out above in connection with the use of the Devnāgarī diacritics *Bindu* and *Chandrabindu* for nasal consonants and nasal vowels respectively, the correspondence is ambiguous for mātrā vowels with superscripts.

The *Bindu* stands for *Anuswāra* or nasal consonants homorganic with the following plosives when placed on vowel mātrās that are not superscripts. For example, कं/ सां/ पुं / can stand for kəm, kən, kəɳ, kəɲ and kəŋ/ sam, san, saɳ, saɲ and saŋ/ pum, pun, puɳ, puɲ and puŋ, respectively.

The *Chandrabindu* stands for *Anunāsika* on vowel mātrās that are not superscripts: thus कँ/ साँ/ पूँ stand for only kə̃/ sã/ pū, respectively.

However, for the superscripted vowel mātrās, the present-day Devnāgarī has only the *Bindu*, which functions for both the *Anuswāra* and the *Anunāsika*: thus कों stands for both *Anunāsika* (kõ as in कोंपल /kõ:pəl/'bud') and *Anuswāra* (kom, kon, koɳ, koɲ, koŋ as in कोंडा /ko:ɳɖa:/, कोंकण /kõ:ŋkəɳ/, etc.). The examples can be given for all the vowel mātrās represented with superscript diacritics, e.g., सिंध /sindʱ/, 'Sindh' and /sĩʧa:i:/ सिंचाई 'irrigation'.

The ambiguity in the use of the *Bindu* with superscript vowel mātrās has to be resolved item-wise, unless the orthography is revised in favour of its wider use and for facilitating technological use of Devnāgarī.

iv. Finally, compound words in Hindi are a problem for Akshara-to-Sound rules. However, the problematic cases are restricted to only those compound words whose first stem (in case of a two-word compound) or whose first and second stems (in case of a three-word compound) ends in a consonant without a mātrā vowel, or, in other words, ends with an inherent schwa, e.g., लोक–सभा /lo:k-səbʱa:/ 'parliament'. If entered in this form, with a hyphen between the two stems, the Akshara-to-Sound rule will give the correct output. However, if the compound is entered without a hyphen, as लोकसभा, then, as pointed out by Choudhary and Basu (2002) and Bali, Talukdar, Krishna, and Ramakrishnan (2004), the word will have a schwa that will not be deleted, rather that will be pronounced with a stress /lo:ˈkəsəbʱa:/. This will be optionally pronounced as /lo:ˈkəsbʱa:/ with internal schwa deletion, an entirely undesirable output form. Many compound words are entered in the unanalysed form (e.g., मनचला /mənʧəla:/ 'sporty', सिरफिरा /sirpʰira:/ 'eccentric', especially reduplicated forms and 'echo-words', that is onomatopoeic reduplicated forms (e.g., खटखटाना /kʰəʈkʰəʈa:na:/ "to knock") that are in a large number in the language. The texts containing such words have to be normalised with a hyphen separating the stems in the compounds. A program to analyse compounds in terms of their stems is of critical importance in a pronunciation lexicon of Hindi.

EVALUATION

The program of Akshara-to-Sound rules described above has yet to be fully evaluated. A preliminary test was carried out for the forms with regard to the deleted schwas both word-finally and word-internally. The evaluation was carried out by researchers with Hindi as their mother-tongue. The program was first run on a file containing 16,000 words both simple and compound, without normalising the text, for example, by introducing the hyphen between stems in a compound word. Of these 14,800 were found to be correct in all, with errors for 1200 words. All the cases of error were for compound words. The percentage of accuracy consequently was approximately 92.5%. However, the researchers ran the program a second time after normalising the compound words and the echo-words by inserting a [-] mark between the stems, e.g., लोक-सभा /loːkə-səbʰaː/ 'parliament' and खट-खटाना [[kʰəʈə]-[kʰəʈaːnaː]] 'to knock'. The percentage of accuracy was found to be 100%. The testing was only for the pronunciation of forms with deleted schwas. There are problems, however, with the nasal vowels, among other features, that cannot be entirely predicted by Akshara-to-Sound rules. The pronunciation lexicon according to the specifications of W3C has ways to circumvent such difficulties, as discussed in the introduction to this paper.

CONCLUSIONS AND IMPLICATIONS

We have tried to account for the relevant issues relating to the formulation and application of Akshara-to-Sound rules for Hindi. There is evidence for some lexical and morphological knowledge required in processing the written Hindi forms. The cases that were discussed above are the following:

(29) i.   Part-of-Speech information for word-stress in subsets of lexical items, e.g., imperative   forms of verbs,

ii. individual words, both simple and complex, having irregular Akshara-to-Sound   correspondence, either on account of use (in the case of simple words) or on account of   output-to-output relation between the stem and the word (in the case of complex   words),

iii. complex words having output-to-output relation between Aksharas and the sounds,

iv. the diacritic "*bindu*" being ambiguously used for both nasal consonants and nasal   vowels with superscript mātrā vowels, and

v.   compound and echo words and without vowel-sandhi and hyphen marks.

It was shown that the first of these is accounted for by using the variable of Part-of-Speech by the Akshara-to-Sound rules, as there is provision for including Part-of-Speech information in the rules within the specifications of pronunciation lexicons according to World Wide Consortium. For the last of these, namely, compound words without vowel-sandhi and hyphen marks, the processing of lexical items requiring morphological information can be facilitated with the normalisation of texts, introducing hyphen marks between the stems. For the others, item-wise lexical specification of pronunciations is required.

It is logical to assume that all those cases that are a problem for the application of the Akshara-to-Sound rules for a pronunciation lexicon of Hindi will also need to be addressed for the acquisition of reading of Devnāgarī for Hindi. Some of the recalcitrant cases militating against systematic prediction by the set of the Akshara-to-Sound rules have

indeed been found also to be problematic in the work on acquisition and processing of Akshara-based writing systems. For instance, Vasanta's (2004) study shows that when tested on words with the bindu used for homorganic consonants in Telugu, children behaved differently. Sircar and Nag (in press) show that word-internal schwa deletion in Bangla can be vulnerable to errors. They arrive at the result by testing on the reading by children of non-words for forms that have inconsistent akshara-syllable matching in the word-medial position as $/CVCaCV/\sim/CVC^0CV/$. They found that either of the output forms were produced by the children.

In more general studies on reading acquisition (e.g., Goswami, 1997), it has been argued that for all orthographies, strategies are used that involve both correspondence between individual graphemes and sounds and the reorganisation and restructuring of the correspondence. We have produced evidence here for the pronunciations of written words in Hindi that depend on both one-to-one correspondence between the grapheme and the sound as well as the overall grouping and regrouping of syllables leading to deletion of vowels, gemination of consonants and word-stress. Wimmer and Goswami (1994) presented evidence for the adoption of two distinct word recognition styles by English- and German-speaking children. While English-speaking children used direct word recognition strategy of whole word recognition, German-speaking children used the indirect strategy of assembling the pronunciation of words based on letter to sound correspondence. A consideration of the Akshara-to-Sound rules and the cases of output-to-output correspondence in Hindi provides evidence of the need to use both the strategies of word recognition by Hindi-speaking children—the output-to-output or lexically determined cases must involve direct means, while the rest must involve the indirect means of assembling the correspondence by grouping and regrouping of sounds into syllables. Dyslexic children for Hindi (Gupta, 2004) and Kannada (Karanth, Mathew, & Kurien, 2004) have been found to have difficulties with strategies requiring syllabic-level synthesis and lexical decisions on the pronunciations of words.

Ziegler and Goswamy (2005) consider the *inconsistency problem* as one of the three important problems in a theory of reading acquisition termed as 'psycholinguistic grain size theory', the other two problems being the *availability problem* and the *granularity problem*. The *consistency problem*, according to them, 'reflects the fact that some orthographic units have multiple pronunciations and that some phonological units have multiple spellings...' (p. 3). The types of inconsistency found in the patterning of stress and its consequences on the realisation of segments (e.g., /ˈkəsrəti:/ vs */kəˈsərti:/ in (26b)) discussed above provide useful data for non-obvious inconsistency at the grain-size level of the word. The problems of how to read and to spell in relation to an inconsistency type such as those need further exploration. It is hard to imagine how such inconsistencies would surface without an investigation of the kind reported here.

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